

Experiment 8: Microcontroller on an FPGA

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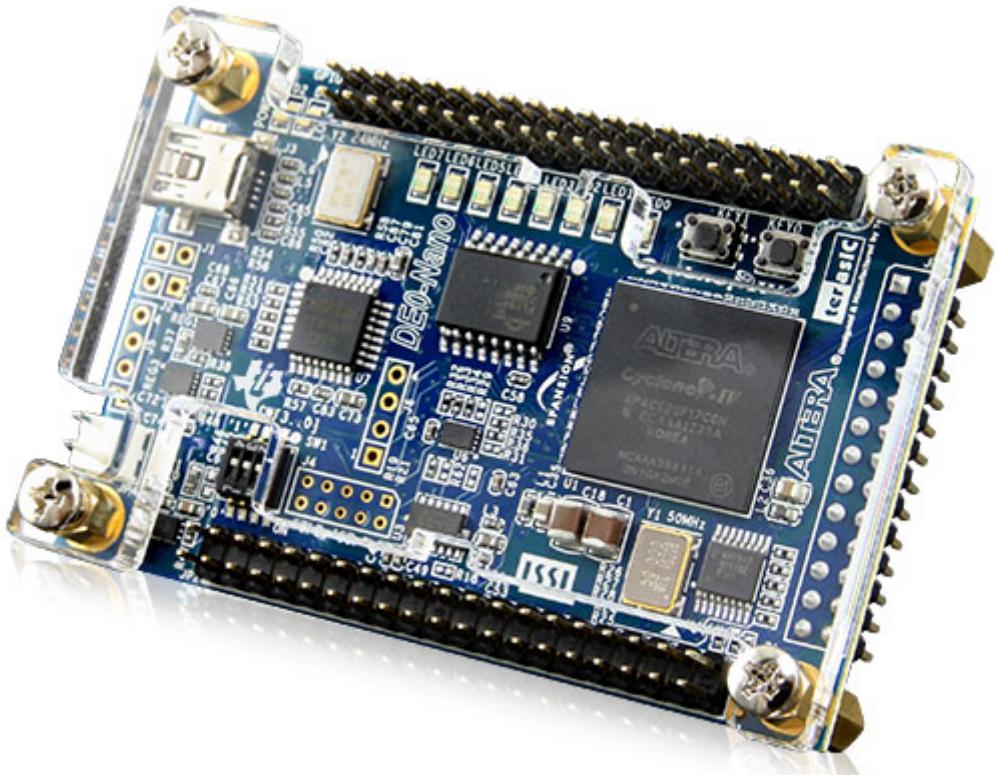
1. Objectives

In this experiment, you will learn about the hardware of a microcontroller by:

- Building a microcontroller system on an FPGA by integrating Altera's Nios II soft processor and a few peripherals
- Writing software for the FPGA-based microcontroller system

2. Parts List

- Altera DE0-Nano FPGA board



- USB A-Type to Mini-B cable

3. Background

This experiment involves two main tasks:

1. Building the hardware for a microcontroller system using an FPGA device.

We will use Altera's *DE0-Nano* FPGA development board, which incorporates a small FPGA device and a number of peripherals. To create the microcontroller system, we will configure the FPGA device to implement a soft processor and a number of required components for the processor to function properly.

To configure the FPGA, we will use Altera's *Quartus II* design software. To build the soft processor system, we will use Altera's *Qsys* system integration software to implement a system around Altera's Nios II soft processor core.

2. Developing software to exercise your microcontroller system.

We will use Altera's Eclipse-based *Nios II Embedded Design Suite (EDS)* software development environment to build software for the Nios II-based hardware system.

Intel (Altera) Software

You can obtain and install all the required software for this experiment freely from Altera's website. You will want to download and install *Quartus II Web Edition software*, which includes Qsys, the Nios II EDS, and Altera IP Library.



Intel acquired Altera in 2015. Altera Quartus II software suite has been renamed to Intel Quartus. Qsys has been renamed to Platform Designer.

The free version of Quartus software is now called Intel Quartus Prime Lite Edition.

For more details on available Altera software, software licensing, download options, and hardware and software requirements, consult the [Intel® FPGA Software Installation and Licensing](#) document.

3.1. The DE0-Nano FPGA Board

The DE0-Nano is a low-cost, low-power, portable, compact board (49 mm x 75 mm) aimed at developing embedded soft processor systems using the Nios II processor.

Board Features

- Three-axis accelerometer with 13-bit resolution
- Eight-channel, 12-bit resolution analog-to-digital (A/D) converter
- Expansion headers: two 40-pin headers and one 26-pin header
- Two-pin external power header
- 32-MB SDRAM
- 2-Kb EEPROM
- Eight green LEDs
- Four dual in-line package (DIP) switches
- Two push-button switches

3.2. The Nios II Processor

Nios II is a RISC soft processor architecture. A soft processor is a processor that can be implemented on reconfigurable logic, e.g. an FPGA.

Nios II Processor Features

- Full 32-bit instruction set, data path, and address space
- 32 general-purpose registers
- 32 interrupt sources
- External interrupt controller interface for more interrupt sources
- Optional floating-point instructions for single-precision floating-point operations
- Access to a variety of on-chip peripherals, and interfaces to off-chip memories and peripherals
- Hardware-assisted debug module enabling processor start, stop, step, and trace under control of the Nios II software development tools
- Optional memory management unit (MMU) to support operating systems that require MMUs
- Software development environment based on the GNU C/C++ tool chain and the Nios II Software Build Tools (SBT) for Eclipse

The Nios II Processor Reference Handbook states that:

A Nios II processor system is equivalent to a microcontroller or "computer on a chip" that includes a processor and a combination of peripherals and memory on a single chip. A Nios II processor system consists of a Nios II processor core, a set of on-chip peripherals, on-chip memory, and interfaces to off-chip memory, all implemented on a single Altera device. Like a microcontroller family, all Nios II processor systems use a consistent instruction set and programming model.

— Nios II Processor Reference Handbook



For more information on the Nios II processor, consult [its extensive documentation](#).

3.3. Design Flow

Unlike previous experiments, we need to create the hardware of the microcontroller system before we can program it.

In order to create a Nios II soft processor system on the Altera DE0-Nano FPGA board, and write software for it, you are going to use the following software tools:

System Builder

used to generate a preconfigured Quartus II project for the DE0-Nano FPGA development board.

Quartus II

used to compile all design files, including those generated by Qsys, into an FPGA configuration file, known as an *SRAM Object File* (.sof), which can be downloaded into the FPGA device to implement the designed system.



Altera vs. Xilinx Tools

Quartus II is the design software used to develop hardware for Altera FPGAs. DE0-nano is a development board that contains an Altera FPGA chip.

In contrast, for Xilinx FPGAs, ISE design suite is the design software used to develop hardware for Xilinx FPGAs, and Spartan, for example, is a board that contains a Xilinx FPGA chip.

Qsys (Platform Designer)

used to specify the Nios II processor core(s), memory, and other components your system requires. Qsys automatically generates the interconnect logic to integrate the components in the hardware system.

Nios II EDS

the Nios II Embedded Design Suite includes Nios II Software Build Tools (SBT) for Eclipse, which is an eclipse installation preconfigured to use a set of plugins to support developing software for the Nios II processor. To create a new Nios II C/C++ application project, the Nios II SBT for Eclipse uses information from the files generated by Qsys to learn about the target hardware.

Here is a summary of the general flow steps; the details will come later

1. Use the System Builder utility to generate a Quartus II project preconfigured for the DE0-Nano board. This step is specific to the DE0-Nano board.
2. Use Qsys to generate the hardware description of your processor system. In addition to the HDL files, Qsys generates an .sopcinfo file that describes the system.

3. Use Quartus II to compile the hardware description generated by Qsys into an FPGA configuration file ([.sopcinfo](#)), and to download the configuration file into the FPGA to implement the system's hardware.
4. Use Nios II SBT for Eclipse to develop the software for the configured hardware. Nios II SBT for Eclipse learns about the hardware from the Qsys-generated [.sopcinfo](#) file, in order to compile the software for the generated hardware.

3.4. Creating a Quartus II Project

The Quartus II project will eventually contain all the information required to generate and implement the hardware of our system.

The DE0-Nano kit ships with a convenient software utility called *System Builder*, which creates preconfigured Quartus II projects for the DE0-Nano board. For example, it automatically configures the project for the FPGA device in the DE0-Nano, and configures the pin locations for the selected peripherals.

Run the DE0-Nano's System Builder utility, and choose the following configuration options:

- CLOCK
- LED x 8

Then, press *Generate* to create a Quartus II project. After that, open the generated project in Quartus II by opening the [.qpf](#) file. In the next section, we will use Qsys from within this project.

	Avoid using directories with spaces in their names for your Quartus II or Nios II EDS projects.
	<p>Since the purpose of this experiment is to understand the makeup of a microcontroller system, it is suggested to create a minimal system by only including the few peripherals listed above. But you are welcome to include any of the other available peripherals.</p> <p>For example, the DE0-Nano FPGA board has a built-in accelerometer. You are free to try to use it if you manage to complete the listed tasks in this experiment!</p>

3.5. Building the Processor System Using Qsys

Qsys allows you to put together the hardware components that make up your microcontroller system, and to create all the required connections, including the system bus.

We would like to build a Nios II system that includes the following hardware components:

- Nios II/s core with 2 KB of instruction cache
- 20 KB of on-chip memory
- Timer
- JTAG UART
- Eight output-only parallel I/O (PIO) pins
- System ID component

	For more information about these and other components, refer to the Embedded Peripherals IP User Guide .
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To build this system, run Qsys from the *Tools* menu in Quartus II, and follow the instructions in the [Nios II Hardware Development Tutorial](#), page 1-11 (*Define the System in Qsys* section).



Qsys Errors

While you are adding the components, connecting them, and configuring them, there will be error messages disappearing gradually till you correctly complete your design. These error messages can be useful in reminding you of any missed step.



Qsys Notes

1. Edit the export column for the three components: clk_in, clk_in_reset, and external connection.
2. Edit the name of the memory component to use a simple short name (e.g. ram).
3. After adding the CPU core, use the name of your memory component as Reset Vector memory and exception Vector memory.
4. Edit the IRQ numbers in the IRQ column to be 16 for the JTAG UART component, and 1 for the timer.
5. Edit the PIO component name to a simple short name that you can remember. You will need it later.
6. Generate the base addresses automatically by choosing Assign Base Addresses from the Tools menu in Qsys.
7. Finally, use the generate button in Qsys to generate the project files and save them in a known directory.



Qsys Components

By following the Nios II Hardware Development Tutorial, you may have some questions about some of the components. Here are some answers for such anticipated questions:

1. Although the tutorial asks you to set the cache size, we don't care about the cache in this experiment. We can use a CPU with no cache. It makes no difference for the purposes of this experiment.
2. JTAG UART is used by the development environment to communicate with the microcontroller that we are creating on the FPGA, especially to download and debug software. JTAG is a standard created for this purpose specifically.
3. System ID is similarly used by the development tools to identify the target hardware and determine which software to download to which hardware. You can set the target system ID value in the IDE to match the value you may set in the System ID hardware component, in case you use a non-default value.
4. Usually, IRQ numbers need to be configured in device drivers or system software. The values set for the JTAG UART and the timer components are the numbers configured in the base system software generated by the Nios II IDE.

Your completed Qsys system should look like this:

Use	Connections	Name	Description	Export	Clock	Base	End	IRQ
<input checked="" type="checkbox"/>		clk_0	Clock Source					
		clk_in	Clock Input	clk				
		clk_in_reset	Reset Input	reset				
		clk	Clock Output	clk_0				
		clk_reset	Reset Output					
<input checked="" type="checkbox"/>		onchip_mem	On-Chip Memory (RAM or ROM)					
		clk1	Clock Input	clk_0				
		s1	Avalon Memory Mapped Slave	[clk1]		0x00008000	0x0000cff	
		reset1	Reset Input	[clk1]				
<input checked="" type="checkbox"/>		cpu	Nios II Processor					
		clk	Clock Input	clk_0				
		reset_n	Reset Input	[clk]				
		data_master	Avalon Memory Mapped Master					
		instruction_master	Avalon Memory Mapped Master					
		jtag_debug_module_re...	Reset Output					
		jtag_debug_module	Avalon Memory Mapped Slave					
		custom_instruction_m...	Custom Instruction Master					
<input checked="" type="checkbox"/>		jtag_uart	JTAG UART					
		clk	Clock Input	clk_0				
		reset	Reset Input	[clk]				
		avalon_jtag_slave	Avalon Memory Mapped Slave	[clk]		0x00011030	0x00011037	16
<input checked="" type="checkbox"/>		sys_clk_timer	Interval Timer					
		clk	Clock Input	clk_0				
		reset	Reset Input	[clk]				
		s1	Avalon Memory Mapped Slave	[clk]		0x00011000	0x0001101f	
<input checked="" type="checkbox"/>		sysid	System ID Peripheral					
		clk	Clock Input	clk_0				
		reset	Reset Input	[clk]				
		control_slave	Avalon Memory Mapped Slave	[clk]		0x00011038	0x0001103f	
<input checked="" type="checkbox"/>		led_pio	PIO (Parallel I/O)					
		clk	Clock Input	clk_0				
		reset	Reset Input	[clk]				
		s1	Avalon Memory Mapped Slave	[clk]		0x00011020	0x0001102f	
		external_connection	Conduit Endpoint	led_pio_external...				

3.6. Integrate the Qsys System into the Quartus II Project

To integrate the Qsys system with the Quartus II project, we need to:

1. Add the Qsys system to the Quartus II project
2. Instantiate the Qsys system
3. Connect the ports of the Qsys system to signals in the Quartus II project.

For Quartus II to be able to recognize the Qsys system, the Qsys system, represented by its Quartus II IP file (**.qip**), must be added to the Quartus II project as follows:

1. From the Quartus II menu, select *Project > Add/remove Files in project*
2. Click the browse button (...) next to the *File name* field
3. Select the file **<qsys_project_directory>/synthesis/<qsys_project_name>.qip**
4. Click *Add* to include **.qip** file in the project, then click *OK* to close the dialog box

To instantiate the Qsys-generated Nios II system, and to connect each port of the Qsys system instance to the appropriate signal in the top-level module of the Quartus II project, use the following Verilog instantiation code in the top-level module of your Quartus II project, which is typically named **<quartus_project>.v**, where **<quartus_project>** is the name of your Quartus II project.

Verilog Code to Instantiate the Qsys-Generated System

```
<qsys_project> u0(
    .clk_clk (CLOCK_50),
    .reset_reset_n (1'b1),
    .led_pio_external_export (LED)
);
```

About the Qsys-system-instantiation Verilog Code

In the Verilog code above, replace <qsys_project> with the name of your Qsys project.



The code creates an instance, named **u0**, of the Qsys system, and maps, i.e. connects, the ports of the Qsys system (the names following the periods) to signals declared in the module in which this code resides (the names between parentheses). **1'b1** is a single-bit constant value of **1**.

The exported port names of the Qsys system are derived from the Qsys system definition.

3.7. Compile and Download the Hardware Design

The Quartus II hardware compiler consists of a set of modules that perform different compilation steps. The modules are *Analysis & Synthesis*, the *Fitter*, the *Assembler*, and the *TimeQuest Timing Analyzer*. To obtain the downloadable **.sof** FPGA configuration file, we need to run the assembler. Running the assembler will trigger all other required modules.

After compiling the Quartus II Project, connect the DE0-Nano board to your PC in order to download the hardware design.



To download the FPGA configuration data file (**.sof**) to a the FPGA device, you use Altera's USB-Blaster download cable, which interfaces a USB port on your host computer to the Altera FPGA.

The USB-Blaster cable requires a driver for the host computer to recognize it. For details on using the USB-Blaster and installing its driver, refer to the [USB-Blaster Download Cable User Guide](#).

The driver has already been installed on the lab PCs.

To download your hardware design to the FPGA:

1. Run the programmer from the *Tools* menu in Quartus II
2. Click the *Hardware Setup* button and choose *USB-Blaster* if it is not selected
3. Click the *Start* button to start downloading the **.sof** file to the FPGA chip on your board.



Don't close the *OpenCore Plus Status* dialog when it appears.



For more details on downloading your design to the FPGA, refer to the *Download the Hardware Design to the Target FPGA* section of the [Nios II Hardware Development Tutorial](#) (page 1-31).

3.8. Software Development Using Nios II SBT

Now, you have a Nios II hardware system running on the Altera FPGA board. To make use of this system, we

need to write some software to be executed on it.

To be able to do that, you need a toolchain (compiler, assembler, debugger) that can compile code for the Nios II CPU. We will use Altera's Nios II SBT for Eclipse, which is already installed on lab machines.



You can open and then edit some Nios II example programs as follows: . Select File > New > Nios II Application and BSP from Template . In the wizard, browse to your Qsys project directory, and open the SOPC Information File ([.sopcinfo](#)) of your design. . Choose the program that you would like to run.. Name your software project. . Click Finish.

We will first start with a simple program to explore the software development process. We will use the Hello World Small template program by following the instructions on the [My First Nios II Software Tutorial](#), page 1-32 (Develop Software Using the Nios II SBT for Eclipse section), only use the Hello World Small template instead of the Count Binary template.



The difference between the Hello World Small template and the Hello World template is that the former is configured to generate an optimized-for-space program that would fit in the small on-chip memory that was created in Qsys.

You can use the Hello World template instead of the Hello World Small template, but you would then need to adjust the properties of the BSP project in order to minimize the memory footprint of the software, as described on page 1-34 of the [Nios II Hardware Development Tutorial](#).

To make the program slightly more interesting, replace your code with the one on page 1-9 of the [My First Nios II Software Tutorial](#),



In the function call `IOWR_ALTERA_AVALON PIO DATA`, replace the first argument with your system's base address of the PIO peripheral. Look the address up in your `system.h` file.

To understand how this program works, read the *Why The LED Blinks* section on page 1-10.

4. Tasks

4.1. Build and Download the Hardware Design

1. Using the *System Builder* program, create a Quartus II project for the DE-Nano board. Configure your project to use the board's CLOCK, LEDs, EEPROM, and SDRAM.
2. Build a Nios II system using Qsys.
3. Instantiate your Nios II system in the Quartus II project.
4. Compile and download the hardware design to the DE0-Nano board.

4.2. Build and Download the Software

1. Create a software project for your Nios II system using Nios II SBT for Eclipse. Use the Hello World template.
2. Run Hello World application on your Nios II system on the DE0-Nano board.
3. Create and run another application that blinks an LED on the DE0-Nano.
4. Create a third program that blinks all eight LEDs on the DE0-Nano sequentially.

4.3. Discussion

- What peripherals are readily available for inclusion in this microcontroller system? (list three)
- What peripherals would you add to your microcontroller systems?
- What is the address of your PIO peripheral, which is driving the LEDs?
- How can you change it?

4.4. Bonus Task: Accelerometer

- Create a new Quartus project using the system builder and include the accelerometer.
- Add **Accelerometer SPI mode** peripheral in Platform Designer.
- Add the necessary connections to the system.
- Export **external_interface** to be connected to the top level Verilog module.
- Use the following Verilog instantiation code to instantiate the new Qsys project.

Verilog Code to Instantiate the Qsys-Generated System

```
<qsys-project> u0 (
    .clk_clk          (CLOCK_50),
    .reset_reset_n   (1'b1),
    .led_export       (LED),
    .acc_spi_I2C_SDAT (I2C_SDAT),
    .acc_spi_I2C_SCLK (I2C_SCLK),
    .acc_spi_G_SENSOR_CS_N (G_SENSOR_CS_N),
    .acc_spi_G_SENSOR_INT (G_SENSOR_INT)
);
```

- Develop a software to read the values of the accelerometer and display them on the screen using **printf**

5. Grading Sheet

Task	Points
Build the processor system using Qsys	2
Instantiate the processor system in a Quartus project	2
Run the <i>Hello World</i> program	2
Run an LED-blinking program	2
Discussion	2
Bonus Task	+2

Resources

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