Laboratory Exercise 10

Image Processing

CPUs are general-purpose computational devices that are capable of a wide variety of tasks. This level of flexibility however, comes at a cost; CPUs are slower at some tasks than specialized devices. Because of this factor, some applications can execute more quickly if parts of the implementation run on a specialized device, such as a custom circuit in a field-programmable gate array (FPGA). This approach, of offloading computation to a faster device, is known as *hardware acceleration*.

In this laboratory exercise, we will implement two versions of an image processing application that detects the edges of an image. The first version will run entirely on the CPU. This discussion assumes that you are using the ARM processor in the DE1-SoC Computer to run your programs. The second version of the application will make use of hardware acceleration, by offloading most of the image processing operations to a hardware accelerator implemented inside an FPGA. We will assume that image files are represented in the *bitmap* (BMP) file format, using *24-bit true color*.

The Canny Edge-Detection Technique

In this exercise, we will implement a variation of the *Canny edge detector*, which is a widely-used edge-detection scheme. Figures 1 and 2 show a sample image that is provided as the input to a Canny edge detector, as well as the resulting edge-detected output image.

As illustrated in Figure 3 the Canny edge-detection algorithm involves five stages, which are applied to the input image in succession. The following sections describe each stage of the algorithm and show how the sample image from Figure 1 is transformed as it passes through each stage.

Figure 1: Original image.

Figure 2: Edge-detected image.

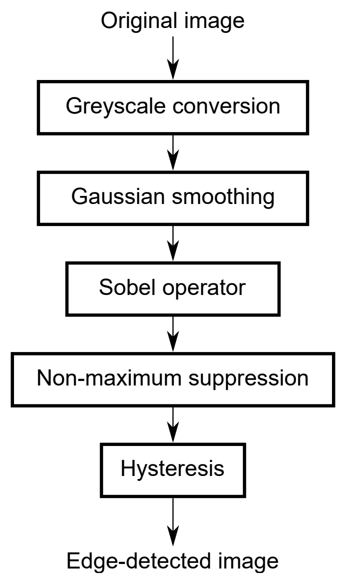


Figure 3: The Canny edge-detection algorithm.

Stage 1: Grayscale Conversion

Figure 4 shows the state of our sample image at the end of the grayscale conversion stage. This stage converts the input 24-bit bitmap color image (8 bits each for red, green, and blue) into an 8-bit grayscale image. The grayscale value at each pixel is calculated as the average of the three 8-bit color values of the original image.

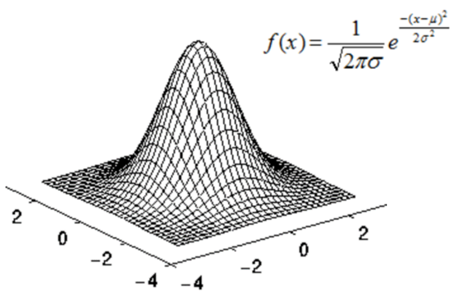
Figure 4: The sample input image after the grayscale conversion stage.

Stage 2: Gaussian Smoothing

The purpose of the Gaussian smoothing stage is to remove some of the "noise" in the image. Smoothing of the image allows the edge-detection mechanism to focus on changes in image intensity that correspond to features in the image, as opposed to random variations that can be attributed to image noise. Figure 5 shows the state of our sample image at the end of the Gaussian smoothing stage.

Figure 5: The sample input image after the Gaussian smoothing stage.

Smoothing, or blurring, of the image is accomplished by using a *Gaussian filter*, which modifies noisy pixels (pixels that are unlike their neighbouring pixels) to be more like their neighbours. An example of a Gaussian function is illustrated in Figure 6a. By choosing different values for the parameters σ and μ, the amplitude and shape of the function can be selected. For this exercise we are using a digital version of the Gaussian, specified as a 5×5 filter, or *kernel*. This kernel corresponds to a Gaussian function with standard deviation $\sigma = 1$ and mean $\mu = 0$. Part (b) of Figure 6 shows how the kernel is applied to the image. The * operator denotes *convolution*, A is the original image, and B is the resulting filtered image.



(a) Gaussian function

$$B = 1/273 \begin{bmatrix} 1 & 4 & 7 & 4 & 1 \\ 4 & 16 & 26 & 16 & 4 \\ 7 & 26 & \boxed{41} & 26 & 7 \\ 4 & 16 & 26 & 16 & 4 \\ 1 & 4 & 7 & 4 & 1 \end{bmatrix} * A$$

(b) Gaussian kernel and convolution

Figure 6: Gaussian functions and filters.

For a pixel in row i, column j of the image A, the kernel generates the dot-product

$$\begin{aligned} B_{i,j} \quad = \quad & (A_{i-2,j-2} + 4A_{i-2,j-1} + 7A_{i-2,j} + 4A_{i-2,j+1} + A_{i-2,j+2} + \\ & 4A_{i-1,j-2} + 16A_{i-1,j-1} + 26A_{i-1,j} + 16A_{i-1,j+1} + 4A_{i-1,j+2} + \\ & 7A_{i,j-2} + 26A_{i,j-1} + 41A_{i,j} + 26A_{i,j+1} + 7A_{i,j+2} + \\ & 4A_{i+1,j-2} + 16A_{i+1,j-1} + 26A_{i+1,j} + 16A_{i+1,j+1} + 4A_{i+1,j+2} + \\ & A_{i+2,j-2} + 4A_{i+2,j-1} + 7A_{i+2,j} + 4A_{i+2,j+1} + A_{i+2,j+2}) \div 273 \end{aligned}$$

The convolution operation performs this calculation for every pixel i, j so that each resulting pixel $B_{i,j}$ gets assigned the weighted average value of $A_{i,j}$ and the $5{\times}5$ grid of pixels surrounding it (if a pixel is near the top/bottom or left/right of the image, then 0's are inserted for any "missing" pixels that are needed for the calculation). Each dot-product result is divided by 273, which is the sum of the weights in the kernel, so that the overall intensity of pixels in the image does not change.

Stage 3: Sobel Operator

The Sobel stage is used to identify *edges* in the image B produced as the output of the Gaussian stage. It works by finding changes in the image intensity in both the horizontal (rows) and vertical (columns) directions. If we consider B to be a two-dimensional function $f(x, y)$, then changes in the image across each row are calculated by finding the *partial derivative* of the image in the x direction, $\partial f/\partial x$. Similarly, the partial derivative in the y direction, $\partial f/\partial y$, is used to find changes in the image along each column. To see how the partial derivatives can be calculated, consider the expressions in Figure 7.

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}$$

(a) Derivative of *f(x)*

$$f'(x) = \lim_{h \to 0} \frac{f(x+0.5h) - f(x-0.5h)}{h}$$

(b) Modified form of the derivative of *f(x)*

10	20	10	200	210	250	250

$$f'(x) = \frac{f(x+1) - f(x-1)}{2} = \frac{210 - 10}{2} = 100$$

-1	0	1

derivative filter

(c) Example derivative for a pixel, and derivative filter

Figure 7: The calculation of partial derivatives.

Part (a) of Figure 7 gives the traditional expression for the derivative of a function $f'(x)$, which is the limit as h approaches 0 of $\Delta f/\Delta x$, where $\Delta f = f(x+h) - f(x)$ and $\Delta x = h$. To calculate the derivative of an image at each pixel it is better to use the modified expression in Figure 7b, in which $\Delta f = f(x+0.5h) - f(x-0.5h)$. Part c of the figure provides an example that illustrates how this expression applies to a pixel in a row of an image. To find the derivative of the pixel in the middle of the row (which has the intensity 200) we use the pixels immediately to the right and left. Thus, $\Delta f = 210 - 10$ and $\Delta x = 2$. The key idea for finding derivatives at each pixel in an image is expressed by the *derivative filter* shown on the right hand side of Figure 7c. It represents the calculation of Δf and is used as the basis for the Sobel stage convolution described below.

The Sobel stage uses convolution similar to the Gaussian stage, but with two different 3×3 kernels. The kernels and convolution operations are given below.

$$\frac{\partial f}{\partial x} = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * B \qquad \frac{\partial f}{\partial y} = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} * B$$

These kernels represent versions of the derivative filter, extended to two dimensions, that is derived in Figure 7. For each pixel, the value of $\partial f/\partial x$ depends on three rows, where pixels in the same row are weighted by a factor of two. For example, $(\partial f/\partial x)_{i,j}$ for the pixel in row i, column j is calculated as

$$\begin{aligned} \left(\frac{\partial f}{\partial x}\right)_{i,j} &= B_{i-1,j+1} + 2B_{i,j+1} + B_{i+1,j+1} - \\ &\quad (B_{i-1,j-1} + 2B_{i,j-1} + B_{i+1,j-1}) \end{aligned}$$

Similarly, the value of $\partial f/\partial y$ for each pixel depends on three columns. Considered as a vector, the partial derivatives in the x and y directions are referred to as the *intensity gradient*:

$$\nabla f = \left[\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}\right]$$

The *magnitude* of the intensity gradient at each pixel reflects whether that pixel is on an "edge" from the original image, and the *angle* of the gradient indicates the direction of the corresponding edge. In this exercise we define the magnitude of the gradient as the average of the absolute values of the partial derivatives:

$$\|\nabla f\| = \frac{1}{2}\left(\left|\frac{\partial f}{\partial x}\right| + \left|\frac{\partial f}{\partial y}\right|\right) \tag{1}$$

If Equation (1) generates a result that is too large to fit into a pixel's eight-bit grayscale value, then the pixel is set to its maximum value of 255. The angle of the gradient is defined by:

$$\theta = tan^{-1}\left(\frac{\partial f/\partial y}{\partial f/\partial x}\right) \tag{2}$$

The angle θ reflects the direction of greatest ascent (in the image) at the pixel. Thus, if the pixel is on a horizontal edge then $\theta = \pm 90°$, and if the pixel is on a vertical edge then $\theta = 0°$ or $\theta = 180°$.

Figure 8 shows the results produced by the Sobel stage. Parts (a) and (b) of the figure illustrate the partial derivatives and part (c) shows the overall gradient. In these images the edges of the original image are highlighted as brighter pixels. Non-edges, which are areas with low intensity gradients, appear as darker pixels.

(a) $\frac{\partial f}{\partial x}$ (b) $\frac{\partial f}{\partial y}$ (c) ∇f

Figure 8: Images representing the partial derivatives and the image gradient.

To illustrate the effect of the Sobel operator, let us examine different image boundaries that may exist in an image as shown in Figure 9. For each 3×3 image shown, we can use the Sobel operator to calculate the intensity gradient at the center pixel. Let us examine the vertical example, where there is a boundary between darker pixels on the left side of the image and brighter pixels on the right side. In this example, $\partial f/\partial x$ of the center pixel can be calculated as $91+2(89)+92-(1+2(1)+3) = 355$. In the vertical direction, $\partial f/\partial y$ is $1+2(49)+91-(3+2(46)+92) = 3$. The intensity gradient for this pixel is high in the horizontal direction, and low in the vertical direction, which is to be expected along a vertical boundary. The overall intensity gradient is $\nabla f = \frac{1}{2}(355 + 3) = 179$. This is a bright pixel value, meaning that the Sobel operator has detected this boundary as a strong edge. The gradient angle $\theta = 0°$ because the direction of steepest ascent is left-to-right.

Vertical			Horizontal			\ Diagonal			/ Diagonal			No Edge		
1	49	91	2	1	1	50	93	91	91	93	50	69	73	65
1	47	89	43	47	46	3	47	89	89	47	3	67	70	69
3	46	92	94	92	91	1	2	46	46	2	1	65	65	66

	Vertical	Horizontal	\ Diagonal	/ Diagonal	No Edge
$\frac{\partial f}{\partial x}$	355	2	258	-258	1
$\frac{\partial f}{\partial y}$	3	-364	276	276	19
θ	0°	-90°	45°	-45°	87°
$\lVert\nabla f\rVert$	179	183	267	267	10

Figure 9: Examples of edges in an image.

In the horizontal case given in Figure 9, using the Sobel operator to calculate the intensity gradient at the center we see that the vertical gradient is high ($\partial f/\partial y = -364$) and the horizontal gradient is low ($\partial f/\partial x = 2$). The angle $\theta = -90°$ because the direction of greatest ascent from darker to brighter pixels is downward from the top of the image. For each of the diagonal cases in Figure 9, the gradients are high in both the x and y directions. The values of $\theta = \pm 45°$ represent the directions from darker to brighter pixels in each image. Finally, for the non-boundary case, the gradients are low in both directions with $\partial f/\partial x = 1$ and $\partial f/\partial y = 19$. As the gradients are low, the center pixel would become dark with a value of $\nabla f = \frac{1}{2}(1 + 19) = 10$.

Stage 4: Non-Maximum Suppression

After the Sobel stage, some of the edges identified in the image may be thick and/or blurry. The non-maximum suppression stage is used to enhance and sharpen the edges by making them thinner. This stage examines each pixel in the image that is on an edge and compares the pixel with its neighbours that may be part of the same edge—if the pixel is brighter than its neighbours, then its intensity is retained, else it is set to 0. Figure 10 shows the state of our sample image at the end of the non-maximum suppression stage.

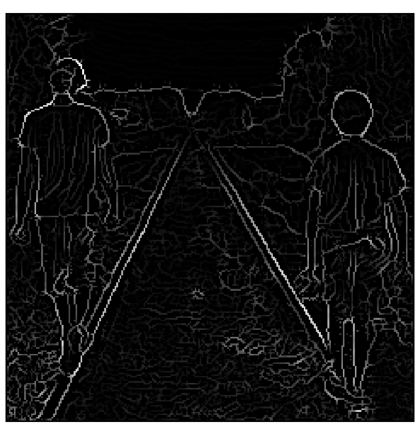


Figure 10: The sample input image after the non-maximum suppression stage.

0	41	134	45	0
0	43	135	46	0
0	35	136	41	0
0	41	132	35	0
0	44	131	41	0

Non-maximum Suppression $\longrightarrow$

0	0	134	0	0
0	0	135	0	0
0	0	136	0	0
0	0	132	0	0
0	0	131	0	0

Figure 11: The effect of nonmaximum suppression on a blurred vertical line.

The effect of non-maximum suppression on a sample image containing a blurry vertical line is illustrated in Figure 11. The vertical line, which is originally three-pixels wide, becomes one-pixel wide in the output image. Non-maximum suppression works by examining each pixel in the image in turn. The value of the gradient direction θ produced during the Sobel stage for the pixel indicates the type of associated edge. If θ is close to $0°$ or $180°$ then the pixel is on a "vertical" edge. In this case, the non-maximum suppression algorithm compares the intensity of its left and right neighbours to the pixel. If its intensity is higher, then the pixel is preserved in the output image from this stage, else it is set to 0. Similarly, a pixel with θ near $\pm 90°$ is preserved if its intensity is higher than the ones above and below it, and pixels with θ around $\pm 45°$ are preserved only if their intensity is greater than the appropriate neighbours that would be a part of the same "diagonal" edge. Following this process for each pixel in the image has the effect of producing thinner edges.

Stage 5: Hysteresis

The goal of the hysteresis stage is to remove any pixel that does not belong to an edge. Additionally, weak edges are erased altogether by removing any pixel that does not meet a user-defined intensity threshold. The hysteresis algorithm examines each pixel to determine whether: the pixel exceeds the user-defined threshold value, and there exists at least one adjacent pixel (horizontally, vertically, or diagonally) that exceeds the intensity threshold. If both conditions are met, the pixel is preserved, else it is removed by turning it black. Figure 12 shows the end result of the hysteresis stage.

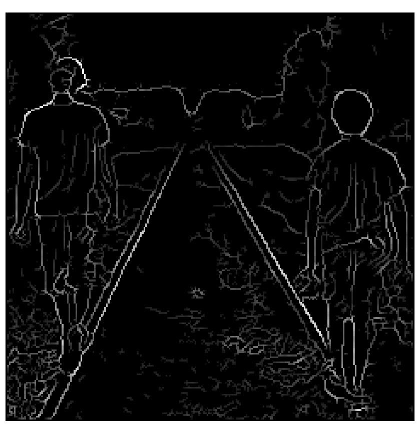


Figure 12: The sample input image after the hysteresis stage.

Part I

Write a C-language program that implements the five stages of the canny edge detector as described above, and run your code on the DE1-SoC Computer. Some sample images are provided along with this exercise. Sample skeleton code for this part is provided in Figure 13. It contains functionality for loading and storing bitmap images. The *main* function for the program is given in part (c) of the figure. Once a 24-bit true-color image is loaded into memory, the code calls functions to transform the pixels according to the five edge-detection stages, and then writes the resulting image into an output file. The first step of edge-detection, in which the image is converted to grayscale, is provided in the code, but you have to write the other stages. The code in Figure 13 also shows how to measure the runtime of your program, which will allow you to compare with the hardware-accelerated version developed later in this exercise. The code in Figure 13 is provided along with this exercise. Some additional functionality not shown in the figure is also included, such as code that can draw the images on an output video display.

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <time.h>

int width, height; // the dimensions of the image
struct pixel {
    unsigned char b;
    unsigned char g;
    unsigned char r;
};

// Read BMP file and extract the pixel values (data) and header.
// Data is data[0] = BLUE, data[1] = GREEN, data[2] = RED, data[3] = BLUE, etc...
int read_bmp(char *filename, unsigned char **header, struct pixel **data) {
    struct pixel *data_tmp;
    unsigned char *header_tmp;
    FILE *file = fopen (filename, "rb");
    if (!file) return -1;

    // read the 54-byte header
    header_tmp = malloc (54 * sizeof(unsigned char));
    fread (header_tmp, sizeof(unsigned char), 54, file);

    // get height and width of image from the header
    width = *(int*)(header_tmp + 18);  // width is a 32-bit int at offset 18
    height = *(int*)(header_tmp + 22); // height is a 32-bit int at offset 22

    // Read in the image
    int size = width * height;
    data_tmp = malloc (size * sizeof(struct pixel));
    fread (data_tmp, sizeof(struct pixel), size, file); // read the data
    fclose (file);

    *header = header_tmp;
    *data = data_tmp;
    return 0;
}
```

Figure 13: An outline of the software for edge detection (part a).

```c
// Set the grayscale 8-bit value by averaging the r, g, and b channel values.
// Store the 8-bit grayscale value in the r channel.
void convert_to_grayscale(struct pixel *data) {
    int x, y;

    // declare image as a 2-D array, to allow the syntax image[row][column]
    struct pixel (*image)[width] = (struct pixel (*)[width]) data;
    for (y = 0; y < height; y++) {          // y = 0 is the bottom row
        for (x = 0; x < width; x++) {       // x = 0 is the left side
            // Use the 8 bits of the r field to hold the grayscale image
            image[y][x].r = (image[y][x].r + image[y][x].b + image[y][x].g) / 3;
        }
    }
}

// Write the grayscale image to disk. The 8-bit grayscale values should be
// inside the r channel of each pixel.
void write_bmp(char *filename, unsigned char *header, struct pixel *data) {
    FILE* file = fopen (filename, "wb");
    // declare image as a 2-D array, to allow the syntax image[row][column]
    struct pixel (*image)[width] = (struct pixel (*)[width]) data;

    // write the 54-byte header
    fwrite (header, sizeof(unsigned char), 54, file);
    int y, x;

    // the r field of the pixel has the grayscale value; copy to g and b.
    for (y = 0; y < height; y++) {          // y = 0 is the bottom row
        for (x = 0; x < width; x++) {       // x = 0 is the left side
            image[y][x].b = image[y][x].r;
            image[y][x].g = image[y][x].r;
        }
    }
    int size = width * height;
    fwrite (image, sizeof(struct pixel), size, file); // write the data
    fclose (file);
}

// Gaussian blur. Operate on the .r fields of the pixels only.
void gaussian_blur(...) {
    unsigned int filter[5][5] = {
        { 1,  4,  7,  4, 1 },
        { 4, 16, 26, 16, 4 },
        { 7, 26, 41, 26, 7 },
        { 4, 16, 26, 16, 4 },
        { 1,  4,  7,  4, 1 }
    };
    // ... code not shown
}
```

Figure 13. An outline of the software for edge detection (part *b*).

```c
void sobel_filter(...) {
    int sobel_x[3][3] = {    // Sobel x direction (finds vertical edges)
        { -1,  0,  1 },
        { -2,  0,  2 },
        { -1,  0,  1 }
    };
    int sobel_y[3][3] = {    // Sobel in y direction (finds horizontal edges)
        { -1, -2, -1 },      // y == 0 (bottom) row
        {  0,  0,  0 },      // y == 1 (middle) row
        {  1,  2,  1 }       // y == 2 (top) row
    };
    // ... code not shown
}

void non_maximum_suppressor(...) {
    // ... code not shown
}

void hysteresis_filter(...) {
    #define strong_pixel_threshold 32  // example value
    // ... code not shown
}

int main(int argc, char *argv[]) {
    struct pixel *image;      // used to hold the image after each stage
    signed int *G_x, *G_y;    // used to hold the partial derivatives after Sobel
    unsigned char *header;
    time_t start, end;

    if (argc < 2) {          // Check inputs
        printf("Usage: part1 <BMP filename>\n");
        return 0;
    }
    // Open input image file (24-bit true color bitmap)
    if (read_bmp (argv[1], &header, &image) < 0) {
        printf("Failed to read BMP\n");
        return 0;
    }
    start = clock ();    // Start measuring time

    convert_to_grayscale (image);
    // gaussian_blur (&image);
    // sobel_filter (&image, &G_x, &G_y);
    // non_max_suppress (&image, G_x, G_y);
    // hysteresis_filter (&image);

    end = clock();

    printf("TIME ELAPSED: %.0f ms\n", ((double) (end - start)) * 1000 /
        CLOCKS_PER_SEC);

    write_bmp ("edges.bmp", header, image);
    return 0;
}
```

Figure 13. An outline of the software for edge detection (part *c*).

Part II

For Part I you used the DE1-SoC Computer system to run your program. For this part, you will use a different computer system, which is illustrated in Figure 14. This system include an edge-detection mechanism that is implemented as a hardware circuit in the FPGA device. As indicated in the figure, the hardware edge-detection mechanism consists of five components that are connected in sequence. The first component is called *Mem-to-Stream DMA*. This component is a *direct memory access* (DMA) controller that reads a 24-bit color image from memory. As the DMA reads these pixels, it *streams* (sends in sequence) them to the *RGB24-to-Grayscale* color-space converter. This converter implements stage one of the canny edge detector, converting the 24-bit color pixels into 8-bit grayscale pixels. The grayscale pixels are then streamed to the *Edge Detector* component, which implements stages two to five. The *Grayscale-to-RGB24* color-space converter then transforms the grayscale image back into the RGB24 format, which the *Stream-to-Mem DMA* then writes back into memory.

Figure 14 shows two types of memory ports in the FPGA: an SDRAM port, and an Onchip-memory port. The physical address ranges of these memories are `0xC0000000` to `0xC3FFFFFF` for SDRAM and `0xC8000000` to `0xC807FFFF` for Onchip memory. For the DE1-SoC board the edge-detection mechanism and video-out port are connected to the SDRAM port. When the SDRAM memory is being used, the edge-detection mechanism assumes that the image size is 640×480 pixels, and the image is stored in the memory starting at address `0xC0000000`. The edge-detected output image is saved to the address `0xC2000000`. When the Onchip memory is being used, the image size is 320×240 pixels. The original image is stored at address `0xC8000000`, and the edge-detected result *overwrites* the original and is therefore stored at the same address.

The DMA controllers shown in Figure 14, as well as the video-out port, require that each pixel in memory is *word-aligned*. Every 32 bits in memory should store one pixel, where bits 31 to 24 are (unused) padding bits, 23 to 16 are the red component, 15 to 8 are green, and 7 to 0 are blue.

For the DE1-SoC board the video-out port is initialized to read pixel data starting at the address `0xC0000000` (SDRAM).

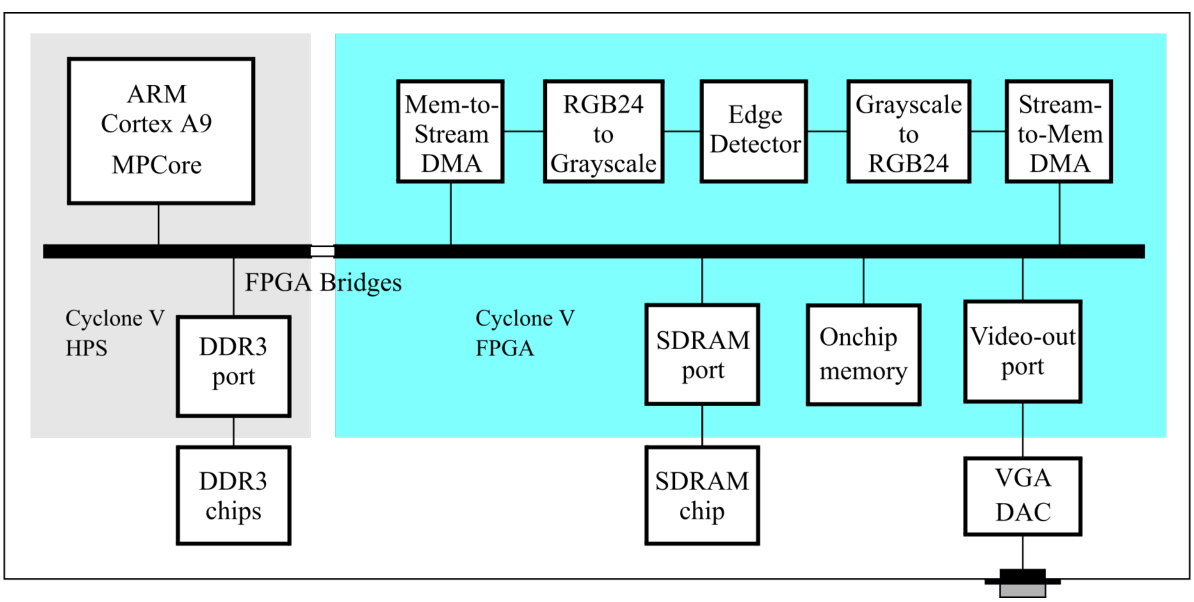


Figure 14: The components of the edge-detection system.

Perform the following:

1. Reconfigure the FPGA with the *Edge_Detector_System.rbf* file. An easy way to program the FPGA is to execute the Linux command `/home/root/misc/program_fpga` (a description of the FPGA programming process is provided in the appendix of the tutorial *Using Linux on DE-series Boards*). For this part you will make use of only the video-out capability of the system; the edge-detection capability will be used in Part III.

2. Consider the code in Figure 15. It first calls *read_bmp*, shown in Figure 13a, to read a bitmap image from a file into a data structure. The code then generates virtual addresses that allow access to SDRAM memory at physical address `0xC0000000`, and the FPGA lightweight bridge at address `0xFF200000`. The functions *open_physical* and *map_physical* use the */dev/mem* mechanism and the Linux system function *mmap* to provide virtual memory mappings of physical addresses. More details are provided in the tutorial *Using Linux on DE-series Boards*.

3. You are to write the function *memcpy_consecutive_to_padded* to complete the code in Figure 15. This function has to write a 32-bit value into the SDRAM buffer corresponding to each 24-bit pixel in the image.

4. Compile and test your code. Some sample images that have the correct dimensions are provided with this lab exercise (640×480 pixels for the DE1-SoC board). You should see the bitmap image, upside down, on the video display.

5. Write a function called *flip* that flips the image vertically before writing it into the SDRAM buffer. Test your code to see that the image is now displayed right-side up.

Part III

For this part you are to extend your program from Part II so that it makes use of the hardware edge-detection mechanism. You will need to access the programming registers of the DMA controllers, which are illustrated in Figure 16. The register at the `Base` address is called the *Buffer* register, and the one at address `Base+4` is the *Backbuffer* register. Each of these registers stores the address of a memory buffer. The `Buffer` register stores the address of the buffer that is *currently* being used by the DMA controller.

The operation of the DMA controller can be turned *off* by writing the value `0` into the *Status* register, at address `Base+12`. Writing the value `0x4` turns the DMA controller *on*, so that it performs transfers from/to memory starting at the address in the *Buffer* register.

It is possible for software to directly write into the *Backbuffer* register to change its contents, but not the *Buffer* register. To change the *Buffer* register it is necessary to perform a *swap* operation, explained below.

A buffer register swap is caused by writing the value `1` to the *Buffer* register. This write operation does not directly modify the content of the *Buffer* register, but instead causes the contents of the *Buffer* and *Backbuffer* registers to be swapped. The swap operation does not happen right away; it occurs at the end of the current DMA operation, when all pixels have been transferred. Software can poll the value of the S bit in the *Status* register to see when a DMA operation has been completed (an entire image has been processed). Writing the value 1 into the *Buffer* register causes S to be set to 1. Then, when the DMA operation is completed, S is reset back to 0.

The addresses of the programming registers for the three DMA controllers shown in Figure 14 are given in Table 1. The last two columns in the table give the initial contents of the *Buffer* and *Backbuffer* registers for each DMA. The columns labeled SDRAM and Onchip show the contents when the SDRAM memory or Onchip memory are being used, respectively. For the video-port DMA controller, the *Buffer* address is set to the start of memory, and the *Backbuffer* address points to the start of the edge-detected image. Performing a swap operation allows either the original image or the generated edge-detected image to be displayed.

```c
int main(int argc, char *argv[]){
   struct pixel *data;      // used to hold the image pixels
   byte *header;            // used to hold the image header
   int width, height;       // image size
   int fd = -1;             // used to open/read/etc. the image file
   void *SDRAM_virtual;
   void *LW_virtual;

   // Pointer to the DMA controller for the original image
   volatile unsigned int *mem_to_stream_dma = NULL;

   // Check inputs
   if (argc < 2){
      printf ("Usage: edgedetect <BMP filename>\n");
      return 0;
   }
   // Open input image file (24-bit bitmap image)
   if (read_bmp (argv[1], &header, &data, &width, &height) < 0){
      printf ("Failed to read BMP\n");
      return 0;
   }
   printf ("Image width = %d pixels, Image height = %d pixels\n", width, height);

   if ((fd = open_physical (fd)) == -1)   // Open /dev/mem
      return (-1);
   SDRAM_virtual = map_physical (fd, 0xC0000000, 0x03FFFFFF);
   LW_virtual = map_physical (fd, 0xFF200000, 0x00005000);
   if ((LW_virtual == NULL)  (SDRAM_virtual == NULL))
      return (0);

   // Set up pointer to edge-detection DMA controller
   mem_to_stream_dma = (volatile unsigned int *)(LW_virtual + 0x3100);
   *(mem_to_stream_dma+3) = 0; // Turn off edge-detection hardware DMA

   // Write the image to the memory used for video-out and edge-detection
   memcpy_consecutive_to_padded (data, SDRAM_virtual, width*height);

   free(header);
   free(data);

   unmap_physical (SDRAM_virtual, 0x03FFFFFF);  // release mem mapping
   unmap_physical (LW_virtual, 0x00005000);     // release mem mapping
   close_physical (fd);                         // close /dev/mem

   return 0;
}
```

Figure 15: The software code for Part II.

Address	31 … 24	23 … 16	15 … 12	11 … 8	7 6	5 … 2	1	0	
Base	front buffer address								Buffer register
Base + 4	back buffer address								Backbuffer register
Base + 8	Y		X						Resolution register
Base + 12	m	n	Unused	BS	SB	Unused	A	S	Status register

Figure 16: DMA controller registers.

DMA	Address	Register	SDRAM	Onchip
Video-out	`0xFF203020`	Buffer	`0xC0000000`	`0xC8000000`
	`0xFF203024`	Backbuffer	`0xC2000000`	`0xC8000000`
	`0xFF203028`	Resolution		
	`0xFF20302C`	Status		
Mem-to-Stream	`0xFF203100`	Buffer	`0xC0000000`	`0xC8000000`
	`0xFF203104`	Backbuffer	`0xC0000000`	`0xC8000000`
	`0xFF203108`	Resolution		
	`0xFF20310C`	Status		
Stream-to-Mem	`0xFF203120`	Buffer	`0xC2000000`	`0xC8000000`
	`0xFF203124`	Backbuffer	`0xC2000000`	`0xC8000000`
	`0xFF203128`	Resolution		
	`0xFF20312C`	Status		

Table 1: DMA register addresses.

Your program should do the following:

1. Disable the *Mem-to-Stream* and *Stream-to-Mem* DMA controllers. Recall that you will first need to obtain virtual addresses for accessing the physical addresses in Table 1. Refer to the tutorial *Using Linux on DE-series Boards* if needed.
2. Copy the pixels of the input image to memory at address `0xC0000000` (or `0xC8000000`). The bitmap image should now appear on the video display.
3. Enable the DMAs to start the edge-detection operation. Then, perform a swap operation and wait until both DMA controllers are finished.
4. Disable the DMAs.
5. Perform a swap operation for the video DMA, so that the edge-detected image appears on the display.
6. Save the edge-detected image into a file *edges.bmp*, for later display.
7. Test your program by using the images provided with this lab exercise. Compare the run-time of your program with the software-only solution from Part I, to see the benefits of using hardware acceleration.