
02203 Design of Digital Systems (Fall 2024)

Assignment 2: Edge Detection

A digital circuit design assignment using VHDL or SystemVerilog,
XILINX Vivado, and an Artix-7 FPGA board.

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Abstract

This document describes the edge detection design project, which is part of course 02203 “Design of Digital Systems” at DTU. The project will result in an FPGA realization of an edge detection hardware accelerator for monochrome video. Edge detection is an important aspect in analyzing a video scene and can be used, for example, in surveillance systems. The edge-detector is expected to identify abrupt intensity changes in a streaming video, which occur at the boundaries of objects. Further analysis of the edges may identify the type of object, e.g., a car or a human. Using VHDL or SystemVerilog, you will develop an executable specification of the edge detection unit and a synthesizable design, which is implemented on an Artix-7 FPGA board using Xilinx Vivado. **It is up to you to decide if you want to use VHDL or SystemVerilog (or both).**

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1 Introduction

In this project, you will design an edge detection hardware (HW) accelerator for monochrome images. The images are represented in PMG format and the size of an image frame is 352x288 pixels, i.e., 288 lines each with 352 pixels. The intensity of a pixel is represented by an 8-bit number that provides an integer range of 0 to 255, where 0 and 255 refer to black and white, respectively. The pixels are stored successively in a single-port RAM that uses 32-bit words. Consequently, each *read-transaction* or *write-transaction* issued by the HW accelerator may access four pixels. The original image and the processed image are stored in separate non-overlapping areas in the RAM. The HW accelerator is triggered by a signal *start* from the CPU and raises a signal *finish* as soon as the last pixel in a frame is processed. The architecture of the system is depicted in Figure 1. The number of frames that your circuit can process per second will depend on your implementation.

You will be given the entity/module of the HW accelerator to get started with the implementation, as well as a testbench and a model of the RAM.

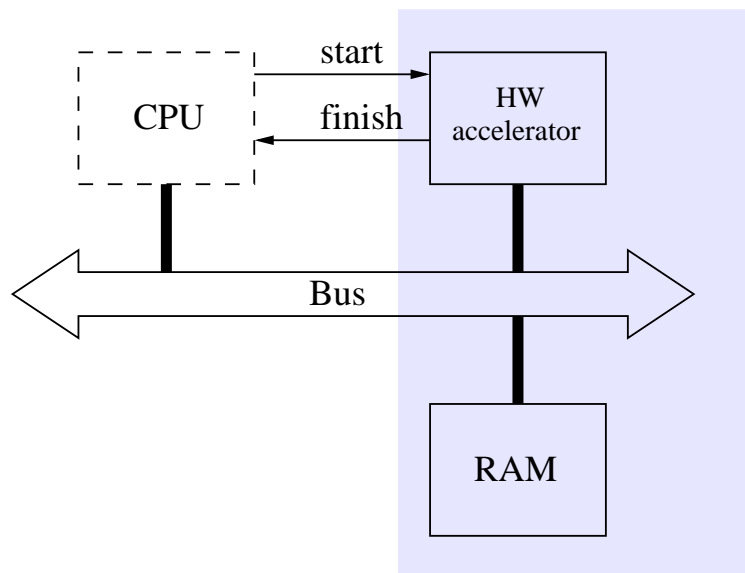


Figure 1: System architecture.

2 Edge detection

The algorithm used for *edge detection* is referred to as the Sobel operator. Edge detection is accomplished by computation of the derivatives of the intensity signal in the x - and y -direction. Thereafter, the minima and maxima in the derivatives need to be found, indicating where intensity changes most rapidly.

The Sobel method approximates the derivatives in each direction by a process called *convolution*. In other words, convolution is performed by an addition of the current pixel **and** weighted (filtered) intensity of the 8 surrounding neighbor pixels. The coefficients of the weighting function are represented by convolution masks G_x and G_y for the derivatives in the x - and y -directions, respectively, as shown in Figure 2.

$$G_x = \begin{array}{c|c|c} -1 & 0 & +1 \\ \hline -2 & 0 & +2 \\ \hline -1 & 0 & +1 \end{array} \quad G_y = \begin{array}{c|c|c} +1 & +2 & +1 \\ \hline 0 & 0 & 0 \\ \hline -1 & -2 & -1 \end{array}$$

Figure 2: Sobel convolution masks.

The derivative image is computed by centering each pixel with the convolution masks. This needs to be done over successive pixels in the original frame. The coefficients in each mask are multiplied with the underlying intensity and the nine (six) products are added to form two partial derivatives value D_x and D_y , as

$$D_x(n) = G_x * S(n), \quad (1)$$

and

$$D_y(n) = G_y * S(n), \quad (2)$$

where $*$ and n denote the convolution operator and pixel number in a scan line, respectively. The minima and maxima in the magnitude are computed by an approximation as

$$|D(n)| = |D_x(n)| + |D_y(n)|. \quad (3)$$

Finally, the value computed in (3) is stored in the RAM that holds a processed frame, and the Edge detector may continue with the next frame.

The details of the Sobel calculation are illustrated in the following. Figure 3 shows the pixels in a 3×3 pixel fragment of a picture.

s_{11}	s_{12}	s_{13}
s_{21}	s_{22}	s_{23}
s_{31}	s_{32}	s_{33}

Figure 3: Matrix showing nine pixels

The derivatives in the x and y directions for pixel s_{22} in the result picture are approximated in equations 4 and 5. In equation 4, the difference (or change) between the third and the first column is calculated, and the pixels in the middle of the column are weighted stronger. The same happens for the first and the third line in equation 5. The value calculated in equation 6 is adapted to the used number range and stored in the memory area for the processed picture corresponding to the pixel s_{22} . It is obvious that this value is big for high intensity changes and small for small intensity changes.

$$D_x(n) = s_{13} - s_{11} + 2(s_{23} - s_{21}) + s_{33} - s_{31} \quad (4)$$

$$D_y(n) = s_{11} - s_{31} + 2(s_{12} - s_{32}) + s_{13} - s_{33} \quad (5)$$

$$|D(n)| = |D_x(n)| + |D_y(n)| \quad (6)$$

3 The HW accelerator and its interfaces

The HW accelerator is integrated into a system including also a CPU, a BUS, and a RAM module, as shown in Figure 1. The HW accelerator and the RAM will be implemented in the FPGA on the Nexys4DDR or Nexys A7 board.

3.1 The CPU

In a realistic scenario, a CPU would control the HW accelerator as shown in Figure 1. However, in this project, its functionality will be emulated by a push button and an LED on the FPGA board. The push button triggers the accelerator to start, and the LED indicates that the processing of a frame has finished.

3.2 The HW accelerator

The HW accelerator processes 8-bit monochrome CIF video. The bottleneck for the frame rate is expected to be the access to the external memory. The HW accelerator is triggered by the *start* signal and it raises the *finish* after the last pixel of the last image line has been processed.

3.3 The Memory

The memory is a synchronous RAM with a word size of 32 bits. Figure 4 shows the organization of an image and how the source image and the processed image are stored in separate areas in the RAM. The upper left pixel in an image is pixel (0,0), and images are stored row by row.

We provide two VHDL/SystemVerilog models of the memory: one for simulation and one for synthesis. From the point of view of the HW accelerator, there is no difference between the two models; they implement the same interface. The only difference is how

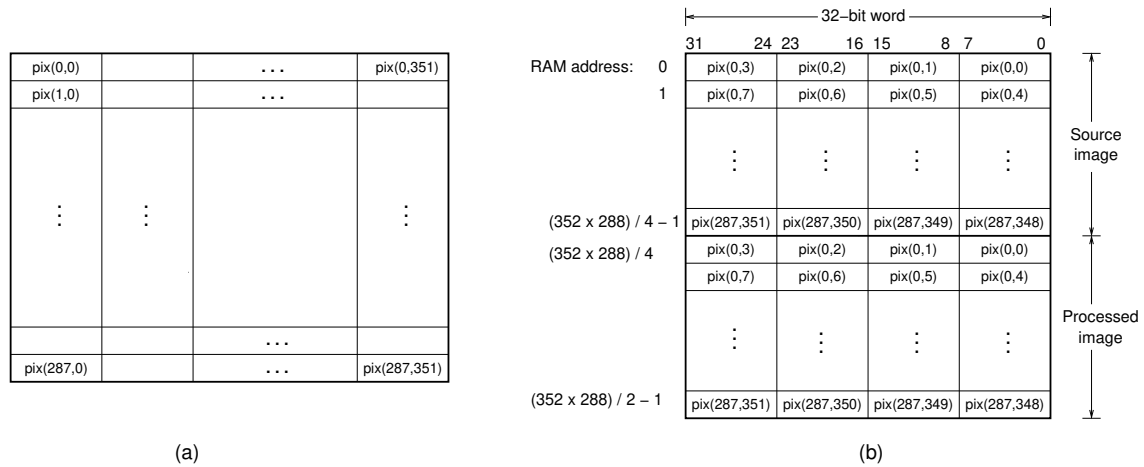


Figure 4: (a) A 352 x 288 pixel image and (b) illustration of how the source image and the processed image are stored in the RAM.

images are loaded into and read out of the simulation model and the real RAM on the board. These procedures are explained later.

3.4 The Bus Protocol

The interface between the HW accelerator and the memory follows the protocol depicted in Figure 5 and 6, where the former shows the signals and the latter the protocol. The interface is synchronous and only two transactions are provided: *Write Word* and *Read Word*.

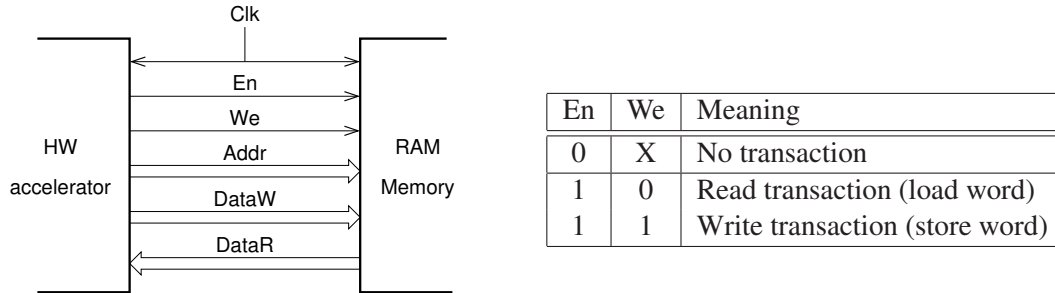


Figure 5: The memory interface.

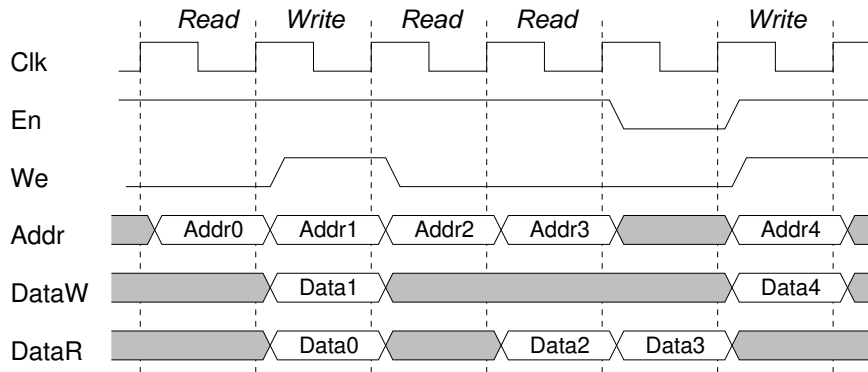


Figure 6: Timing diagram showing read and write transactions.

Using the signal *En*, a bus master indicates on a clock cycle basis if it is active or not. *En* is active high, and, when active, the signal *We* indicates if the bus master is performing a read (*We*=0) or a write transaction (*We*=1). The signals *En* and *We* are valid from just after the rising edge of the clock and throughout the clock period. Similarly, the master must provide a stable address (*Addr*) throughout the entire clock period. During a write transaction, the master must provide stable data (*DataW*) for the entire clock period. During a read transaction, a device *must* provide stable data (*DataR*) in the *following* clock cycle. The RAM that we use implements this using an output register (i.e., the read data is valid immediately after the rising edge of the clock and throughout the entire clock period that follows).

In a real system, there may be more masters (CPU, HW accelerator, etc.) and more devices (memory modules, IO units, etc.). In this case, the bus in Figure 1 should be seen

as a component with multiple ports to which masters and devices are attached using the interface and the protocol shown in Figures 5 and 6. In this project, there is only one HW accelerator and one RAM; hence, they can be connected directly as shown in Figure 5.

4 Design and implementation

You can choose to do the assignment in either VHDL or SystemVerilog. For the VHDL version of the assignment, the files are provided in a ZIP file on DTU-Learn. For the SystemVerilog version, you can clone or download the following GitHub repository: https://github.com/OttoWRas/02203_A2_SystemVerilog. More information on the provided files can be found in Section 7.

4.1 Task 0: Getting started

The edge detector HW accelerator is quite a complex design. The design process includes procedures for loading and viewing images in simulation as well as on the FPGA board. One way to get started is to solve a similar but simpler problem. This can be an HW accelerator that simply inverts the pixels in the image, turning white into black and black into white, e.g., $\text{pix_result} \leq 255 - \text{pix_source}$. This can be done by repeatedly reading four pixels, inverting them, and writing them back to the memory. This is a much simpler design, but it exercises how to access the memory and how to use the image-viewing tools. In addition, it involves a simple ASMD-chart description and a corresponding FSM implementation.

As an initial task, you should start designing and implementing this simpler pixel-inversion circuit and, in parallel, work on task 1: the paper-and-pencil design of your HW accelerator. For task 0, you can use the same files as we provide for tasks 2 and 3, and you should follow the same steps as described in tasks 2 and 3.

4.2 Task 1: Design of the HW accelerator

Before coding any VHDL/SystemVerilog, you need a design. This is Task 1. You need to understand the problem and consider possible implementations. You need to think about how much data your HW accelerator will buffer internally, how pixels are accessed from the memory, and how many times the same pixel is read from memory during the processing of an image frame. In this process, you may also try to estimate bounds on the time it takes to process an image. A lower bound can be established by calculating the time it takes your design to read from and write to the memory. You may be able to think of other bounds and estimates that characterize your design. To keep the size of the design manageable, you may ignore the boundary conditions and simply produce an image that is smaller than the original (missing the left and right columns of pixels and the upper and lower rows of pixels).

Draw a block diagram showing the datapath you have designed and develop an ASMD-chart specification of your design.

4.3 Task 2: Simulating the HW accelerator in Xilinx Vivado

When you have a design, a sketch of a data path, and an ASMD description of your design, it is time to start coding your design in VHDL or SystemVerilog. We provide you with: (1) a testbench to be used in Xilinx Vivado, (2) a simulation model (entity and architecture or module) of the memory, and (3) an entity/module declaration of the HW accelerator. Your task is to describe your design in VHDL or SystemVerilog. You can check the correctness of your design by simulating using the testbench and comparing the processed image against a reference picture provided by us.

The testbench takes a filename as a parameter. This file contains a source image in ASCII format. When you simulate the design using Xilinx Vivado, the source image is first loaded into the VHDL model of the memory, then the simulation is performed, and finally, the processed image is written into a PGM-file ready for viewing.

Among the files in the task2 folder is a source image file, *pic1.pgm*. When you run the simulation, the result image *pic1.pgm_result.pgm* is produced. The resulting image will be written to the simulation folder relative to your Vivado project file (ending with *.xpr*). Specifically, assuming a project name of *MyProject*, the path will be:

proj/MyProject/MyProject.sim/sim_1/behav/xsim

If you want to use your own source image, this is possible as well. All the pgm-files can be viewed using the program IrfanWiew¹.

4.4 Task 3: Synthesizing the HW accelerator using Xilinx Vivado

The next step is to synthesize your design and test it on the FPGA board. To do this, we need a new top-level entity that instantiates a number of components in addition to your edge detection hardware accelerator. These additional components are: (1) a debouncer for the signal *Req*, (2) a clock divider that can provide a clock with a lower frequency than 100 MHz if this is necessary, (3) a memory, (4) a controller, and (5) a UART. In addition to these files, you will also make use of a small serial interface program that executes on your PC. All these files are in the task3 folder.

The memory we use in task 3 has two ports: the one towards your hardware accelerator (subsection 3.4) and another port towards the controller. Via the UART, the controller “talks” to a serial interface program you run on your PC. This infrastructure allows you to download images from your PC to the memory on the FPGA board, and it allows you to upload processed images from the memory on the FPGA board to your PC. This connection uses the same USB-cable as you use for powering and programming the FPGA board. The serial interface program is controlled using a simple GUI shown in Figure 7. Before using the upload or download functionality, you first need to setup the serial connection. For details on using the serial interface program click on the Help button (bottom left).

¹Link: <https://www.irfanview.com/>

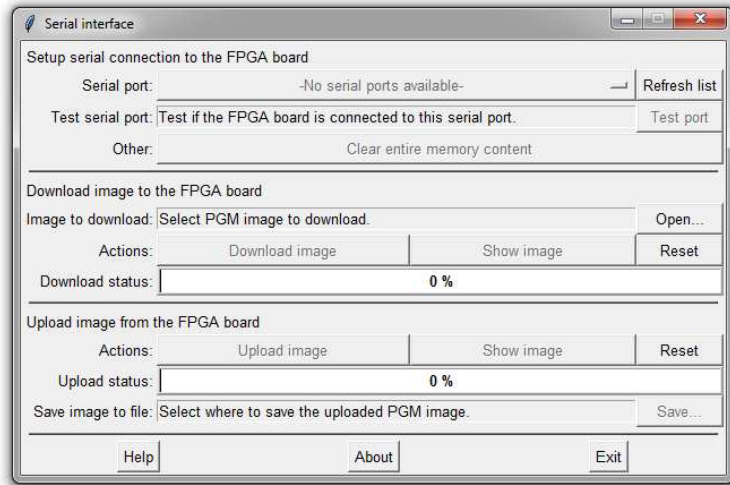


Figure 7: The GUI of the serial interface program.

5 Optional tasks

For those who want to explore more, we offer the following ideas.

5.1 Task 4a: Boundary conditions

A simple technique to compute the values at the edges and the corners is mirroring. This may be done by considering the pixel information of the first and the last line/column, respectively, as presented in Figure 8. The dotted framed pixels outside the image boundary carry information that is copied from the pixels with a solid frame. To calculate the first pixel in the first line, you copy the pixel information from the original frame, e.g., to compute the upper left pixel according to equation 3, pixel (0,0) from the original frame needs to be copied three times, as illustrated in the upper left corner.

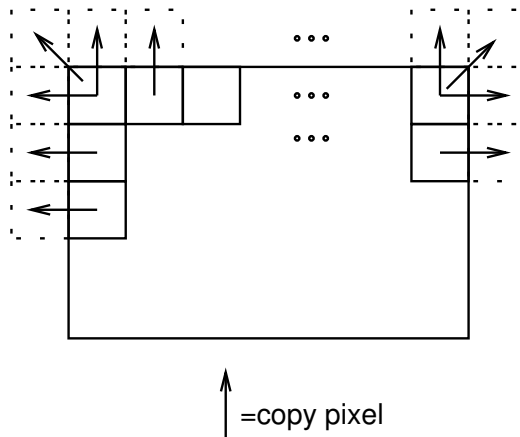


Figure 8: Boundary conditions.

5.2 Task 4b: Using Block RAM or Distributed RAM resources in the FPGA

By buffering whole rows of pixels in the HW accelerator, some speedup may be achieved, as pixels are only read once. Such a design may use Block RAM or Distributed RAM resources in the FPGA.

6 Your report

Write a short report describing your solutions to tasks 0, 1, 2, 3, and 4.

Each team must hand-in an electronic version of the report in PDF format and the source files as ZIP archive. In the ZIP file, only include the VHDL or SystemVerilog files and any relevant file you have produced. *Do not include the large Vivado files.* The hand-in is done by one student. The remaining students in the group should make sure they join the group so that we have everybody registered. The deadline is stated in the assignment facility of DTU-Learn.

The report must have a cover page containing the following elements: (i) the title of the report, (ii) your team number, and (iii) the name and student ID of each team member. In addition, you must include the following statement at the bottom of the cover page:

*We confirm that this report contains our own independent and original work.
Unless otherwise explained in the preface of the report, all group members
have contributed equally to all parts of the work.*

The report (and this Assignment) will contribute approximately 35% towards your final grade in this course.

7 Overview of design files

As previously mentioned, you can choose to do the assignment in either VHDL or SystemVerilog. For the VHDL version of the assignment, the files are provided in a ZIP file on DTU-Learn. For the SystemVerilog version, you can clone or download the following GitHub repository:

https://github.com/OttoWRas/02203_A2_SystemVerilog

For both versions, all the files you need to complete the project. The archive contains four directories: task2, task3, serial_interface, and other_images. In the following, you will find a description based on the VHDL version. For the SystemVerilog version, the same applies, but the files will have the `.sv` extension. In addition, for the SystemVerilog version, you can also refer to the README file in the repository.

Task 0

Use the files provided for tasks 2 and 3.

Task 1

This is an entirely paper-and-pencil design. No files are provided.

Task 2

types.vhd

Defines common types for the all modules.

clock.vhd

A 50 MHz clock generator. Only for simulation.

memory2.vhd

A VHDL *model* of the memory including procedures for reading and writing PGM-files from/to local hard drive. Used for simulation only. Images can be viewed using IrfanView.

acc2.vhd

The HW accelerator. The entity and an empty architecture body.

test2.vhd

A test bench instantiating a clock generator, the HW accelerator and the memory. Complete with clock, reset, start and finish signals. The name of the file containing the source image is given as a parameter.

pic1.pgm

A 352x288 source image in PGM-format. Can be viewed using Irfan-View.

Task 3

types.vhd

Defines common types for the all modules.

top.vhd

A top-level entity connecting all the components.

clock_divider.vhd

Divides the 100 MHz on-board clock and delivers as default a 50 MHz clock for use in the design.

debounce.vhd

The push-buttons on the board are not debounced. A digital circuit for debouncing the start signal is needed.

memory3.vhd

The memory to be implemented on the FPGA board. One port towards the accelerator following the specification in section 3.4 and a second port towards the UART controller.

uart.vhd

The UART used for serial communication between the controller and PC.

Nexys4DDR_edge.xdc

XDC-file specifying the pinout of the entire design including UART etc.

acc2.vhd

Your entity and architecture from task 2.

Serial Interface**serial_interface.py**

Source code for the serial interface program.

serial_interface.exe

The executable code for the serial interface.

HELP.txt

How to use the tool.

LICENSE.txt

License.

README.txt

Readme.

Other images

A few more images ...