phoeniX RISC-V Core V0.1

Arvin Delavari – Faraz Ghoreishy

arvin7807@gmail.com – farazghoreishy@gmail.com

Summer 2023

Iran University of Science and Technology

Electronics Research Center – Digital Design Laboratory

This page was initially left blank.

Preface:

phoeniX is a 5 stage pipelined 32-bit RISC-V processor written in Verilog HDL. This project was started in summer of 2023 in Digital Design Laboratory of Electronics Research Center at Iran University of Science and Technology. This document contains technical specifications and user manual for version 0.1 of phoeniX processor. This version of the processor is able to execute RV32I (integer operations extension) instructions of official RISC-V instruction set manual [1]. Other extensions will be supported by the core in the future updates.

phoeniX core is capable of execution of assembly and C codes using iverilog simulator. Guidance is included in this document for the flow of code execution in this processor. For execution of C codes, the processor will use RISC-V GCC compiler toolchain and for assembly codes, you can use GCC compiler or Venus simulator which is a free extension for the recognized code editor, Microsoft Visual Studio Code. Further descriptions are included to relative sections of this document.

This project is an open source CPU under the GNU V3.0 license [2] and is free to use. You can find source codes and documentations in the following GitHub repository:

<https://github.com/ArvinDelavari/phoeniX-RV32>

We would like to express our sincere gratitude to the following individuals for their invaluable guidance and remarkable insights, which played a pivotal role in the completion of this project:

* Professor Sattar Mirzakuchaki PhD

Iran University of Science and Technology

* Professor Hadi Shahriar Shahhoseini PhD

Iran University of Science and Technology

* Nima Amirafshar MSc

Iran University of Science and Technology

Arvin Delavari – Faraz Ghoreishy

Iran University of Science and Technology – Summer 2023

Contents:

1. Introduction
   1. phoeniX core structure
   2. phoeniX software interface
   3. Required software
2. Building Blocks (Modules)
   1. Fetch Unit
   2. Instruction Decoder
   3. Immediate Generator
   4. Address Generator
   5. Arithmetic Logic Unit
   6. Register File
   7. Hazard Detection and Forwarding Unit
   8. Jump and Branch Unit
   9. Load Store Unit
3. Memory Interface Logic
4. Code Executant Software
   1. Code execution and simulation flow
   2. Windows (Venus Simulator)
   3. Linux (RISC-V GCC toolchain)
5. Synthesis Result
   1. Qflow toolchain
   2. TSMC 180nm PDK
   3. phoeniX ASIC result
6. References

Chapter 1

Introduction

The phoeniX project was initiated in summer of 2023 in Electronics Research Center at Iran University of Science and Technology [3]. This RISC-V processor was designed in order to be an original base processor with acceptable performance and specification which aims to lay a solid groundwork and foundation for future computer architecture research and development endeavors.

The processor uses RISC-V open source Instruction Set Architecture (ISA) with a custom designed microarchitecture. The core is written in Verilog HDL and it is synthesizable for both FPGA and ASIC targets. Building blocks of this core were all written in separate modules which would help developers to add features and test computer architecture techniques on the base core. This modular design leads to a simpler way of debugging and also extending the core.

In the following version (V0.1), phoeniX is a 5 stage pipelined RV32I processor which supports “I-Extension” of RISC-V ISA. Other extensions will be added to the core in the upcoming updates soon.

phoeniX stands out with its user-friendly and straightforward flow for simulating and executing C and assembly codes on the processor. Unlike many other open-source processors, phoeniX offers a simplified approach that is easier to follow. The repository of this project provides comprehensive documentation, offering step-by-step guidance on executing codes on the core. This resource is highly accessible and designed to facilitate a seamless development experience in computer architecture and digital design field.

* 1. phoeniX core structure

In the beginning, one of the most specialties of this processor which should be mentioned is not having a single control unit. This processor uses a “Distributed Control Logic” which leads to elimination of control unit from the building blocks. By DCL it means that after decoding the instructions, relative fields such as opcodes, funct3, funct7 and other fields are straightly directed to the linked modules, and the process of control signals generation will be taken place in the target module hardware. For example, in a basic processor decoded fields are sent to control unit and inside this module, signals will be generated to define ALU operation, ALU multiplexers (for selection of registers bus or immediate value), bypassing and forwarding multiplexers and etc. In phoeniX processor, all of these control signals are determined inside the target modules, by sending the relative decoded fields directly to the target. In fact, modules are somehow known to be self-controllable which in this case we call the general system, Distributed Control Logic.

phoeniX is a 5 stage pipelined processor which has the classic machine cycle stages: Fetch, Decode, Execute, Memory Interface and Write back. Building blocks of the processor are mostly designed in separated modules which gives developers freedom for changes and the mentionable benefit of modularity. Registers used for latching data in different stages of the core are not designed as modules are completely written inside the main module named “phoeniX”. Detailed descriptions about the hardware design of the core and its modules are included Building Blocks (Modules) section of this documents.

Memory interface of the core is completely written and described in testbench file because of the limitations of memory simulation using Hardware Description Languages. Further information about the interface logic is inside Memory Interface section of this document.

The phoeniX core also has a hazard detection unit which gives the core, the ability of performing data-forwarding and bypassing techniques in order to skip stalls in the code including dependencies and hazards.

The maximum delay time (critical path) of phoeniX processor analyzed using Yosys [4] open-source synthesis tool and Vesta [5] static time analysis software, in different stages is something about 3800-3900 picoseconds which leads us to clock cycle width of 4 nanoseconds. This means the phoeniX processor will perform in a frequency rate of nearly 250MHz which is a remarkable number in benchmarking with other processor. Most of the commercial and industrial embedded processors designed by ARM with Cortex M0, M3 and M4 [6] microarchitecture will not reach this frequency rate. These processors find extensive integration with microcontroller series such as STM32 (by ST) or LPC (by NXP), making them highly prevalent and widely employed in the field of embedded systems.

Even other open-source RISC-V embedded processors such as PicoRV32 by Claire Wolf [7] won’t reach a higher frequency than the mentioned. PicoRV32, is one of the most recognized open-source processors and even used in fabricated microcontroller chips has a frequency rate ranged in 50 to 100MHz depending to the technology. Another well-known RISC-V processor is named ibex core by ETH Zurich [8] university which also has a frequency range between 100MHz and 300MHz in highest performance.

The phoeniX processor is a reliable and user-friendly solution, offering modularity and easy extensibility for developers and computer architecture researchers. It features a simplified design that is easy to understand, while still delivering competitive performance compared to other processors.

* 1. phoeniX software interface

The phoeniX processor uses standard GCC compiler toolchain [9] which is officially verified by RISC-V organization, in order to run C codes and assembly codes on the processor. This codes are turned into a firmware file including hex format of instructions and addresses by the compiler toolchain. The generated firmware file is given to the testbench of phoeniX CPU as the instruction memory. The processor can simulate the executed code using iverilog [10] version 12 tool. There is a shell script included in the repository which helps users to install all software requirements for simulating and coding on phoeniX processor.

The simulation and execution flow is very simplified by phoeniX code executants which will be described briefly in the upcoming sections of this document. There are easy solutions to simulate assembly and C codes both Windows and Linux systems on phoeniX processor. Linux systems can use the makefile in the main directory which will do the complete process of compiling, assembling, generating firmware file and executing on the phoeniX core without any complexity and additional user interference. There is a second solution which can be used for both Windows and Linux systems, but it can only help with simulation of assembly codes on the processor. You can write and simulate your RISC-V assembly code using Venus simulator which is a Microsoft Visual Studio Code extension. This extension has an output file which includes hex instructions of the assembly code. The output will be given to a code executant python script and after that, the desired firmware will be generated and ready to execute on phoeniX processor.

The phoeniX processor streamlines the simulation and execution process, ensuring a user-friendly and intuitive experience. Its simplified flow enables effortless utilization, making it accessible and straightforward for users of all levels of expertise. Additional details regarding the integration of further descriptions can be found in the Code Executant Software section of this document, providing comprehensive insights into how the phoeniX processor incorporates advanced functionalities and features.

* 1. Required Software

As mentioned before, there is a shell script integrated with the main directory of phoeniX RV32 core repository, which helps user to install all of the required software for simulation and execution flow without any problem. In this section there are some additional information about the software in use of phoeniX core execution flow.

* Python3: Python [11] is also required to be installed on the system in order to execute the code executant and firmware generator scripts. Linux distributions such as Ubuntu has Python3 installed at the beginning by default. On Windows systems Python needs to be installed individually.
* Iverilog: it is an open-source Verilog simulation and synthesis tool used for designing and testing digital circuits. It supports the IEEE 1364-2005 Verilog standard and provides a command-line interface for compiling and simulating Verilog code. Iverilog allows users to simulate and verify the behavior of their digital designs before actual hardware implementation, making it a valuable tool for digital circuit development and verification. In phoeniX processor project we used iverilog version 12 for HDL simulation process and final execution of C and assembly codes on the processor.
* GTKWave: GTKWave is an open-source waveform viewer for analyzing and visualizing electronic waveforms. It is commonly used in digital design and verification processes, particularly in the field of hardware description languages (HDL) and digital circuit simulation. With GTKWave, you can load waveform files and view the signal waveforms, timing diagrams, and other attributes of digital signals in phoeniX core. GTKWave also supports advanced features such as hierarchical waveform viewing, cross-probing between source code and waveforms, and the ability to apply filters and color schemes to enhance waveform visualization.
* RISC-V GCC Compiler toolchain: The RISC-V GCC compiler toolchain refers to a collection of software tools that enable the compilation and development of software for RISC-V architecture-based processors. It includes a set of open-source tools, primarily based on the GCC (GNU Compiler Collection), specifically tailored for the RISC-V instruction set architecture (ISA). The RISC-V GCC compiler toolchain plays a crucial role in the development and software ecosystem surrounding the RISC-V architecture, enabling the creation of applications, firmware, and operating systems for RISC-V processors.
* Venus Simulator (Visual Studio Code): The Venus simulator is a RISC-V instruction set architecture (ISA) simulator developed by the University of Victoria. It allows users to simulate and execute RISC-V assembly language programs, providing a platform for learning, testing, and debugging RISC-V code. The Venus simulator Visual Studio Code extension is an extension specifically designed for the Visual Studio Code (VS Code) integrated development environment. This extension integrates the Venus simulator directly into the VS Code environment, offering an enhanced development experience for RISC-V programming. With the Venus simulator extension, users can write RISC-V assembly code directly in VS Code, benefit from syntax highlighting and code completion features, and seamlessly run and debug their code using the Venus simulator. The extension provides an interactive interface within VS Code, allowing users to step through their code, set breakpoints, inspect registers and memory, and observe program execution.

In References section of this document there are useful links with detailed descriptions about the tools used in this project and their installation guides. While the provided shell script smoothly automates the installation process on Linux systems, it's important to note that for Windows operating systems, the required software needs to be downloaded and installed separately.

Chapter 2

Building Blocks (Modules)

In the following chapter, we will provide a comprehensive overview of the essential components that form the foundation of the phoeniX core. We will delve into the intricate details regarding the structure and architecture of these modules, presenting them in the order of the dataflow within the pipeline.

Within this project, we have identified 9 key modules that play a crucial role in its operation. Each of these modules will be meticulously described, ensuring a thorough understanding of their individual contributions to the overall data processing pipeline. By following the logical progression of the dataflow, you will gain valuable insights into how these modules interact and collaborate to achieve the desired outcomes.

Through this comprehensive examination, you will acquire a profound knowledge of the phoeniX core's inner mechanisms, empowering you to comprehend its intricate design and appreciate the optimized performance it offers.

In the end there is a top module named phoeniX which acts as a unifying entity that brings together all the aforementioned building blocks, along with additional registers and latches, within the pipeline. By integrating these components into a cohesive unit, the phoeniX module forms the backbone of the processor, orchestrating the flow of data and executing the desired operations.

The memory interface logic is a critical component that facilitates communication between the processor and the memory subsystem. Although it is not directly included within the individual modules, its role is of utmost importance in ensuring the overall functionality of the system. The memory interface logic is implemented separately in a dedicated testbench file. In the forthcoming chapter dedicated to Memory Interface Logic, we will provide a thorough explanation of this logic, delving into its intricate workings. We will explore how it manages the flow of data between the processor and the memory subsystem, and we will highlight its significance within the broader system architecture.

Before we introduce each of this modules, there is a table included in this section which explains what is the role of each module of the core in a short and brief way. It is needed to not that in the upcoming versions of the processor, new features and new modules will be added to the phoeniX core and the mentioned modules in this chapter are the foundation of phoeniX V0.1 CPU.

Below is the list of these modules, along with concise descriptions of their critical functions and roles in phoeniX core:

|  |  |
| --- | --- |
| Modules | Description |
| Register File | Parametrized register file suitable for GP registers and CSRs |
| Arithmetic Logic Unit | ALU with support for `I\_TYPE` and `R\_TYPE` RISC-V instructions |
| Instruction Decoder | Decoding instructions and extracting `opcode`, `funct` and `imm` fields |
| Immediate Generator | Generating immediate values according to instructions type |
| Fetch Unit | Instruction Fetch logic and program counter addressing |
| Load Store Unit | Load and Store operations for aligned addresses and word size management |
| Branch Unit | Condition checking for all branch instructions |
| Address Generator | Generating address for BRANCH, JUMP and LOAD/STORE instructions |
| Hazard Forward Unit | Hazard detection and data forwarding logic in pipelined processor |

Table 1. phoeniX core modules and descriptions

* 1. Fetch Unit

The Fetch Unit module is responsible for fetching instructions from memory in a processor design. Let's go through the description of the module:

Input signals:

* enable: This input signal is used to enable the memory interface module.
* PC: Represents the Program Counter, which holds the address of the next instruction to be fetched.
* address: This input signal represents the branch or jump address generated by the Address Generator module.
* jump\_branch\_enable: This signal indicates whether a branch or jump operation is

enabled.

Output signals:

* next\_PC: This output signal is a 32-bit register that represents the Program Counter (PC) value of the next instruction to be fetched.

Memory Interface Signals:

* memory\_interface\_enable: This output signal is a 1-bit register that enables the memory interface.
* memory\_interface\_state: This output signal is a 1-bit register that indicates the state of the memory interface operation. In this module, it is set to READ, implying that the memory interface is performing a read operation.
* memory\_interface\_address: This output signal is a 32-bit register that represents the address being accessed by the memory interface. In this module, it is set to the current value of PC.
* memory\_interface\_frame\_mask: This output signal is a 4-bit register that specifies the frame mask for the memory interface. It is set to 4'b1111, indicating that all four bytes of the memory frame are enabled.

The next\_PC output is determined based on the jump\_branch\_enable input signal:

* If jump\_branch\_enable is asserted (1), indicating a branch or jump operation, next\_PC is set to the value of address.
* If jump\_branch\_enable is not asserted (0), next\_PC is calculated as the current PC value plus 4 (32'd4), representing the increment of the Program Counter by 4 bytes (the size of an instruction).

In summary, the Fetch Unit module generates the necessary signals for the memory interface and determines the next instruction's Program Counter based on the control signals received.

Figure 1. Fetch Unit schematic output from Xilinx Vivado software

* 1. Instruction Decoder

The Instruction Decoder module is responsible for decoding instructions in a processor design. Let's go through the description of the module:

Input signals:

* instruction: This input signal is a 32-bit value representing the instruction to be decoded.

Output signals:

* instruction\_type: This output signal is a 3-bit value representing the type of the instruction. It is assigned one of the predefined values: R\_TYPE, I\_TYPE, S\_TYPE, B\_TYPE, U\_TYPE, J\_TYPE, or 1'bz (for an unknown or invalid instruction type).
* opcode: This output signal is a 7-bit value representing the opcode of the instruction.
* funct3: This output signal is a 3-bit value representing the funct3 field of the instruction.
* funct7: This output signal is a 7-bit value representing the funct7 field of the instruction.
* funct12: This output signal is a 12-bit value representing the funct12 field of the instruction.
* read\_index\_1: This output signal is a 5-bit value representing the register index used for the first read operation.
* read\_index\_2: This output signal is a 5-bit value representing the register index used for the second read operation.
* write\_index: This output signal is a 5-bit value representing the register index used for the write operation.

Internal signals:

* instruction\_type\_i, instruction\_type\_b, instruction\_type\_r, instruction\_type\_i, instruction\_type\_u, instruction\_type\_j: These internal signals evaluate whether the instruction falls into a specific type category (I\_TYPE, B\_TYPE, R\_TYPE, etc.).
* read\_enable\_1, read\_enable\_2, write\_enable: These internal signals control the read and write enable signals for the register file based on the instruction type.

Behavior:

The opcode, funct3, funct7, funct12, read\_index\_1, read\_index\_2, and write\_index outputs are assigned values based on specific bits of the instruction input signal.

The instruction\_type output is determined based on the evaluation of the internal signals instruction\_type\_i, instruction\_type\_b, instruction\_type\_r, instruction\_type\_s, instruction\_type\_u, and instruction\_type\_j.

The read\_enable\_1, read\_enable\_2, and write\_enable signals are evaluated based on the instruction\_type value using a case statement. Each case assigns the appropriate values to these signals for the corresponding instruction type.

Additionally, there is a conditional check to disable the write\_enable signal when the destination register index (write\_index) is x0 (all zeros), as writing to register x0 is typically invalid.

Figure 2. Instruction Decoder schematic output form Xilinx Vivado software

In summary, the Instruction Decoder module decodes instructions and generates control signals based on the instruction type, opcode, and other fields of the instruction. It also determines the appropriate register read and write enable signals based on the instruction type.

* 1. Immediate Generator

The Immediate Generator module is responsible for generating the immediate value for instructions based on the instruction type. Let's go through the description of the module:

Input signals:

* instruction: This input signal is a 32-bit value representing the instruction.
* instruction\_type: This input signal is a 3-bit value representing the type of the instruction. It is used to determine how the immediate value should be generated.

Output signals:

* immediate: This output signal is a 32-bit value representing the immediate value generated for the instruction.

Behavior:

Inside the always block, there is a case statement that evaluates the instruction\_type value.

Depending on the value of instruction\_type, the immediate value is assigned specific values based on the structure of the instruction.

For example, if the instruction\_type is I\_TYPE, the immediate value is assigned by concatenating 21 copies of the most significant bit of the instruction with bits 30 to 20 of the instruction. You can find the immediate generation algorithm for each type in RISC-V original instruction set architecture documents.

Similarly, for other instruction types (S\_TYPE, B\_TYPE, U\_TYPE, J\_TYPE), the immediate value is generated by concatenating specific bits of the instruction with appropriate padding bits.

If the instruction\_type does not match any of the predefined types (default case), the immediate value is assigned 32 bits of 1'bz (unknown value).

In summary, the Immediate Generator module takes an instruction and the instruction type as inputs and generates the immediate value based on the instruction type. The immediate value generated is then assigned to the immediate output signal.



Figure 3. Immediate Generator schematic output from Xilinx Vivado software

* 1. Address Generator

The Address Generator module is responsible for generating addresses based on the opcode and other inputs. Let's go through the description of the module:

Input signals:

* opcode: This input signal is a 7-bit value representing the opcode of the instruction.
* rs1: This input signal is a 32-bit value representing the value of register rs1.
* PC: This input signal is a 32-bit value representing the program counter.
* immediate: This input signal is a 32-bit value representing the immediate value.

Output signals:

* address: This output signal is a 32-bit value representing the generated address.

Internal Signals:

* value: This internal signal is a 32-bit value used to hold intermediate values based on the opcode.

Behavior:

Inside the always block, there is a case statement that evaluates the opcode value.

Depending on the value of opcode, the value signal is assigned specific values based on the opcode.

For example, if the opcode matches STORE, the value signal is assigned the value of rs1. Similarly, for LOAD, JAL, JALR, and BRANCH, the value signal is assigned the values of rs1 and PC, respectively.

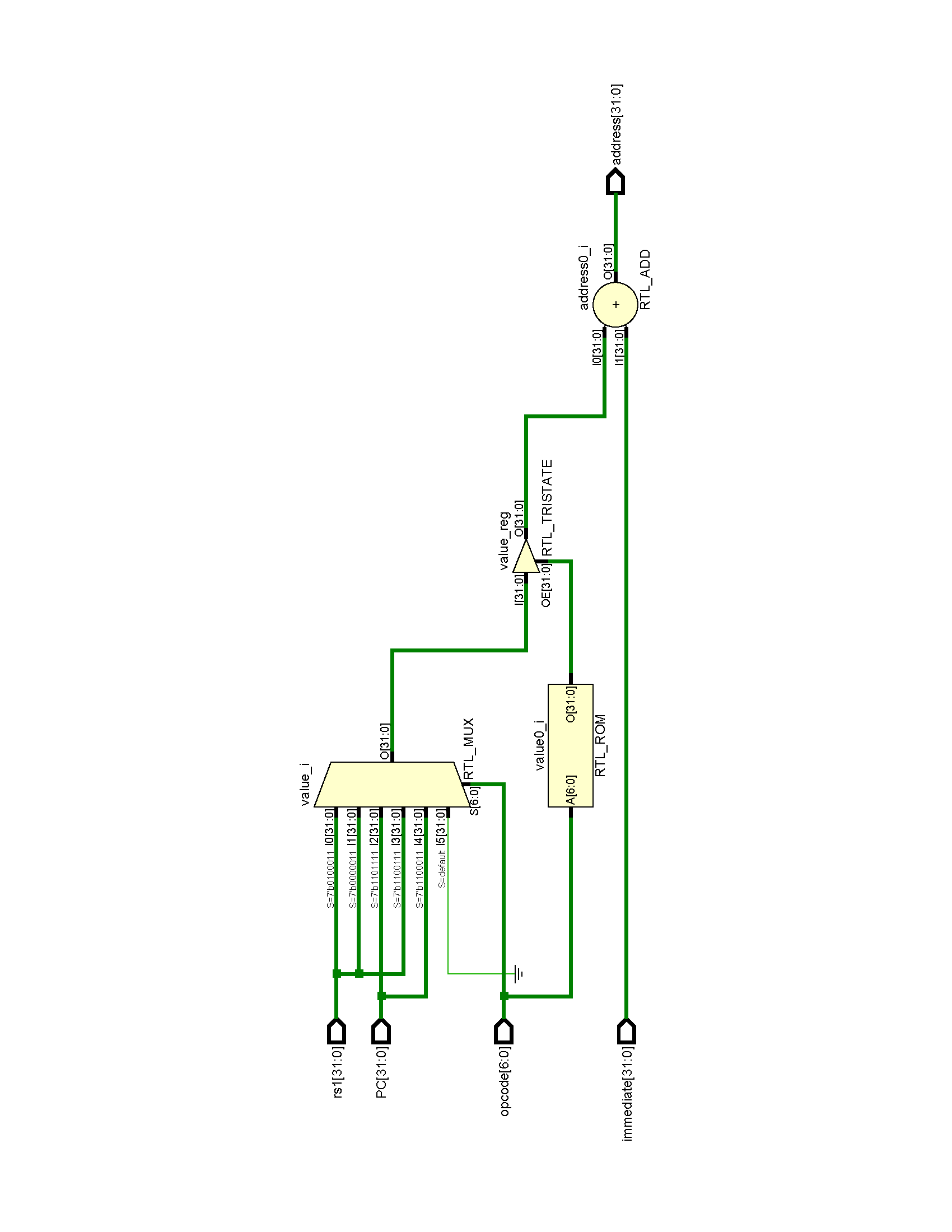
If the opcode does not match any of the predefined opcodes (default case), the value signal is assigned 1'bz (unknown value).

Figure 4. Address Generator schematic output from Xilinx Vivado software

Finally, the address output signal is assigned the value of value plus the immediate value.

In summary, the Address Generator module takes the opcode, rs1 value, program counter (PC), and immediate value as inputs. Based on the opcode, it generates the appropriate address by combining the value of rs1, PC, or other intermediate values with the immediate value. The generated address is then assigned to the address output signal.

* 1. Arithmetic Logic Unit

Chapter 6

References

[1] RISC-V ISA

[2] GNU LICENSE

[3] IUST ERC WEBSITE

[4] Yosys

[5] Vesta

[6] ARM Cortex M

[7] PicoRV32

[8] ibex

[9] GCC compiler toolchain

[10] iverilog

[11] Python