

Complex State Machines and Video Graphics Array (VGA) Display

## 1 Introduction

The purpose of this laboratory is to further expand your understanding of finite state machines (FSMs) and to learn how one can use a “Video Graphics Array” (VGA) Adapter to create pictures and animation on a computer screen. You will create FSMs to interact with a VGA Adapter “core” that has been implemented for you to control and generate images and animations on the screen.

## 2 Preparation

To prepare for this laboratory, first read the VGA Adapter documentation provided at:

[http://janders.eecg.toronto.edu/ece241\\_13F/](http://janders.eecg.toronto.edu/ece241_13F/)

Be sure to read the four sections: “How do monitors work?”, “How does the VGA Adapter work?”, “VGA Adapter’s Interface” and “Changing Adapter Parameters”

Also, download the lab starter kit located at:

[http://janders.eecg.toronto.edu/ece241\\_13F/Lab7\\_starterkit.zip](http://janders.eecg.toronto.edu/ece241_13F/Lab7_starterkit.zip)

Once you have read the VGA Adapter documentation proceed to complete Parts I and II described below. Your preparation, to be shown to your TA at the beginning of the lab, must consist of the following:

1. The code used to implement each of the circuits described in Parts I and II. The code should be printed and pasted in your lab book before you arrive in the lab.
2. Simulation of the FSM and the datapath for the circuit in Part II. First simulate the FSM and the datapath separately, then put them together. The simulation must clearly indicate the operation of each circuit. The simulation must be printed and commented before the lab begins. The comments must explain why the simulation is correct.
3. Answer to the following question: Suppose that you set the VGA Adapter to work at a resolution of 160 by 120 pixels. Further, suppose that you want to change the colour of a pixel located at coordinates (x,y), where x corresponds to the last two digits of your student number and y corresponds to the second last two digits of your student number (e.g. If your student number is 123456789, then x=89 and y=67). Which location in the VGA Adapter memory would you have to change to alter to colour of the specified pixel? Give the exact memory address.

You need not include Part III in your preparation. This part is a *bonus* part to this lab and deals with the creation of animation using the VGA Adapter. If your ECE241 project involves creating graphics using the VGA Adapter, you are encouraged to attempt this part to better understand some of the challenges you will face in your project.

### 3 In the lab

In the lab you will have to implement and test circuits described in the sections below. In Part I, you will familiarize yourself with the VGA Adapter and learn how to draw images using the adapter. In Part II, you will extend the VGA Adapter and create a system that can draw a filled square on the screen at any location. Finally, you are encouraged to try the bonus Part III and complete a full digital animation circuit.

To simplify some of the steps a starter kit has been provided (link above). The starter kit is a .zip archive containing Quartus II projects for each part of the lab.

#### 3.1 Part Ia

To familiarize yourself with the VGA Adapter module you will perform a simple exercise to display a custom image on the screen. To do this you will need to use the bmp2mif converter provided in the starter kit. It is a program that converts a bitmap image into a stream of bits that can be programmed into the memory on an FPGA.

To be able to display a picture you must first draw a picture using a graphics editing tool that can save files in BMP format. The Microsoft Windows "Paint" program is one such tool. The image you will draw will cover the entire screen and thus has to be created correctly. Perform the following steps to draw an image:

1. Start the Paint program, typically available from the Start Menu: that is Start->Programs->Accessories->Paint
2. Select the menu item Image->Attributes. In the dialog box set "width" equal to 160 and "height" equal to 120, as this is the resolution of the monitor that the adapter uses. Select "pixels" as the unit. Select "colours" as well.
3. Draw a picture of your own design; use simple colours like Red, Green and Blue.
4. Save the file, using File->Save As and save it as a 24-colour bitmap image.bmp.
5. Run the bmp2mif.exe converter program (a windows program described on the VGA website and available from the download directory on that site) to convert your BMP file to a Memory Initialization File (MIF) we will use next. (To do that, start up a DOS command shell on windows using Start->Run and type "cmd" into the Open: box that pops up. This will create a window you can type commands into. Change into a folder that contains both bmp2mif.exe and the file.bmp you wish to convert. Then type "bmp2mif file.bmp." This will produce two .mif files - image.mono.mif and image.colour.mif.)

To ensure that you understand how the MIF file is used and what it represents, you are required to add a cyan 2x2 square with the top left corner placed at the position you used to answer question 3 in the preparation. You must use the MIF editor to do this. The MIF editor can be launched by simply opening the .mif file in Quartus. Refer to Figure 1 for an illustration of how the VGA framebuffer is organized.

Recall from the description of the VGA Adapter that it uses memory to store the current colour of each pixel on the screen. Usually, this memory is initialized to 0 at first and hence you only see a black background. However,

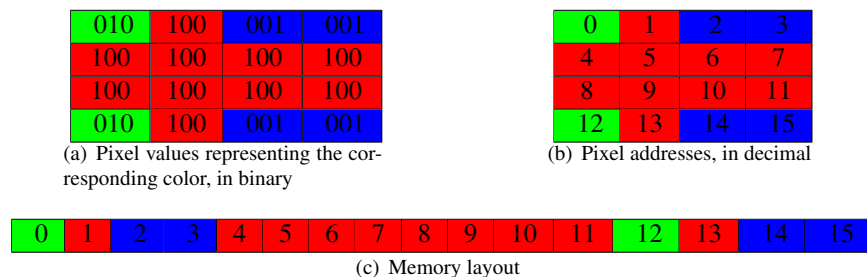


Figure 1: In-memory representation of the 4x4 pixel image. Each box holds a pixel color, a 3 bit value in our case

we can change the initial state of the VGA Adapter memory, causing it to display an image. You will use the image you created earlier with paint as that background.

Perform the following steps to change the initial image displayed by the Adapter:

1. The project for this part is provided in the starter kit. Open the project named *background* in the *part1* subdirectory to begin your work.
2. The BMP2MIF converter created a file called *image.colour.mif*, where your background image is stored. Copy this file to your working directory and change its name to **display.mif**. **Note:** The choice of the file name is not accidental. If you look carefully at the implementation of the VGA Adapter you will see that it has a parameter called `BACKGROUND_IMAGE`. This parameter is set to "display.mif" by default and signifies that the Quartus II software should use display.mif file to initialize the memory for the VGA Adapter. Note also that there can only be **one** display file which is programmed into the memory when the FPGA is configured (when you 'download' your design). It is a common mistake to think that you can create many of these files and somehow cause the FPGA to switch through them; this isn't possible as the download only happens once.
3. Assign pins to your project and compile it.
4. Program the circuit described in the preparation onto the Altera DE2 board.

When you program the DE2 board and connect a monitor to its graphics port, you should be able to see the image you have drawn.

**IMPORTANT:** Make sure you understand how this initialization process works: the memory (in the case of the VGA adapter, this memory is the framebuffer) is initialized with the contents of the MIF file (which stands for "Memory Initialization File") *only* when the FPGA is programmed. The MIF file is just the stream of raw data, and is not specific to the VGA Adapter - it can be used to initialize any kind of memory. The memory initialized this way can be changed - by modifying individual pixels on the screen as discussed in the VGA Adapter documentation. Note that as soon as you draw a pixel using the VGA Adapter, the contents of this memory will be altered. Thus, if you used a background image as we have shown above, the background image will be permanently altered. Resetting the VGA Adapter will NOT restore the "background image."

### 3.2 Part Ib

In this part you are asked to design a very simple circuit using the VGA adapter. The circuit has to perform the following functions:

1. Accept the X and Y coordinate inputs and the color input from the switches on the DE2 board.

- Set the given color of the pixel at the given coordinates when a push-button is pressed.

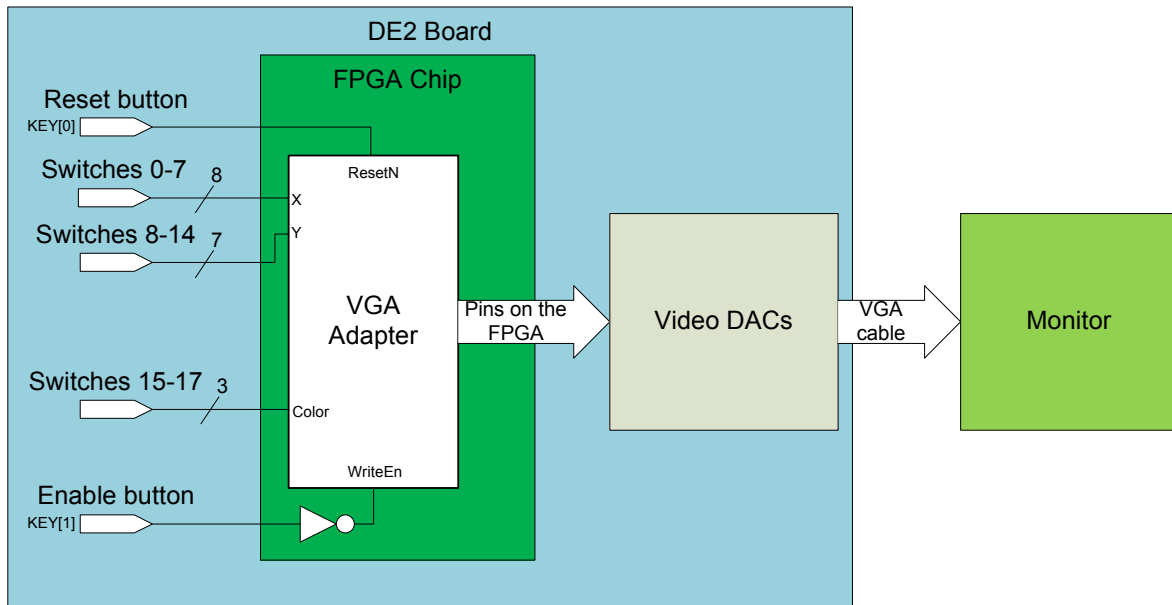


Figure 2: Full schematic of the circuit.

The schematic of the circuit is given in Figure 2. You should reuse the project file from *Part Ia* and design a circuit that connects up the switches on the DE2 board as given in the figure.

After completing this circuit you will be able to manually (and tediously) draw any picture on the screen. You will do this by choosing a (binary) value for the X and Y location of each pixel to change, choose a value for the colour, and then pushing the “enable” button to cause the specific pixel to change.

Observe that any image which you loaded in *Part Ia* is over-written as you change the colors of the pixels. This is because the VGA adapter has only one block of memory to store the value of each pixel (this block is called a *frame buffer* in the graphics world). This buffer was initialized with your image, but as you change the colors of the pixels, the old values are overwritten and lost.

### 3.3 Part II

In this part, you will design a circuit to draw a *filled* square on the screen at any location in any colour. As in the previous part, your circuit will accept an X and Y location as input, as well as a colour. The circuit should then draw a  $6 \times 6$  pixel square whose *upper-left* corner is at the X,Y location specified by the input. The top half of the square (3 pixels high  $\times$  6 pixels wide) should be filled with the colour specified by the switches and the other half of the square should be filled by the complement of the colour. For example, if the colour is  $1\ 1\ 0$  then the complement colour is  $0\ 0\ 1$ . The filled square should be drawn when an enable button (active-low) is pressed. The inputs to the circuit are the same as in Part I(b). An active-low reset should cause the entire screen to be cleared. Squares that straddle the right edge or bottom of the screen should be truncated (i.e. they do not wrap around). After a square has been drawn, your circuit should allow additional squares to continue to be drawn (say, at different locations in possibly different colours). The high-level design of the circuit for the system is given in Figure 3. It contains 3 major blocks:

1. The VGA adapter responsible for the drawing of pixels on the screen, which you have been learning about in Parts I and II.
2. The 'datapath' that contains arithmetic circuitry and registers, controlled by the FSM, that compute the X,Y values that are fed into the VGA Adapter in order to draw the  $5 \times 5$  filled square.
3. A finite state machine that serves as a controller for the datapath.

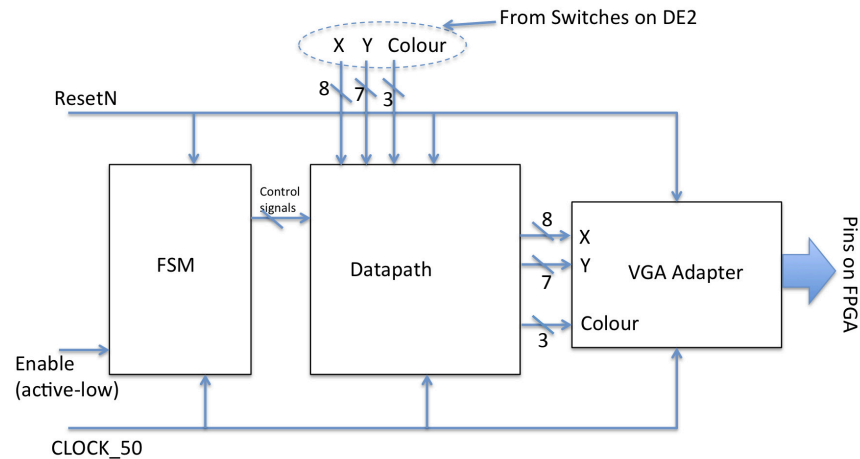


Figure 3: Design Overview - State Machine, Datapath and VGA Adapter. Although not shown, ResetN signal should be connected to all the registers in the circuit (including FSM state register).

Use the same pin assignments as in Part I(b) above.

### 3.4 Part III (Bonus)

Now that we covered drawing pixels on the screen we can proceed to create a simple animation. We will create a circuit that takes a small image (16x16 pixels) and moves it around the screen. To accomplish this, your circuit will have to make it seem as though the image is seamlessly moving around the screen. You will implement the circuit in two steps. First, you will design a module that is able to draw (or erase) the image at a given location. Then you will design another module that moves the image around the screen by quickly redrawing it at the different locations.

#### 3.4.1 Drawing the image

To implement this part, you will have to create a circuit that takes as input the (screen\_X,screen\_Y) coordinate of where the top left corner of the image is to be drawn or erased.

The circuit will then either draw the image from the memory (LPM\_RAM\_DQ module) or erase the image starting at position (screen\_X,screen\_Y). Images are drawn or erased pixel by pixel. To draw an image, read a single entry from memory and pass that value to the "Color" line on the VGA adapter. During this process, you must set the X,Y values on the VGA adapter to the appropriate values. Erasing an image is a similar process, however, instead of passing the values from the "Image RAM" to "Color", you will set "Color" to black (constant 000). To accomplish these steps, you will need to create a state machine that performs the following:

1. Set Counter\_X and Counter\_Y to 0.
2. While Counter\_X is less than 16, either load a pixel value from memory containing image.mif, or set the pixel value to black (if erasing). Then draw that pixel at location (screen\_X+Counter\_X,screen\_Y+Counter\_Y) on the screen. Increment Counter\_X.
3. If Counter\_Y is less than 15, then increment Counter\_Y and set Counter\_X to 0. Go to step 2.
4. Stop when Counter\_Y reaches 16.

The suggested circuit diagram is shown in figure 4. The “Blank” and “Plot” inputs may be used in several different ways. One way is to have “Blank” input select whether the image should be drawn or erased (i.e., if the “Blank” is high when “Plot” is asserted, the image is erased). Another way is to have two separate inputs, one to start drawing (“Plot”), and another to start erasing (“Blank”). You are free to choose whichever method you want.

Implement the circuit by completing the following steps:

1. The project for this part is provided in the starter kit. Open the project named *part3* in the *part3* subdirectory to begin your work.
2. Create a 16x16 bitmap image that is to move around the screen. Make sure to set the image width and height to 16 pixels.
3. Use the bmp2mif.exe converter to convert the image into an MIF file. Call it image.mif.
4. In your design instantiate a memory using an LPM\_RAM\_DQ and use image.mif as its memory initialization file.
5. Create a circuit to draw an image at a specified location on the screen as discussed above.
6. Compile the circuit and download it onto the DE2 board. When your circuits starts you should be able to see the image you have drawn somewhere on the screen.

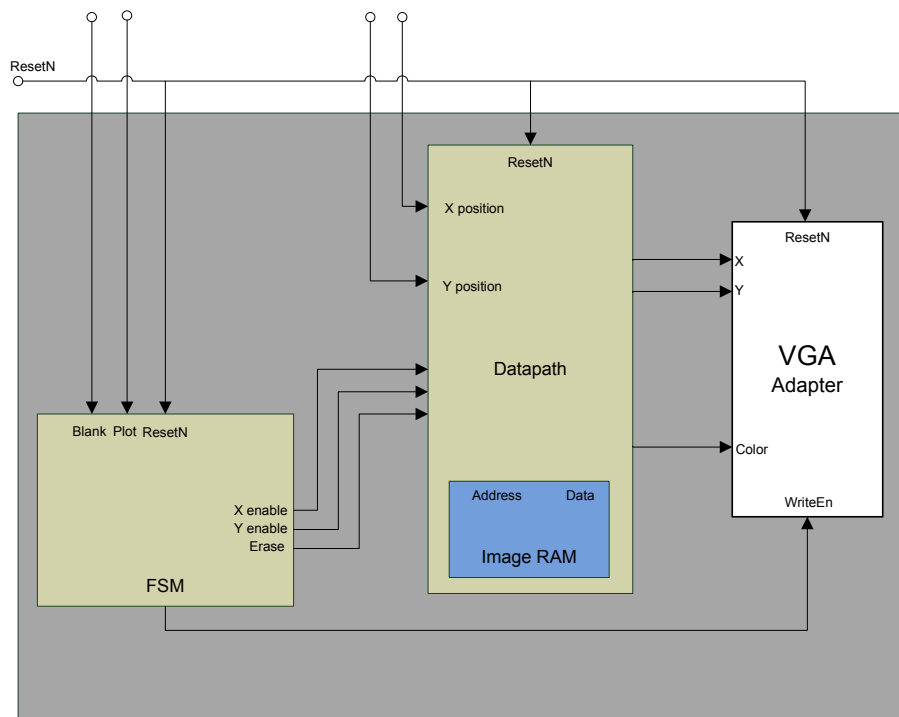


Figure 4: Suggested circuit layout for drawing the image

### 3.4.2 Animation

The circuit from step 1 can be used to draw an image at any location (X,Y). To move the image, you will have to first erase it from the location it is currently at and then draw it again at an alternate location.

There is a simple way to do that when the screen background is black. First, we draw an image at location (X,Y). Then to move the image we simply draw a black box on top of the image (using the erase function of the circuit from step 1) and redraw the image somewhere else. A suggested circuit is shown in figure 5, and you may use it as a starting point.

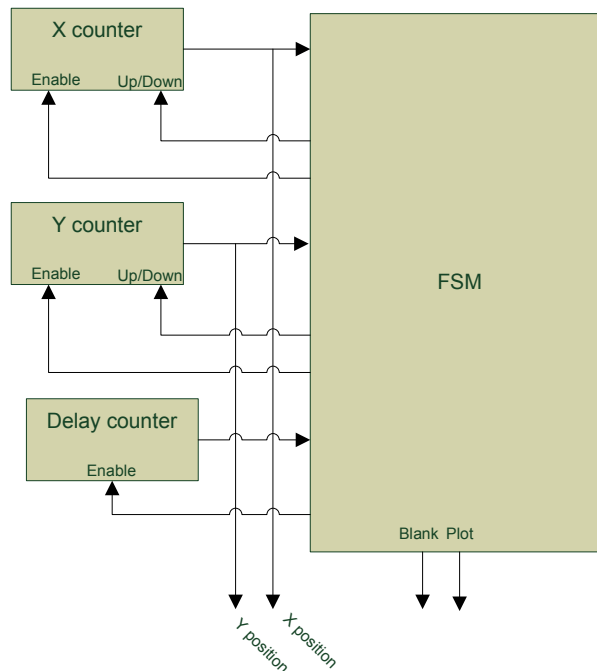


Figure 5: Suggested circuit layout for creating an animation

To complete the circuit, perform the following:

1. Create a circuit to change the location of the top left corner of where the image is to be drawn, once every 60<sup>th</sup> of a second. You may use circuit shown in figure 5 as a reference.
2. Put the circuits together to see if your image moves around the screen. Compile the circuit and program it onto the FPGA to see if it works.
3. If the circuit works, think of a way to get the image to bounce of the sides of the screen as it moves about. Implement the enhancement and show the circuit to your Teaching Assistant.