

DEVELOPMENT OF SINGLE BOARD COMPUTER BASED ON  
32-BIT 5-STAGE PIPELINE RISC PROCESSOR

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DEVELOPMENT OF SINGLE BOARD COMPUTER BASED ON  
32-BIT 5-STAGE PIPELINE RISC PROCESSOR

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*To my beloved family, friends and lecturers  
who have guided and supported me along this journey*

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## ABSTRACT

In 21<sup>st</sup> century, embedded system design is a popular alternative to typical microprocessor design as it takes advantage of application characteristics to optimize its design for adequate performance at lower cost. Single Board Computer is a standalone digital system which capable to perform logical computation and data manipulation. Single Board Computer has CPU (Central Processing Unit), memory controller hub and I/O devices controller hub (interface chip) embedded to a single platform such as SoC (System-on-Chip) and embedded system. It is an economical and portable digital system with optimum logic gates and devices utilization. Single Board Computer has capability to synchronize data transfer between CPU and I/O peripheral devices, perform CPU operation as well as running program coded in machine code that utilize all its interfacing hardware devices. This thesis proposes a design of Single Board Computer in Verilog RTL, by extending from previous UTM student's research on 32-bit 5-stage pipeline RISC processor, targeted at FPGA implementation in System-on-Chip (SoC) designs. ISA (Instruction Set Architecture) of RISC(Reduced Instructions Set Computer) processor is enhanced to cover control instruction. I/O controllers are designed to support insertion of input data and display of output data. This Single Board Computer is designed in compact form and generalized to comply with RISC CPU specifications and some basic I/O protocols, which will be a valuable asset in UTM soft core IP bank as to help in its future SoC researches.

## ABSTRAK

Pada abad ke-21, rekaan sistem *embedded* merupakan satu alternatif popular kepada rekaan sistem mikro pemprosesan kerana ia direka berdasarkan cara penggunaannya yang spesifik dan ini dapat membantu untuk menghasilkan rekabentuk yang mempunyai fungsi yang memcukupi dengan kos yang lebih murah. Komputer dalam satu platform (*Single Board Computer*) merupakan satu sistem digital yang mampu beroperasi secara tunggal untuk pemprosesan logikal dan data manipulasi. Komputer dalam satu platform ini mempunyai peranti pemprosesan mikro, peranti pengawalan blok ingatan dan peranti pengawalan input dan output seperti rekaan *System-on-Chip* (SoC) dan rekaan sistem *embedded*. Ia merupakan satu rekaan digital yang murah dan mudah-alih dengan penggunaan peranti dan logik yang optimum. Ia berkemampuan untuk melaraskan semua data penghantaran di antara peranti pemprosesan mikro dan peranti persisiran, melaksanakan operasi pengkomputeran dan melaksanakan program yang ditulis dalam bahasa mesin dengan bantuan semua peranti persisiran yang disambungkan kepadanya. Thesis ini melanjutkan penyelidikan pelajar UTM yang lalu yang berasaskan peranti pemprosesan mikro *RISC* dengan 32-bit 5-pipeline untuk menghasilkan sebuah komputer dalam satu platform dengan *Verilog RTL*. Rekaan ini direalisasikan dengan penggunaan FPGA menerusi rekabentuk SoC. ISA (*Instruction Set Architecture*) untuk *RISC* CPU diperluaskan dengan merangkumi arahan kawalan. Peranti pengawalan input dan output turut direka untuk membolehkan kemasukan data input dan paparan data output. Rekaan ini memenuhi semua spesifikasi piawai untuk CPU dan peranti persisiran. Ia merupakan suatu asset yang penting kepada UTM dalam penyelidikan SoC.

## TABLE OF CONTENTS

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENT</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLE</b>	x
	<b>LIST OF FIGURES</b>	xi
	<b>LIST OF ABBREVIATIONS</b>	xv
	<b>LIST OF APPENDICES</b>	xvi
<b>1</b>	<b>INTRODUCTION</b>	
	1.1. Background and Research Motivation	1
	1.2. Objectives	3
	1.3. Scopes of Work	3
	1.4. Significant of Work and Research Contributions	4
	1.5. Organization of Project Report	5
	1.6. Summary of Chapter 1	6
<b>2</b>	<b>LITERATURE REVIEW</b>	
	2.1. RISC Architecture	7
	2.2. Pipeline Structure	8
	2.3. Pipeline Hazards	12

2.4.	Bootstrapping	13
2.5.	Avalon <sup>®</sup> Interface	14
2.6.	Studies on I/O Protocol for I/O Controller Design	16
2.6.1.	PS/2 Keyboard Port	16
2.6.2.	LCD Display Port	19
2.7.	Summary of Chapter 2	21
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	
3.1.	Research Flow and Methodology	22
3.2.	Design Approaches	24
3.3.	Designing with Altera Quartus II EDA Tool	25
3.4.	Hardware Selection	26
3.5.	Summary of Chapter 3	26
<b>4</b>	<b>RTL DESIGN AND ENHANCEMENT FOR RISC PROCESSOR</b>	
4.1.	RTL Design of RISC Processor	27
4.2.	Enhancement on RISC Processor Verilog HDL Coding	36
4.2.1.	Design of J-Type Instruction	36
4.3.	Summary of Chapter 4	42
<b>5</b>	<b>DESIGN OF I/O CONTROLLERS</b>	
5.1.	Design Considerations	43
5.2.	Keyboard Controller	44
5.2.1.	Deserializer	46
5.2.2.	ScanCode_to_BCD Converter	50
5.2.3.	ScanCode_to_Integer Converter	52
5.2.4.	Operator and Operand Decoding logic	54
5.3.	LCD Display Controller	55
5.3.1.	LCD Controller	56
5.3.2.	Binary_to_BCD Converter	64
5.3.3.	BCD_to_LCD_Pattern Converter	65



5.4	7-Segment LED Display Controller	69
5.5	Summary of Chapter 5	72
<b>6</b>	<b>SINGLE BOARD COMPUTER INTEGRATION</b>	
6.1.	I/O Memory Arbitrator	73
6.2.	Single Board Computer Integration	75
6.3.	Design Practices and Limitations	79
6.4	Summary of Chapter 6	80
<b>7</b>	<b>VERIFICATION AND PERFORMANCE ANALYSIS</b>	
7.1	RISC CPU Test Case	81
7.2.	Basic Calculator (Single Board Computer) Test Case	88
7.3.	Performance Analysis for Single Board Computer	94
7.4.	Summary of Chapter 7	96
<b>8</b>	<b>CONCLUSION AND FUTURE WORK</b>	
8.1	Concluding Remarks	97
8.2	Future Work	98
	<b>REFERENCES</b>	100
	<b>APPENDIX A-D</b>	101

**LIST OF TABLES**

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
4.1	States for RISC Processor in RTL-CS table	29
4.2	Control signal of CU	29
4.3	ALU Operation	30
4.4	Opcode Assignment for RISC Design	35
5.1	RTL-CS Table for PS/2 port Deserializer	48
5.2	Lookup Table for Scan Code to BCD Conversion	51
5.3	RTL-CS Table for LCD Controller FSM, mLCD_st	60
5.4	RTL-CS Table for LCD Controller FSM, st	63
5.5	Truth Table of BCD to 7-Segment Display Decoder	69
6.1	Primary Signals for Single Board Computer	77
7.1	Description of Synthesis Result generated by Altera Quartus II	94
7.2	Summary of Design Performance and Resource Utilization	95

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Basic five stage pipeline in RISC architecture	9
2.2	RISC Pipeline Architecture by Jurij Silc	10
2.3	RISC Pipeline Architecture by Heurings	11
2.4	Pipeline Control Hazard	13
2.5	Bootstrapping Algorithm in Assembly Code	14
2.6	Typical Avalon Interfaces in a System Design with DMA Controller and NIOS II Processor	15
2.7	The Pinouts for each connector of PS/2 port	16
2.8	General Open-Collector PS/2 Interface	17
2.9	PS/2 Device-to-Host Communication	18
2.10	PS/2 Host-to-Device Communication	18
2.11	General Pinouts for LCD Display	19
2.12	General Pin Assignment for Character LCD Display	20
2.13	Character set for LCD Display based on [D7:D0] settings	20
3.1	Summary of Project Flow and Methodology	23
3.2	Top Level block diagram for RISC Single Board Computer via Altera DE2 Board	23
3.3	CAD flow for Verilog Design of FPGA-Based Single Board Computer	26
4.1	Top Level Architecture for RISC Processor	28
4.2	Interconnection within DU	30
4.3	On-Chip Memory	31
4.4	5-Stage Pipeline RISC Processor Data Flow Diagram	32
4.5	ISA design for RISC Processor	33

4.6	ISA design for Instruction Format	33
4.7	Instruction Format for Memory Instruction	34
4.8	Instruction Format for Register Instruction	34
4.9	Instruction Format for Control Instruction	34
4.10	Instruction Format for Other Instruction	34
4.11	Instruction Format for newly coded J-Type Instruction	36
4.12	Verilog design of control logic for Jump, Branch and Conditional Branching instructions – generation of load signal <code>ldPC</code>	37
4.13	Verilog design of control logic for Jump, Branch and Conditional Branching instructions – generation of ALU select signal in CU	38
4.14	Simulation result for Jump Instruction verification	39
4.15	Simulation result for Branch Instruction verification	40
4.16	Simulation result for Conditional Branching Instruction verification	41
5.1	IO Block Diagram of Keyboard Controller	45
5.2	Functional Block Diagram of Keyboard Controller	46
5.3	Timing Characteristic of PS2 DATA and PS2 CLK	46
5.4	ASM Flowchart for PS/2 port Deserializer	47
5.5	State Transition Description for PS/2 port Deserializer	48
5.6	IO Block Diagram for PS/2 port Deserializer	48
5.7	Functional Block Diagram of combinational logic for <code>scan_ready</code>	49
5.8	Functional Block Diagram of combinational logic for <code>oneshot</code>	49
5.9	Keyboard Command and Scan Code when Key ‘1’ on main keyboard is pressed and released.	50
5.10	Flowchart for <code>ScanCode_to_BCD</code> Conversion Algorithm	51
5.11	IO Block Diagram for <code>ScanCode_to_BCD</code> converter	52
5.12	Flowchart for <code>ScanCode_to_Integer</code> Conversion Algorithm	53
5.13	IO Block Diagram for <code>ScanCode_to_Integer</code> Converter	53
5.14	IO Block Diagram of LCD Display Controller	55
5.15	Functional Block Diagram of LCD Display Controller	56

5.16	LCD Module Initialization	57
5.17	Address Counter and DDRAM address for 2 x 16 Character of LCD	58
5.18	ASM Flowchart for LCD Controller FSM, <i>mLCD_st</i>	59
5.19	LCD Controller FSM, <i>mLCD_st</i> State Transition Description	60
5.20	Timing Characteristics for LCD Module Write Operation	61
5.21	ASM Flowchart for LCD Controller FSM, <i>st</i>	62
5.22	LCD Controller FSM, <i>st</i> State Transition Description	63
5.23	Flowchart for Binary_to_BCD Conversion Algorithm	64
5.24	Verilog Design Binary_to_BCD converter	65
5.25	Flowchart for BCD_to_LCD_Pattern Conversion Algorithm	66
5.26	Verilog Design of LCD Pattern Lookup for BCD module	67
5.27	Verilog Design BCD_to_LCD_Pattern converter – part 1	67
5.28	Verilog Design BCD_to_LCD_Pattern converter – part 2	68
5.29	IO Block Diagram for 7-Segment LED Display Controller	70
5.30	Functional Block Diagram for 7-Segment LED Display Controller	70
5.31	Functional Block Diagram for individual 7-Segment LED Display Decoder	71
6.1	Flowchart for I/O Memory Arbitration Algorithm	74
6.2	I/O Block Diagram of I/O Memory Arbitrator	75
6.3	Functional Block Diagram of Single Board Computer	76
6.4	Design Hierarchy of Single Board Computer, <i>mycpu</i>	78
6.5	Resource Utilization	78
7.1	Sequence of Instructions in RISC CPU Test Case	82
7.2	Instruction Memory Content for RISC CPU Test Case	82
7.3	Data Memory Content for RISC CPU Test Case	83
7.4	Vector Source File for RISC CPU Test Case	83
7.5	Timing Simulation result of RISC CPU Test Case for 0 to 0.65us	84
7.6	Timing Simulation result of RISC CPU Test Case for	85

	a) 0.65 to 1us and b) 1 to 1.35us	
7.7	Actual Hardware Result when Reset Button is pressed	86
7.8	Actual Hardware Result for RISC CPU Test Case (0x000068AC)	87
7.9	Actual Hardware Result for RISC CPU Test Case (0xFFFFA988)	87
7.10	Sequence of Instructions in Basic Calculator Test Case	88
7.11	Instruction Memory Content for Basic Calculator Test Case	89
7.12	Data Memory Content for Basic Calculator Test Case	89
7.13	Memory Map for Data Memory Content in Basic Calculator Test Case	89
7.14	Timing Simulation result of Basic Calculator Test Case (Zoom Out)	90
7.15	Timing Simulation result of Basic Calculator Test Case (Zoom Out)	91
7.16	Hardware Setup of Single Board Computer on Altera DE2 Board	93
7.17	Actual Hardware Result for Basic Calculator Test Case	93

**LIST OF ABBREVIATIONS**

ALU	-	Arithmetic logic unit
CU	-	Control Unit
DU	-	Datapath Unit
FPGA	-	Field programmable gate array
FSM	-	Finite State Machine
HDL	-	Hardware Description Language
IR	-	Instruction Register
ISA	-	Instruction Set Architecture
LED	-	Light emitting diode
NOP	-	No operation
MAR	-	Memory address register
PC	-	Program Counter
RAM	-	Random access memory
ROM	-	Read only memory
RTL	-	Register Transfer Level
I/O	-	Input and Output
SBC	-	Single Board Computer
RISC	-	Reduced Instruction Set Computer
USB	-	Universal Serial Bus
VGA	-	Video Graphic Array
BCD	-	Binary coded decimal

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	PIN ASSINGMENT OF CYCLONE II FPGA	101
B	SCAN CODE AND COMMAND FOR PS/2 KEYBOARD	104
C	DATA SHEET FOR CFAH1602B-TMC-JP LCD MODULE	106
D	VERILOG SOURCE CODE FOR SINGLE BOARD COMPUTER	110



## **CHAPTER 1**

### **INTRODUCTION**

This project report proposes the setup of SBC (Single Board Computer) based on 32-bit 5-stage pipeline RISC processor design<sup>1</sup> via FPGA implementation using Altera DE2 Board. The design is to produce a generic and yet robust processor that works well with various I/O devices to provide adequate logical functions. This chapter covers the background, research motivation, objectives, scope of work, and the report organization.

#### **1.1 Background and Research Motivation**

Microprocessor is one of the most revolutionary invention in 20<sup>th</sup> century. In general computing, microprocessor acts as the Central Processing Unit(CPU) that keeps all I/O devices intact together to perform pre-determined task and function stored in memory element. RISC is one of the simple and yet popular processor architectures in computing industry. The design philosophy of RISC processor is to reduce the complexity of the ISA by limiting the instruction set in to a smaller number of more frequently used instruction that yields better efficiency in modern computing.

RISC architecture was first introduced by IBM in 1975. However, RISC designs such as Berkeley's RISC processor and Stanford's MIPS processor which

were introduced by respective university research teams were gaining higher popularity in term of public RISC design. Various research efforts and evolutionary development of RISC processor throughout the years had made the RISC design to become one of the most sophisticated and successful processor core which are widely used in many application. For instance, ARM processor that dominates the embedded system and smart phone such as PDA and cellular phones by major handset manufacturer such as Nokia and Samsung are originated from RISC architecture. Moreover, MIPS is also found in residential gateways and game consoles like Sony PlayStation. Besides, SPARC, Motorola 88000 and DLX are all inheriting the RISC architecture<sup>2</sup>.

SBC (Single Board Computer) are complete computer built on a single circuit board. The design is centered on a microprocessor with memory, I/O and all other features needed to be a functional computer on one board<sup>3</sup>. The recent availability of advanced chip sets providing most of the I/O features as embedded components allows mother board manufacturers to offer motherboards with I/O traditionally provided by daughterboard. This development trend is converging to SBC design especially on those embedded system that requires to be designed in small form factor and lower cost. Besides, the SBC is also improving the user experience as the it is a highly portability digital devices as compared to traditional PC. Furthermore, SBC design is aligned to development of SoC (System On Chip) in semiconductor industry whereby a smaller and more compact digital devices can be placed within a single wafer die with the use of advanced silicon process technology. As a result, SoC design offers great advantage on silicon chip fabrication cost reduction.

In this research, the Single Board Computer of 32-bit 5-stage pipeline RISC processor is implemented on hardware (FPGA) with the interfacing of I/O peripheral devices, which can be booted and execute the pre-programmed instruction based on contents stored in memory module. The target board to be used in this project is Altera DE2 board which is suitable to setup as a SRC (Simple RISC computer) and availability of various on-board I/O devices.

## 1.2 Objectives

From the discussion from previous section, this report set out objectives as listed at below:

- i. To construct Single Board Computer oriented on Altera DE2 board that consists of
  - a. RISC processor design implementation via FPGA (Cyclone II 2C35)
  - b. On board memory modules: ROM and RAM modules for CPU bootstrapping purpose
  - c. I/O devices such as keyboard and LCD display I/O controllers that communicate with RISC CPU core.
- ii. To enhance ISA such as J-type instruction for verilog HDL design of 32-Bit 5-Stage Pipeline RISC Processor.
- iii. To explore the execution of simple test program via RISC processor that link all I/O and memory modules to perform some simple instruction.

## 1.3 Scopes of Work

Based on available resources, limited time frame and expertise, this research project is narrowed down to the following scope of work:

- i. Verilog code of 32-Bit 5-Stage Pipeline RISC Processor Design will be enhanced with appropriate ISA (Instruction Set Architecture) to support the interconnection of I/O peripheral devices for Single Board Computer setup.
- ii. The usage of switches and keyboard as inputs to RISC processor will be developed while on-board LCD display will be enabled as its output. All I/O controller design will be coded in Verilog. Various logic converters are residing in I/O controllers to ensure the input data can be read and stored in memory for RISC CPU processing as well as display the output data in correct format at output devices.

- iii. This project involves HDL design, synthesis, simulate and verify the design correctness with Altera Quartus II.
- iv. Target implementation is Altera DE2 Board which consists of Cyclone II 2C35 FPGA chip.
- v. A simple functional application (written in machine code) that pre-loaded to memory acts as a test case to ensure all interfacing I/O devices are functioning according to their designated functions.

#### **1.4 Significant of Work and Research Contributions**

- i. I/O device compatibility is a crucial aspect to assure the robustness and functionality of Single Board Computer. A RISC processor core with I/O interfacing capability that coded in Verilog HDL and implemented via FPGA on Altera DE2 board provides great flexibility in future enhancement and allows customization and configuration of Single Board Computer design.
- ii. It is important for UTM to have its own 32-bit RISC processor IP thus to enable future Microprocessor / SoC (System On Chip) researches.
- iii. Performance of the processor is important thus pipelining is the most viable technique to improve the performance without pushing clock frequency which consumes more power.

## 1.5 Organization of Project Report

This report is organized into 6 chapters. The outlines of each individual chapter are stated as:

- Chapter 1      A brief introduction to RISC processor, project's objectives and scopes and the organization of this project report.
  
- Chapter 2      Background and ISA of RISC processor and literature review on architectural details on bootstrapping technique, memory interface architecture and on-board hardware I/O devices on Altera DE2 board.
  
- Chapter 3      Research and design methodology, verification and validation procedure and tools involved in this project.
  
- Chapter 4      Discussion of architecture for 32-bit 5-stage pipeline RISC Processor IP core. J-type instruction of RISC processor is coded as prerequisite for bootstrapping implementation. Challenges and solutions of this design and ISA enhancement are discussed throughout this chapter.
  
- Chapter 5      Design of PS/2 Keyboard controller, LCD Display Controller and 7-Segment LED Display Controller are discussed in detail. Verilog design implementation of all decoding logics and logic converter sub-modules such as BCD to Integer, BCD to LCD Pattern, Binary to BCD, Keyboard's ScanCode to BCD and etc. are covered.
  
- Chapter 6      Brief discussion on I/O Memory Arbitrator design and its functions. Single Board Computer integration via modular design approach is illustrated and coded in Verilog design.
  
- Chapter 7      Simulation result from Altera Quartus II and on-board hardware testing observation using Altera DE2 board are obtained and analyzed based on RISC CPU Test Case and Basic Calculator Test Case stored

in memory blocks. Design functionality, performance and resource utilization studies are reported.

Chapter 8 Conclusion and future works

## **1.6 Summary of Chapter 1**

Project background, objective, scopes of work and significance of research are discussed. The project report organization is also discussed.