

CS150 Final Project Report, Team 07

Sahar Mesri, Sagar Karandikar, `cs150-bw`, `cs150-bn`

December 11, 2013

Abstract

Abstract goes here.

1 Overview

1.1 Design - Block Diagrams

1.2 Brief Description of Major Submodules

1.2.1 Downsampler.v, Downsampler4x.v

The Downsampler module converts the original 800x600 image fed into our processing pipeline into a 400x300 image to align with our hardware constraints. The downsampler takes in the image data as a stream of pixels along with a valid signal that is only raised when the input pixel is valid data from the image. In addition to reducing image size, the downsampler is responsible for “generating” the blanking regions (sequences of black pixels) that are used to flush data through our gaussian pipeline. The downsampler ultimately outputs a scaled image as a stream of pixels along with a valid signal and a blankingregion signal that indicate whether the current output pixel is valid and/or a pixel in the blanking region respectively. Downsampler4x.v is identical to Downsampler.v, excluding some constants that are modified to allow this version to downsample from 400x300 images to 200x150 images.

1.2.2 Upsampler.v, Upsampler4x.v

The Upsampler module converts the processed 400x300 image coming out of the processing pipeline back into a 800x600 image for display over the DVI interface. The upsampler takes in the processed image data as a stream of pixels along with a valid signal that is asserted only for data that is both valid pixel data from the image and not part of the blanking regions. It performs basic upscaling by effectively taking each pixel from the processed input and expanding it to cover a 2x2 box of pixels in the final output. The upsampler outputs a pixel at a time in the output image along with a validout signal that is asserted whenever the data on the output is valid pixel data that we ultimately wish to display (blanking regions are non-existent at this point). Upsampler4x.v is identical to Upsampler.v, excluding some constants that are modified to allow this version to upsample from 200x150 images to 800x600 images.

1.2.3 DownsamplerWrap.v, Downsampler4xWrap.v

This module attaches the Downsampler to its output fifo, which mediates between the Downsampler and the gaussian pipeline. This module spans both the first and second clock domains.

1.2.4 UpsamplerWrap.v, Upsampler4xWrap.v

This module attaches the Upsampler to its input fifo, which mediates between the gaussian pipeline and the Upsampler. This module spans both the second and third clock domains.

1.2.5 Check4.v, Check4_4x.v

This module connects the entire Downsampler, Octave, and Upsampler pipeline together. Additionally, it provides the switching functionality that allows our design to display any of the gaussians or differences on-demand.

1.2.6 octave.v

The Octave module contains 5 Gaussian filter blocks and computes the four Difference of Gaussian outputs. The module takes in a stream of pixels (one at a time), along with a valid signal and a blanking signal. It will output a stream of pixels (along with a valid signal) for each Gaussian filter and each Difference of Gaussian. There is no blanking output since blanking pixels are considered invalid at the output. This module also has a special output just for the next octave, which contains the data, valid, and blanking signal from one of the Gaussian filters (the fourth one in this case).

1.2.7 five_by_five_window.v

This module represents one Gaussian filter block, with five coefficients in the horizontal direction and five coefficients in the vertical direction. The input is a stream of pixels (one at a time), along with a valid signal and a blanking signal. The output is also a stream of pixels (after going through the Gaussian filter), along with a valid signal and a blanking signal. Pixels that are marked as blanking are also replaced with zero prior to the output.

1.2.8 x_window.v

This module is used to compute the horizontal portion of the Gaussian filter. It will multiply 5 pixels in the same row by their corresponding coefficients. It will then take the average of those results to find the output value, whose location within the frame corresponds to the center of those five pixels. The input is a stream of pixels (one at a time), along with a valid signal and a blanking signal. The output is also a stream of pixels (after computing the horizontal Gaussian), along with a valid signal and a blanking signal.

1.2.9 five_row_array.v

This module is used to store five rows of pixels at a time, which becomes the input into the y_window module. This module takes in a stream of input pixels (one at a time), along with a valid signal and a blanking signal. It outputs five pixels at a time, one from

each line, along with a valid signal and a blanking signal. These five pixels have the same horizontal position in the frame, and come from consecutive lines within the frame. The center of these five consecutive lines is the pixel at the center of the Gaussian filter block, so the blanking output corresponds to the blanking input for this particular pixel.

1.2.10 `y_window.v`

This module computes the vertical portion of the Gaussian filter. It multiplies 5 input pixels (from the same column) by their corresponding coefficients, and averages those results to find the output value. The location of the output value within the frame corresponds to the center of the input pixels. The input is a stream of pixels (five at a time), along with a valid signal and blanking signal. The output is also a stream of pixels (after computing the vertical Gaussian), along with a valid signal and a blanking signal.

2 System Description

2.1 Datapath

2.1.1 Connections to SRAM

2.1.2 Difference of Gaussian Filter Blocks

octave.v This module is where the each Difference of Gaussian is computed for a single octave. It contains five Gaussian filter blocks, where the output of one block is fed into the input of the next block. The time between the first valid pixel of one block and the first valid pixel of the next block is determined by the time it takes for one pixel to travel through an entire Gaussian filter. To compute a Difference of Gaussian, the same pixel from each Gaussian filter block needs to be used, despite the delay between the two blocks. This means that the output of the first Gaussian must be stored in a shift register with a depth equal to that delay, while also being routed to the next Gaussian filter block. The output of the next Gaussian is then subtracted from the output of the shift register. The result is the Difference of Gaussian.

The blanking signal also needs to be delayed, however the second of the two Gaussians already takes care of that, so the Difference of Gaussian simply uses the blanking signal of the latter Gaussian filter block. Blanking signals are used by other modules within the octave, and indicate whether or not a particular pixel is part of the original image (not blanking), or was added in order to pad the edges of the image (blanking). Blanking pixels are not used by any module outside of the octave, so blanking pixels are simply considered invalid pixels at the output. A diagram of a simple Difference of Gaussian is shown below:

`insert_diagram_here`

five_by_five_window.v This module is one Gaussian filter block. It is split into three sub-modules: `x_window`, `five_row_array`, and `y_window`. This module serves four main purposes: 1) To connect `x_window`, `five_row_array`, and `y_window` to each other and to the inputs and outputs of the `five_by_five_window` module 2) To generate control signals for `five_row_array` and `y_window` 3) To delay the blanking input and ensure a proper blanking output 4) To replace any blanking input pixels and output pixels with zero `x_window`, `five_row_array`, and `y_window` were designed so that they would connect directly to each other, in that particular order. The valid input into the module is fed straight into `x_window`, and the valid output of `y_window` is attached directly to the valid output of the `five_by_five_window`. The three sub-modules do not need the blanking input signal. This signal is instead put into a shift register, whose depth is equal to the delay it takes for one pixel to travel through `x_window`, `five_row_array`, and `y_window`. The output of this shift register is the blanking output signal.

The data into the `five_by_five_window` module first goes into a mux, which chooses between the input data and a zero constant, depending on if the input is part of a blanking region or not. The output of that mux is then fed directly into `x_window`. In the same way, the output of `y_window` goes into a mux, which chooses between the output data or a zero constant, depending on if the output is blanking. The output of this mux is connected to the data output of the `five_by_five_window` module. This replacement of blanking pixels is done because those blanking pixels are used to pad the edges of the image, which is needed to keep the image size constant while feeding it through several Gaussian filters. In particular, the edges of the image need to be padded with zeros. However, running those zero pixels through an averaging filter will make them non-zero, which is why they need to be replaced by zeros between every filter block. The control signals generated by this module for `five_row_array` and `y_window` will be discussed in a later section.

x_window.v This module computes the horizontal portion of the Gaussian filter. The basic idea is that the module will store the 4 previous input pixels and the current pixel. It will also multiply each pixel by its coefficient, add the result of those operations, and scale the result back down to an 8-bit value for the next stage.

The module expects the value of each pixel in the frame as input, one line at a time (top to bottom), starting from the first (leftmost) pixel in the line and ending at the last (rightmost) pixel in the line. This module does not take into account padding. If the image is inputted without extra padding pixels, then the results at the edges of each line may not be accurate. To ensure proper results, there needs to be at least two blanking pixels at the end of this line (assuming the horizontal Gaussian window takes in five pixels). The two pixels can act as padding for both the previous line and the next line. An illustration of this concept is shown below: `insert_diagram_here`. Since all registers are set to zero upon reset, including the registers that store previous pixel values, the first two pixels of the frame are already padded.

In order to ensure maximum clock frequency, there is a register between each consecutive mathematical operation, such as a multiplication and addition. Because of this, computing the sum of all five terms takes several cycles, and adds some latency to this portion of the pipeline. However, once the pipeline is filled, there will be one valid output during every cycle with a valid input (invalid inputs will stall the pipeline). The time it takes to generate an output for a particular input (assuming the pipeline is not stalled after this point) is 7 cycles. This is also the time it takes to fill the pipeline. Therefore, there is a 7 cycle delay between when the valid input signal becomes high and when the valid output signal becomes high (again, assuming there are no stalls).

This module also takes advantage of the symmetry in the Gaussian coefficients, and computes the product of a pixel and its coefficient only once. For example, once the product of some pixel and the coefficient h1 is computed for the first time, that value will be needed again two cycles later. Likewise, the product of some pixel and the coefficient h0 will be needed 4 cycles later. The module will store and shift this value down the pipeline where it will be used for later operations which require this result. This reduces the number of multipliers in the module, which reduces the overall number of DSP SLICES required for this particular module.

The coefficients are scaled in such a way that the result of adding each term (the product of a pixel and its coefficient) is no larger than a 16-bit unsigned number. In order to scale this back down to an 8-bit number, we simply keep the upper 8 bits and drop the lower 8. This is the same as dividing the result by 256, or shifting the result to the right by 8.

five_row_array.v This module stores the results of the x_window module. Each output of x_window is the result of running each pixel through the horizontal portion of the Gaussian filter. This module will store 5 lines worth of pixels, which is needed to compute the vertical portion of the Gaussian filter. The output is five pixel values, all from the same position within a line (column), from five consecutive rows. This is accomplished by creating a 5 shift registers, one for each line, with a depth equal to the number of pixels in a line (including blanking). The module is constantly shifting values in and out of each shift register, as long as there is a valid input. One of the five shift registers gets new values from the input, and every other shift register has its output fed back into the input. This is done to ensure that a pixel of a particular position within a line (such as x=250) is in the same position within all 5 shift registers. The array containing the oldest values gets replaced by newer values. Once that array is full, the module will begin filling/replacing the contents of the next oldest array. An illustration of this concept is shown below:

`insert_diagram_here;`

The input signal asel is used to choose which array to shift the new value into. This is a five-bit, one hot signal. Each bit corresponds to a particular shift register, and if that bit is 1 then the shift register will shift in the new data (instead of shifting in the old data). As long as each new value is shifted into the proper register in the proper order, then the

outputs will also be in the proper order. See the example above for a demonstration on how this is accomplished.

Only the first three rows need to be filled before there is a valid output. This is because the shift registers are set to 0 upon reset, so two of the rows can act as blanking rows. This means that the delay between a valid input and a valid output (assuming no stalls/invalid inputs) is $3 \times \text{width}$, where width is the number of pixels in a row, including blanking. This is also the time it takes to fill this portion of the pipeline, and the time it takes to generate an output for one particular input.

Note that the first shift register does not always correspond to the first line within the vertical Gaussian window (nor does the second shift register correspond to the second line, and so on). This is because the current line being filled with new data is always rotating (according to the input `asel`). This means that the `y_window` module needs to keep track of which line is which, and select the appropriate coefficients for each line. How and where these control signals are generated will be discussed in a later section.

y_window.v This module computes the vertical portion of the Gaussian filter. It will receive five input pixels from the `five_row_array`. Each pixel is from the same position in a line (such as `x=250`), and comes from consecutive lines. It is expected that the pixels will start from the leftmost position within a line, and end at the rightmost position. It is also expected that the groups of lines will be received in order from top to bottom (i.e. lines

1, 2, 3, 4, 5

followed by lines

2, 3, 4, 5, 6

). These pixels are then multiplied by their corresponding coefficients and the results are added together. This sum will then be scaled back down to an 8-bit number. To ensure proper results, at least two extra lines of zeros (blanking/padding), need to be added at the end of each frame. This is similar to the requirement of two extra pixels in each line for the `x_window` module.

In order to ensure maximum clock frequency, there is a register between each consecutive mathematical operation, such as a multiplication and addition. Because of this, computing the sum of all five terms takes several cycles, and adds some latency to this portion of the pipeline. However, once the pipeline is filled, there will be one valid output during every cycle with a valid input (invalid inputs will stall the pipeline). The time it takes to generate an output for a particular input (assuming the pipeline is not stalled after this point) is 5 cycles. This is also the time it takes to fill the pipeline. Therefore, there is a 5 cycle delay between when the valid input signal becomes high and when the valid output signal becomes high (again, assuming there are no stalls). This is shorter than the 7 cycle delay of the `x_window` module because this module receives all 5 pixels at

once, rather than having to store each pixel one at a time until there is enough for a valid output.

As we pointed out in the previous section, the outputs of the `five_row_array` do not always correspond to the same line within the vertical Gaussian window. This means that the inputs to `y_window`, which are connected directly to the outputs of `five_row_array`, also do not correspond to the same line. This also means that the coefficients (that we multiply each input by), cannot be constant. The signal `hsel`, which is a 3-bit number ranging between zero and four, is used to choose the coefficient for each line. In terms of hardware, this means that there is a 5-mux (for each line) which chooses between the five coefficients, and the result is then fed into the multiplier (for each line). The same signal `hsel` is used for all five multiplexers. What is different is the order in which the coefficients are attached to each multiplexer. This allows one signal, `hsel`, to choose between the 5 different ways in which the outputs from `five_row_array` can be arranged. As long as `hsel` and `asel` are in synch, and change at the same time, the proper coefficients will be used. Details on how `hsel` and `asel` are generated will be discussed in a later section.

The coefficients are scaled in such a way that the result of adding each term (the product of a pixel and its coefficient) is no larger than a 16-bit unsigned number. In order to scale this back down to an 8-bit number, we simply keep the upper 8 bits and drop the lower 8. This is the same as dividing the result by 256, or shifting the result to the right by 8.

2.1.3 Connections to ImageBufferWriter

`ImageBufferWriter` only requires a data input and a valid signal, and this comes from the upsampler. In this case, we have two upsamplers, one from each octave. Each octave also has nine outputs: five Gaussian outputs and four Difference of Gaussian outputs. This means that we need to choose which one of those outputs goes into the upsampler, and then choose which upsampler to connect to `ImageBufferWriter`. The selector input for the `Check4` and `Check4_4x` modules is used to choose between the five Gaussian outputs and the four Difference of Gaussian outputs. The value of selector is determined by `GPIO_DIP[3:6]`. Inside of `FPGA_TOP_ML505`, we use `GPIO_DIP[7]` to choose which upsampler to connect to `ImageBufferWriter`. If we consider `GPIO_DIP[3:7]` (a particular combination of switches) to be a 5-bit binary number, then the following table summarizes which image each number corresponds to:

Binary Octave Image 00000 0 gauss0 00001 0 gauss1 00010 0 gauss2 00011 0 gauss3 00100 0 gauss4 00101 0 diff0 00110 0 diff1 00111 0 diff2 01000 0 diff3 10000 1 gauss0 10001 1 gauss1 10010 1 gauss2 10011 1 gauss3 10100 1 gauss4 10101 1 diff0 10110 1 diff1 10111 1 diff2 11000 1 diff3 NOTE: Any missing binary numbers (switch combinations) are considered illegal and will cause the swap controller to stall.

Switching the input to `ImageBufferWriter` at the wrong time could result in a shifted image or a stalled swap controller. In order to mitigate these issues, the `GPIO_DIP` switches

are not connected directly to the selectors/multiplexors. Instead, these values are stored in a register and that register is updated at a time when it is safe to switch. The details of this implementation and the timing will be discussed in a later section.

2.1.4 Downsampler

2.1.5 Upsampler

2.2 Control

2.2.1 Dealing with issues - blank rows, addressing issues

2.2.2 General controller design, by module

octave.v This module does not need any control signals or generate any control signals. However, it does depend on an input signal `validin`, and outputs a valid signal for each Gaussian and Difference of Gaussian. If there is no valid input, then the entire pipeline is stalled, and there are no valid outputs. When there are valid inputs, and the pipeline is still filling up, some Gaussian filter blocks will have a valid output and some will not. This is because the output of one Gaussian filter is fed into the input of the next Gaussian. This also means that the same pixel (for example, the first pixel), will be outputted at different times for different Gaussians. Once the entire pipeline has been filled, all outputs will be valid as long as there is a valid input as well. However, there is still a delay between the time when a particular pixel (i.e. a pixel at one specific location within the frame) shows up on the output of each Gaussian filter block. This delay is just the delay through all of the components of the Gaussian filter block (`x_window`, `five_row_array`, and `y_window`). The total delay is then $(3 * \text{width}) + 12$, where `width` is the number of pixels in one line, including blanking. Suppose `width = 420`, and the octave receives a constant stream of valid outputs starting at cycle 0. Then: `g0_valid = 1 @ cycle 1272` `d0_valid = 1 @ cycle 2544` `g1_valid = 1 @ cycle 2544` `d1_valid = 1 @ cycle 3816` `g2_valid = 1 @ cycle 3816` `d2_valid = 1 @ cycle 5088` `g3_valid = 1 @ cycle 5088` `d3_valid = 1 @ cycle 6360` `g4_valid = 1 @ cycle 6360` This can also be seen in the timing diagram below: `insert_diagram_here`. Any stall in the pipeline (i.e. an invalid input into the octave for `n` number of cycles) will cause an additional delay.

five_by_five_window.v This module does not need any control signals. However, it does generate the control signals `asel` and `hsel` for `five_row_array` and `y_window`, respectively. These signals are only supposed to change when the `x_window` module outputs enough pixels for one complete line. This was done by making a counter, which goes from 0 to `width-1` (where `width` is the number of pixels in one line, including blanking), and increments when there is a valid output from `x_window`. The state machines which generate `asel` and `hsel` will change states whenever the counter is equal to `width-1`. Both state machines are Moore machines which simply rotate between five different states. These

states correspond to the five different ways in which the outputs of `five_row_array` can be arranged. The state diagrams for these machines are below: `insert_diagram_here`. This module also takes in a `valid` signal and outputs a `valid` signal. However, this module does not do anything to these signals; it simply feeds the input into `x_window`, and takes the output directly from `y_window`. The behavior of this module's sub-modules (`x_window`, `five_row_array`, and `y_window`) does mean that this entire module will stall if there is no valid input.

`x_window.v` This module does not need any control signals nor does it generate any control signals. It does have a simple counter to determine if the pipeline has filled up enough so that the output is valid. This counter will increment as long as there is a valid input, and the count is less than seven. Once the count has reached seven, the counter will stop incrementing unless the module is reset. The output of the module is invalid if the counter is less than seven, or the input is not valid. This also means that an invalid input will stall this module. A timing diagram demonstrating the relationship between `validin`, the counter, and `validout` is below: `insert_diagram_here`.

`five_row_array.v` This module does need one control signal, `asel`. What this signal is used for was discussed in the previous section on this module's datapath, and how this signal is generated was discussed in the previous section on `five_by_five_window` control signals. This module also does not generate any control signals. It does have a simple counter to determine if the pipeline has filled up enough so that the output is valid. This counter will increment as long as there is a valid input, and the count is less than $3 \times \text{width}$, where `width` is the number of pixels in a row (including blanking). Once the count has reached $3 \times \text{width}$, the counter will stop incrementing unless the module is reset. The output of the module is invalid if the counter is less than $3 \times \text{width}$, or the input is not valid. This also means that an invalid input will stall this module. A timing diagram demonstrating the relationship between `validin`, the counter, and `validout` is below: `insert_diagram_here`.

`y_window.v` This module does need one control signal, `hsel`. What this signal is used for was discussed in the previous section on this module's datapath, and how this signal is generated was discussed in the previous section on `five_by_five_window` control signals. This module also does not generate any control signals. It does have a simple counter to determine if the pipeline has filled up enough so that the output is valid. This counter will increment as long as there is a valid input, and the count is less than 5, where `width` is the number of pixels in a row (including blanking). Once the count has reached 5, the counter will stop incrementing unless the module is reset. The output of the module is invalid if the counter is less than 5, or the input is not valid. This also means that an invalid input will stall this module. A timing diagram demonstrating the relationship between `validin`, the counter, and `validout` is below: `insert_diagram_here`.

Image Switching When switching inputs into the ImageBufferWriter, timing is critical. If the switch is made at the wrong time, the output might be shifted over, or the swap controller might get stalled. As mentioned in a previous section, GPIO_DIP[3:8] is the input to a register. The register is then connected to the mechanism that determines which image writes into ImageBufferWriter. All that is needed is a safe time to update that register. The best time to do this is right after the ImageBufferWriter has completed one frame. Once the ImageBufferWriter signals that it is finished, using bg_done, the swap controller will send bg_done_ack. Once that has happened, the ImageBufferReader, responsible for the DVI output, will get a swap signal from the swap controller. After the ImageBufferReader sends a swap_ack, the swap controller will issue a start signal to VGA or StaticImage, and wait for start_ack. The following timing diagram illustrates this process: `insert_diagram_here`

This gives us plenty of time to check if one of the switches has moved, reset the entire pipeline (including each octave, downsampler, and upsampler), and then switch the inputs into ImageBufferWriter. We need to reset the pipeline because some of the Gaussian filter blocks may still have some non-blanking pixels inside, which would be considered valid and would then be pushed into ImageBufferWriter. By resetting the pipeline, everything starts over, as if the next frame were actually the first frame. We need all of this time because it takes more than one clock cycle to reset the FIFOs used in the upsampler and downsampler. According to the Xilinx LogiCORE IP FIFO Generator v9.1 User Guide, the FIFOs we are using have an asynchronous reset, and it takes three clock cycles (write or read) after the asynchronous reset is detected on the rising edge read and write clock respectively. Since both the read and write ports of all of the FIFOs are on the same clock, that means it will take 3 clock cycles before the pipeline is actually ready to receive valid data. From the timing diagram above, we see that there will always be enough time to complete a reset. Below is an image, taken from the Xilinx LogiCORE IP FIFO Generator v9.1 User Guide, which demonstrates the behavior of a FIFO during a reset: `insert_diagram_here`

2.2.3 State diagrams and functional timing diagrams

3 Design Metrics

4 Conclusion