
Contents

| | | |
|----------|---|----|
| 1 | Introduction | 1 |
| 1.1 | Hardware Description Languages | 1 |
| 1.2 | Hardware Synthesis | 7 |
| 1.2.1 | High-Level Synthesis | 8 |
| 1.3 | Motivation for Higher Level Tools | 14 |
| 1.3.1 | Lack of Structuring Support | 14 |
| 1.3.2 | Limitations of Static Scheduling | 15 |
| 1.4 | Structure of the Monograph | 16 |
| 2 | Related Work | 19 |
| 2.1 | Verilog and VHDL | 19 |
| 2.2 | The Olympus Synthesis System | 23 |
| 2.2.1 | The HardwareC Language | 23 |
| 2.2.2 | Hercules | 25 |
| 2.2.3 | Hebe | 25 |
| 2.3 | Functional Languages | 26 |
| 2.3.1 | μ FP: An Algebra for VLSI Specification | 26 |
| 2.3.2 | Embedding HDLs in General-Purpose Functional Languages | 28 |
| 2.4 | Term Rewriting Systems | 30 |
| 2.5 | Occam/CSP-Based Approaches | 31 |
| 2.5.1 | Handel and Handel-C | 31 |
| 2.5.2 | Tangram and Balsa | 31 |
| 2.6 | Synchronous Languages | 33 |
| 2.7 | Summary | 34 |
| 3 | The SAFL Language | 35 |
| 3.1 | Motivation | 35 |
| 3.2 | Language Definition | 36 |
| 3.2.1 | Static Allocation | 37 |
| 3.2.2 | Integrating with External Hardware Components | 37 |
| 3.2.3 | Semantics | 38 |

| | | |
|----------|---|-----------|
| 3.2.4 | Concrete Syntax | 38 |
| 3.3 | Hardware Synthesis Using SAFL | 41 |
| 3.3.1 | Automatic Generation of Parallel Hardware..... | 42 |
| 3.3.2 | Resource Awareness | 42 |
| 3.3.3 | Source-Level Program Transformation | 44 |
| 3.3.4 | Static Analysis and Optimisation | 47 |
| 3.3.5 | Architecture Independence | 48 |
| 3.4 | Aside: Dealing with Mutual Recursion | 48 |
| 3.4.1 | Eliminating Mutual Recursion by Transformation | 49 |
| 3.5 | Related Work | 50 |
| 3.6 | Summary | 50 |
| 4 | Soft Scheduling | 51 |
| 4.1 | Motivation and Related Work | 52 |
| 4.1.1 | Translating SAFL to Hardware..... | 54 |
| 4.2 | Soft Scheduling: Technical Details | 55 |
| 4.2.1 | Removing Redundant Arbiters | 56 |
| 4.2.2 | Parallel Conflict Analysis (PCA) | 56 |
| 4.2.3 | Integrating PCA into the FLaSH Compiler | 58 |
| 4.3 | Examples and Discussion | 58 |
| 4.3.1 | Parallel FIR Filter | 58 |
| 4.3.2 | Shared-Memory Multi-processor Architecture | 59 |
| 4.3.3 | Parallel Tasks Sharing Graphical Display | 61 |
| 4.4 | Program Transformation for Scheduling and Binding | 62 |
| 4.5 | Summary | 63 |
| 5 | High-Level Synthesis of SAFL | 65 |
| 5.1 | FLaSH Intermediate Code | 66 |
| 5.1.1 | The Structure of Intermediate Graphs | 67 |
| 5.1.2 | Translation to Intermediate Code..... | 71 |
| 5.2 | Translation to Synchronous Hardware | 73 |
| 5.2.1 | Compiling Expressions | 73 |
| 5.2.2 | Compiling Functions | 75 |
| 5.2.3 | Generated Verilog | 79 |
| 5.2.4 | Compiling External Functions..... | 80 |
| 5.3 | Translation to GALS Hardware | 81 |
| 5.3.1 | A Brief Discussion of Metastability | 81 |
| 5.3.2 | Interfacing between Different Clock Domains..... | 83 |
| 5.3.3 | Modifying the Arbitration Circuitry | 85 |
| 5.4 | Summary | 86 |
| 6 | Analysis and Optimisation of Intermediate Code | 87 |
| 6.1 | Architecture-Neutral versus Architecture-Specific | 87 |
| 6.2 | Definitions and Terminology | 88 |
| 6.3 | Register Placement Analysis and Optimisation | 88 |
| 6.3.1 | Sharing Conflicts | 89 |

| | | |
|----------|--|------------|
| 6.3.2 | Technical Details | 91 |
| 6.3.3 | Resource Dependency Analysis | 92 |
| 6.3.4 | Data Validity Analysis | 93 |
| 6.3.5 | Sequential Conflict Register Placement | 95 |
| 6.4 | Extending the Model: Calling Conventions | 97 |
| 6.4.1 | Caller-Save Resource Dependency Analysis | 97 |
| 6.4.2 | Caller-Save Permanisation Analysis | 99 |
| 6.5 | Synchronous Timing Analysis | 99 |
| 6.5.1 | Technical Details | 100 |
| 6.5.2 | Associated Optimisations | 101 |
| 6.6 | Results and Discussion | 104 |
| 6.6.1 | Register Placement Analysis: Results | 104 |
| 6.6.2 | Synchronous Timing Optimisations: Results | 109 |
| 6.7 | Summary | 110 |
| 7 | Dealing with I/O | 113 |
| 7.1 | SAFL+ Language Description | 113 |
| 7.1.1 | Resource Awareness | 115 |
| 7.1.2 | Channels and Channel Passing | 115 |
| 7.1.3 | The Motivation for Channel Passing | 117 |
| 7.2 | Translating SAFL+ to Hardware | 118 |
| 7.2.1 | Extending Analyses from SAFL to SAFL+ | 120 |
| 7.3 | Operational Semantics for SAFL+ | 121 |
| 7.3.1 | Transition Rules | 124 |
| 7.3.2 | Semantics for Channel Passing | 124 |
| 7.3.3 | Non-determinism | 126 |
| 7.4 | Summary | 126 |
| 8 | Combining Behaviour and Structure | 129 |
| 8.1 | Motivation and Related Work | 129 |
| 8.2 | Embedding Structural Expansion in SAFL | 130 |
| 8.2.1 | Building Combinatorial Hardware in Magma | 130 |
| 8.2.2 | Integrating SAFL and Magma | 134 |
| 8.3 | Aside: Embedding Magma in VHDL/Verilog | 136 |
| 8.4 | Summary | 138 |
| 9 | Transformation of SAFL Specifications | 141 |
| 9.1 | Hardware Software CoDesign | 142 |
| 9.1.1 | Comparison with Other Work | 142 |
| 9.2 | Technical Details | 143 |
| 9.2.1 | The Stack Machine Template | 144 |
| 9.2.2 | Stack Machine Instances | 144 |
| 9.2.3 | Compilation to Stack Code | 146 |
| 9.2.4 | The Partitioning Transformation | 148 |
| 9.2.5 | Validity of Partitioning Functions | 148 |
| 9.2.6 | Extensions | 149 |

XII Contents

| | | |
|-----------------|--|------------|
| 9.3 | Transformations from SAFL to SAFL+ | 151 |
| 9.4 | Summary | 153 |
| 10 | Case Study | 155 |
| 10.1 | The SAFL to Silicon Tool Chain | 155 |
| 10.2 | DES Encrypter/Decrypter | 160 |
| 10.2.1 | Adding Hardware VGA Support | 162 |
| 10.3 | Summary | 167 |
| 11 | Conclusions and Further Work | 169 |
| 11.1 | Future Work | 170 |
| Appendix | | |
| A | DES Encryption/Decryption Circuit | 171 |
| B | Transformations to Pipeline DES | 177 |
| C | A Simple Stack Machine and Instruction Memory | 181 |
| | References | 185 |
| | Index | 193 |