**OPTIMAL VLSI ARCHITECTURAL
SYNTHESIS**
Area, Performance and Testability

THE KLUWER INTERNATIONAL SERIES IN ENGINEERING AND COMPUTER SCIENCE

VLSI, COMPUTER ARCHITECTURE AND DIGITAL SIGNAL PROCESSING

Consulting Editor
Jonathan Allen

Latest Titles

Low-Noise Wide-Band Amplifiers in Bipolar and CMOS Technologies,

Z. Y. Chang, W. M. C. Sansen,
ISBN: 0-7923-9096-2

Iterative Identification and Restoration of Images, R. L. Legendijk, J. Biemond

ISBN: 0-7923-9097-0

VLSI Design of Neural Networks, U. Ramacher, U. Ruckert

ISBN: 0-7923-9127-6

Synchronization Design for Digital Systems, T. H. Meng

ISBN: 0-7923-9128-4

Hardware Annealing in Analog VLSI Neurocomputing, B. W. Lee, B. J. Sheu

ISBN: 0-7923-9132-2

Neural Networks and Speech Processing, D. P. Morgan, C. L. Scofield

ISBN: 0-7923-9144-6

Silicon-on-Insulator Technology: Materials to VLSI, J. P. Colinge

ISBN: 0-7923-9150-0

Microwave Semiconductor Devices, S. Yngvesson

ISBN: 0-7923-9156-X

A Survey of High-Level Synthesis Systems, R. A. Walker, R. Camposano

ISBN: 0-7923-9158-6

Symbolic Analysis for Automated Design of Analog Integrated Circuits,

G. Gielen, W. Sansen,
ISBN: 0-7923-9161-6

High-Level VLSI Synthesis, R. Camposano, W. Wolf,

ISBN: 0-7923-9159-4

Integrating Functional and Temporal Domains in Logic Design: The False Path

Problem and its Implications, P. C. McGeer, R. K. Brayton,
ISBN: 0-7923-9163-2

Neural Models and Algorithms for Digital Testing, S. T. Chakradhar,

V. D. Agrawal, M. L. Bushnell,
ISBN: 0-7923-9165-9

Monte Carlo Device Simulation: Full Band and Beyond, Karl Hess, editor

ISBN: 0-7923-9172-1

The Design of Communicating Systems: A System Engineering Approach,

C. J. Koomey
ISBN: 0-7923-9203-5

Parallel Algorithms and Architectures for DSP Applications,

M. A. Bayoumi, editor
ISBN: 0-7923-9209-4

Digital Speech Processing: Speech Coding, Synthesis and Recognition,

A. Nejat Ince, editor
ISBN: 0-7923-9220-5

Assessing Fault Model and Test Quality, Kenneth M. Butler, M. Ray Mercer

ISBN: 0-7923-9222-1

OPTIMAL VLSI ARCHITECTURAL SYNTHESIS

Area, Performance and Testability

Catherine H. Gebotys

and

Mohamed I. Elmasry

University of Waterloo

Springer Science+Business Media, LLC

Library of Congress Cataloging-in-Publication Data

Gebotys, Catherine H.

Optimal VLSI architectural synthesis : area, performance, and testability / Catherine H. Gebotys and Mohamed I. Elmasry.

p. cm. -- (The Kluwer international series in engineering and computer science. VLSI, computer architecture, and digital signal processing)

Includes bibliographical references and index.

ISBN 978-1-4613-6797-0 ISBN 978-1-4615-4018-2 (eBook)

DOI 10.1007/978-1-4615-4018-2

1. Computer architecture. 2. Integrated circuits--Very large scale integration. I. Elmasry, Mohamed I., 1943- . II. Title.

III. Series.

QA76.9.A73G42 1992

004.2'2--dc20

91-31898

CIP

Copyright 1992 Springer Science+Business Media New York

Originally published by Kluwer Academic Publishers in 1992

Softcover reprint of the hardcover 1st edition 1992

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, mechanical, photo-copying, recording, or otherwise, without the prior written permission of the publisher, Springer Science+Business Media, LLC .

Printed on acid-free paper.

To

Robert Joseph and Kathleen Vanessa Gebotys

and

Elizabeth, Carmen, Samir, Nadia and Hassan Elmasry

Table of Contents

Preface	xiii
PART I: INTRODUCTION	1
1. GLOBAL VLSI DESIGN CYCLE	3
1.1 VLSI DESIGN CYCLE	4
1.2 HYBRID SYSTEMS DESIGN	10
1.3 IMPACT OF TECHNOLOGIES	12
1.4 TEST CONSIDERATIONS	14
1.5 BOTTLENECKS AND OPEN ISSUES	17
1.6 FOCUS OF TEXT	19
2. BEHAVIORAL AND STRUCTURAL INTERFACES	21
2.1 INPUT TO AN ARCHITECTURAL SYNTHESIZER	21
2.2 INTERFACE PRIMITIVES FOR EXTERNAL PROCESSES	25
2.3 OUTPUT PRIMITIVES FROM AN ARCHITECTURAL SYNTHESIZER	31
PART II: REVIEW AND BACKGROUND	37
3. STATE OF THE ART SYNTHESIS	39
3.1 TERMINOLOGY AND SUBTASK DEFINITIONS	39
3.2 HIGH LEVEL TRANSFORMATIONS	43
3.3 INDEPENDENT SUBTASK OPTIMIZATION	45

3.3.1 Scheduling	45
3.3.2 Resource Allocation	46
3.4 ITERATIVE AND SIMULTANEOUS APPROACHES	51
3.5 MATHEMATICAL APPROACHES	55
3.5.1 Branch and Bound	55
3.5.2 Simulated Annealing	57
3.5.3 Makespan Scheduling	58
3.5.4 Feasibility Models	58
3.6 TIMING CONSTRAINED SYNTHESIS	59
3.7 COST FUNCTIONS FOR DESIGN EVALUATION	61
4. INTRODUCTION TO INTEGER PROGRAMMING	63
4.1 APPLICATIONS AND MODELS	64
4.2 SOLUTION OF UNSTRUCTURED IPs	66
4.3 POLYHEDRAL APPROACHES TO SOLVING IPs	71
4.4 THE NODE PACKING PROBLEM	73
4.5 THE KNAPSACK PROBLEM	78
PART III: OPTIMAL ARCHITECTURAL SYNTHESIS WITH INTERFACES	81
5. A METHODOLOGY FOR ARCHITECTURAL SYN- THESIS	83
5.1 REQUIREMENTS FOR HIGH LEVEL SYNTHESIS TOOLS	83
5.2 HIGH LEVEL METHODOLOGY	85

5.3 OASIC METHODOLOGY	88
5.4 AN INTRODUCTION TO OASIC	90
5.5 OASIC TERMINOLOGY, ASSUMPTIONS, AND PREPROCESSING	92
5.5.1 Terminology	92
5.5.2 Assumptions	94
5.5.3 Preprocessing	94
6. SIMULTANEOUS SCHEDULING, AND SELECTION AND ALLOCATION OF FUNCTIONAL UNITS	97
6.1 THE FORMAL MODEL	98
6.2 COST FUNCTIONS	105
6.3 FUNCTIONAL UNIT TYPE SELECTION	106
7. OASIC: AREA-DELAY CONSTRAINED ARCHITEC- TURAL SYNTHESIS	109
7.1 THE PRECEDENCE CONSTRAINED SCHEDULING MODEL	110
7.2 FUNCTIONAL UNIT ALLOCATION	111
7.3 REGISTER ALLOCATION	111
7.4 BUS ALLOCATION	114
7.5 COST FUNCTIONS	119
7.6 APPLICATION SPECIFIC TIGHTENING OF CON- STRAINTS	120
8. SUPPORT FOR ALGORITHMIC CONSTRUCTS	123
8.1 CONDITIONAL CODE	123
8.2 LOOPS	126
8.3 FUNCTIONAL PIPELINING	126

9. INTERFACE CONSTRAINTS	129
9.1 GENERAL INTERFACE: MINIMUM AND MAX- IMUM TIMING CONSTRAINTS	130
9.2 ANALOG INTERFACE: FIXED TIMING CON- STRAINT	131
9.3 ASYNCHRONOUS INTERFACE	132
9.4 UNKNOWN UNBOUNDED DELAYS	138
9.5 COMPLEX TIMING CONSTRAINTS	138
10. OASIC SYNTHESIS RESULTS	141
10.1 ELLIPTICAL WAVE FILTER	144
10.1.1 Structured Model	144
10.1.2 Area-Delay Optimized	150
10.2 NEURAL NETWORK ALGORITHM	162
10.3 CONDITIONAL CODE EXAMPLE	169
10.4 ANALOG AND ASYNCHRONOUS INTERFACE EXAMPLES	171
10.6.1 Analog Interface	172
10.6.2 Asynchronous Interface	172
PART IV: TESTABLE ARCHITECTURAL SYNTHESIS	177
11. TESTABILITY IN ARCHITECTURAL SYNTHESIS	179
11.1 DESIGN AND TEST	180
11.1.1 Choices in Design and Test	183
11.2 APPROACHES TO TESTABILITY	188
11.2.1 Test Measures and Tools	188

11.2.2 Design Modifications for Testability	193
11.3 PREVIOUS RESEARCH IN DESIGN FOR TEST	200
11.4 APPROACHES TO TEST WITH SYNTHESIS	202
11.4.1 Previous Research	202
11.4.2 Commercial Systems	203
11.5 INADEQUACIES OF CURRENT SYNTHESIS WITH TEST	204
11.5.1 Feedback	204
11.5.2 Integration	205
11.5.3 Constraint Estimation	205
12. THE CATREE ARCHITECTURAL SYNTHESIS WITH TESTABILITY	207
12.1 PROBLEM DESCRIPTION	208
12.2 COMPARISON WITH PREVIOUS RESEARCH	212
12.3 TWO SYNTHESIS WITH TEST METHODOLOGIES: CATREE & CATREE2	213
12.4 CATREE DESIGN SYNTHESIS STAGES	216
12.4.1 Input Specification	217
12.4.2 Design Allocation	217
12.4.3 CATREE Area and Delay Estimates	224
12.4.4 Test Incorporation	226
12.4.5 Feedback	231
12.5 CATREE SYNTHESIS RESULTS	235
12.6 CATREE DISCUSSION	239

12.7 CATREE2 DESIGN SYNTHESIS STAGES	243
12.7.1 Tree Formation and Functional Unit Binding	244
12.7.2 Test Incorporation	245
12.7.3 (Test) Register and Bus Binding	248
12.7.4 Feedback	250
12.8 CATREE2 EXPERIMENTS	251
12.9 CATREE2 DISCUSSION	254
PART V: SUMMARY AND FUTURE RESEARCH	259
13. SUMMARY AND FUTURE RESEARCH	261
13.1 OASIC SUMMARY	261
13.2 CATREE SUMMARY	266
13.3 FUTURE EXTENSIONS	267
13.4 CONCLUDING REMARKS	269
REFERENCES	271
INDEX	287

PREFACE

Although research in architectural synthesis has been conducted for over ten years it has had very little impact on industry. This in our view is due to the inability of current architectural synthesizers to provide area-delay competitive (or "optimal") architectures, that will support interfaces to analog, asynchronous, and other complex processes. They also fail to incorporate testability. The OASIC (optimal architectural synthesis with interface constraints) architectural synthesizer and the CATREE (computer aided trees) synthesizer demonstrate how these problems can be solved.

Traditionally architectural synthesis is viewed as NP hard and therefore most research has involved heuristics. OASIC demonstrates by using an IP approach (using polyhedral analysis), that most input algorithms can be synthesized very fast into globally optimal architectures. Since a mathematical model is used, complex interface constraints can easily be incorporated and solved.

Research in test incorporation has in general been separate from synthesis research. This is due to the fact that traditional test research has been at the gate or lower level of design representation. Nevertheless as technologies scale down, and complexity of design scales up, the push for reducing testing times is increased. One way to deal with this is to incorporate test strategies early in the design process. The second half of this text examines an approach for integrating architectural synthesis with test incorporation. Research showed that test must be considered during synthesis to provide good architectural solutions which minimize

area delay cost functions.

Though originally developed separately, OASIC and CATREE can be integrated so that OASIC simultaneously schedules and allocates the architecture and CATREE performs binding (and reallocating) of the architecture for testability.

Part I introduces the motivation and current open problems with high level CAD. Part II provides the necessary background material on architectural synthesis and integer programming. This part includes a definition of problems in both areas and a brief review of previous approaches to solving these problems. Part III outlines the OASIC methodology, models, the solution techniques used, and some synthesized results. Part IV outlines the CATREE methodology, the algorithms and data structures used and some synthesized results. Part V provides a brief discussion and concluding remarks concerning how we will interface with CAD tools of the future.

The book can be used at the senior undergraduate and graduate levels in courses dealing with computer architectures, computer organization, VLSI design, computer-aided design, VLSI digital signal processing, testing, or integer programming. It will be also of value to researchers dealing with these topics.

C.H. Gebotys

M.I. Elmasry

Waterloo, Ontario, Canada