Augmented Reality on FPGA

Realtime Object Recognition and Image Processing

Logan Williams   José E. Cruz Serrallés

6.111 Fall 2011

15 November 2011

Introduction

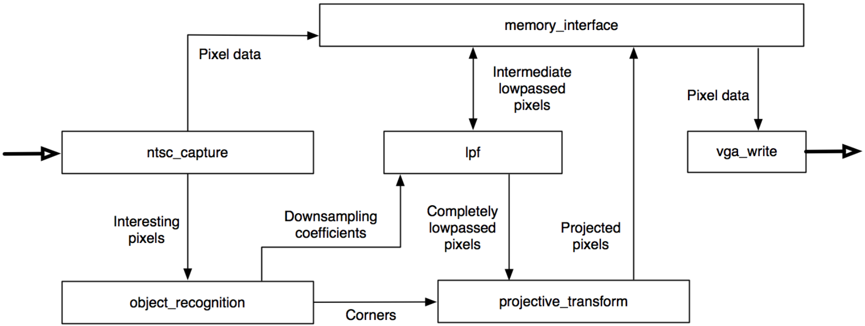
- Overlay a digital image on a physical object in realtime.
- In this case, we want to identify a picture frame in captured video, and output video with another image distorted to fit on top of the picture frame.

Example Image

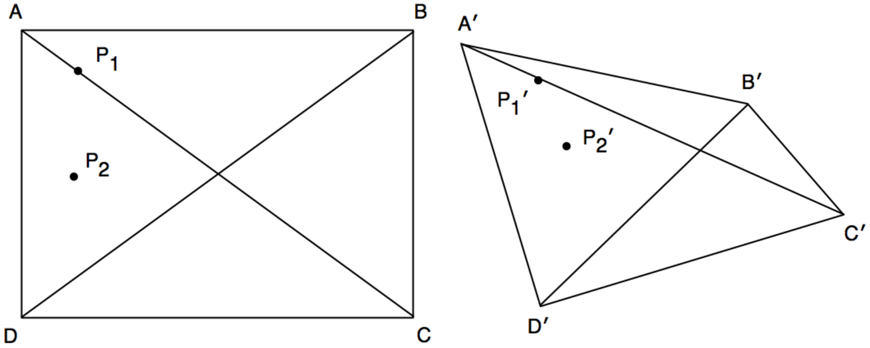
Example Image

Example Image

Top-Level Overview

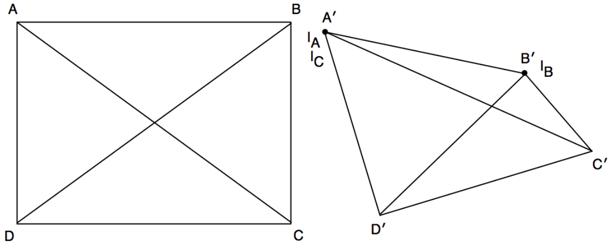


`projective_transform`: Purpose



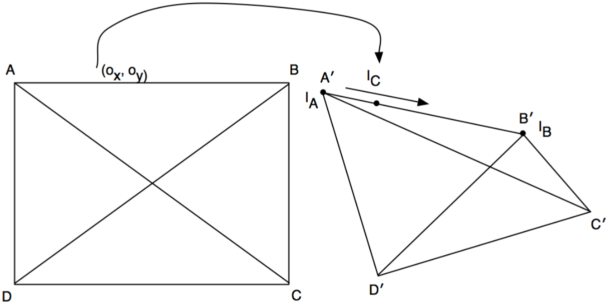
- Skew to any arbitrary convex quadrilateral

projective_transform: How the algorithm works



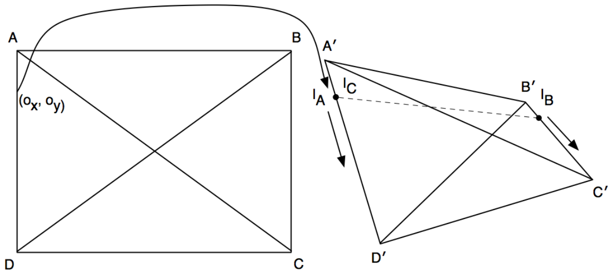
1. Calculate the distance of line $\overline{A\prime D\prime}$ and assign it to d_{ad}.
2. Do the same for $\overline{B\prime C\prime}$ and assign it to d_{bc}.
3. Create two "iterator points," point I_A and I_B initially located at $A\prime$ and $B\prime$.
4. Let $o_x = 0$ and $o_y = 0$
5. Calculate the distance between the iterator points, assign it to d_i.
6. Create a third iterator point, I_C at the location I_A.

`projective_transform`: How the algorithm works



7. Assign the pixel value of I_C to pixel (o_x, o_y) in the original image.
8. Move I_C along line $\overline{I_A I_B}$ by an amount $= \frac{d_i}{width_{original}}$.
9. Increment o_x.
10. Repeat steps 7–9 until $I_C = I_B$.

`projective_transform`: How the algorithm works



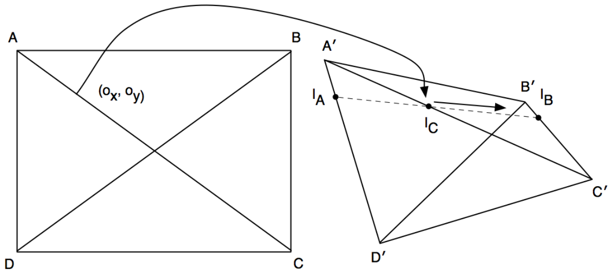
11 Move I_A along line $\overline{A\prime D\prime}$ by an amount $= \frac{d_{ad}}{height_{original}}$.

12 Move I_B along line $\overline{B\prime C\prime}$ by an amount $= \frac{d_{bc}}{height_{original}}$.

13 Increment o_y.

14 Repeat steps 5–13 until $I_A = D\prime$ and $I_B = C\prime$.

`projective_transform`: How the algorithm works



11 Move I_A along line $\overline{A\prime D\prime}$ by an amount $= \frac{d_{ad}}{height_{original}}$.

12 Move I_B along line $\overline{B\prime C\prime}$ by an amount $= \frac{d_{bc}}{height_{original}}$.

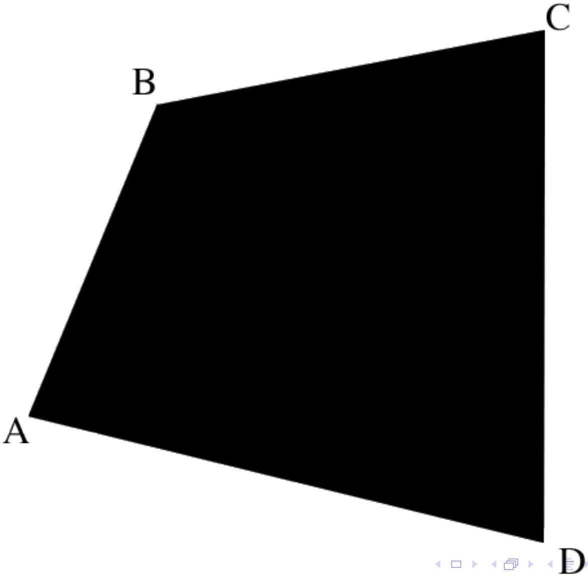
13 Increment o_y.

14 Repeat steps 5–13 until $I_A = D\prime$ and $I_B = C\prime$.

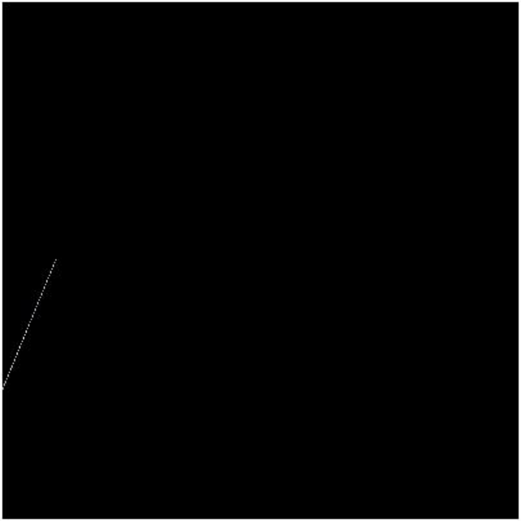
`projective_transform`: Example

Figure: The original image

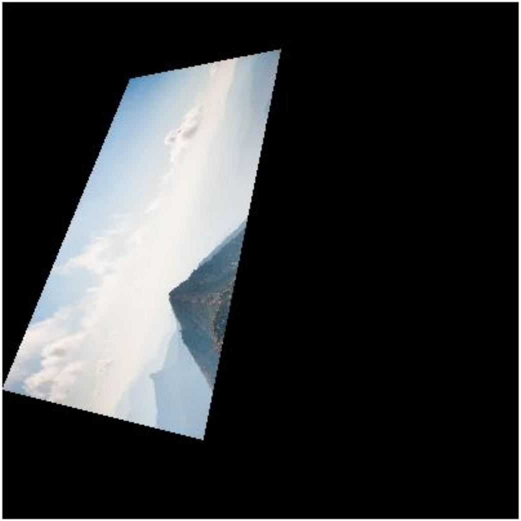
`projective_transform`: Example



projective_transform: Example



`projective_transform`: Example

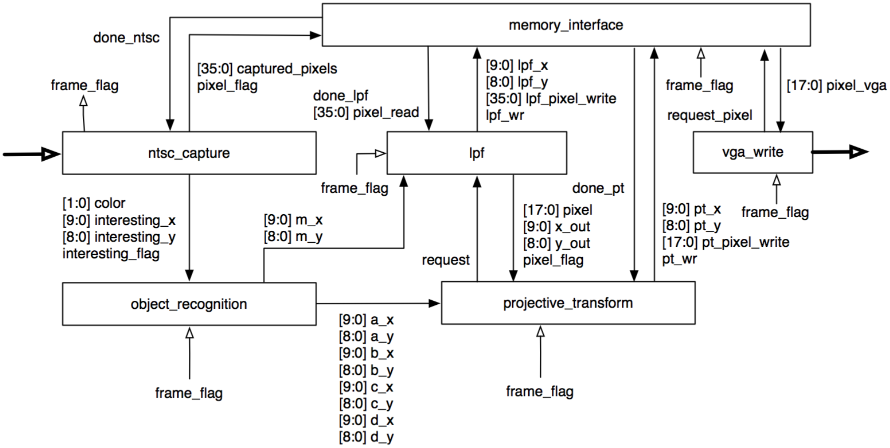


`projective_transform`: Example

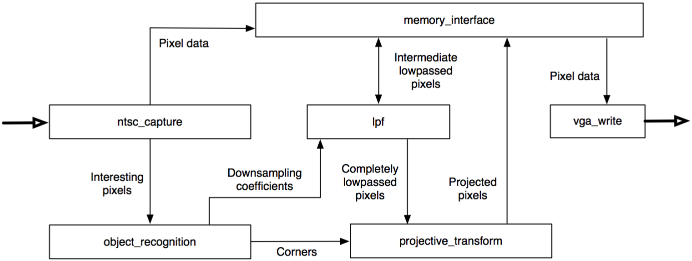
`projective_transform`: FPGA implementation

- Straightfoward implementation of the above algorithm
- Uses coregen Divider modules for the divisions
- Requires only 2*640*480 + 4*480 multiplications per clock cycle
- Uses an iterative algorithm for finding distances (pipelined at the end of each line of the image)
- Processes pixels “on-the-fly” from `LPF`
- Negligible memory requirements (a handful of registers)

projective_transform: How it Interfaces



object_recognition



- Mark corners of frame with four differently colored dots.
- Recognition begins in the `ntsc_capture` module, which detects these colors as it is capturing data and sends the pixel info to the `object_recognition` module.

object_recognition

- Take linear weighted center of mass for each image
- Sums the (x,y) coordinates for each color as it receives them. (8 running sums, 2 for each color)
- When the frame is done, divide each sum by the number of summed items
- The resulting 4 (x,y) pairs are the corners of the frame
- By looking for pixels in `ntsc_capture` we significantly reduce the amount of time spent in `object_recognition`

LPF: its purpose

- `projective_transform` → aliasing

Original

LPF: its purpose

- projective_transform → aliasing
- Aliasing reduces the quality of an image

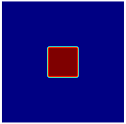
Original Aliased

`LPF`: its purpose

- `projective_transform` → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing

Original

Aliased

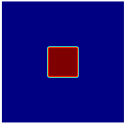


Mag. of Filter

`LPF`: its purpose

- `projective_transform` → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing

Original



Mag. of Filter

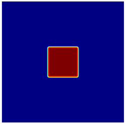
Filtered

LPF: its purpose

- `projective_transform` → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing

Original

Aliased



Mag. of Filter

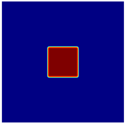
Filtered

LPF: its purpose

- projective_transform → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing
- Information of an image is mostly phase


Original


Aliased


Mag. of Filter

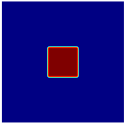

Filtered

LPF: its purpose

- `projective_transform` → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing
- Information of an image is mostly phase
- Symmetric Type I FIR filter → 0 phase distortion

Original

Aliased



Mag. of Filter

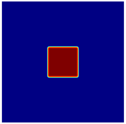
Filtered

LPF: its purpose

- `projective_transform` → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing
- Information of an image is mostly phase
- Symmetric Type I FIR filter → 0 phase distortion
- Parks-McClellan: reasonable accuracy, symmetric, easily calculable

Original

Aliased



Mag. of Filter

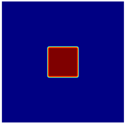
Filtered

LPF: its purpose

- `projective_transform` → aliasing
- Aliasing reduces the quality of an image
- Lowpass filtering prevents aliasing
- Information of an image is mostly phase
- Symmetric Type I FIR filter → 0 phase distortion
- Parks-McClellan: reasonable accuracy, symmetric, easily calculable
- FIR PM filter reduces mem. acceses to 1.5/pixel

Original

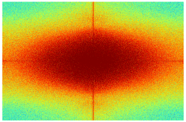
Aliased



Mag. of Filter

Filtered

1. Given an arbitrary image & skewing coefficients M_x & M_y.

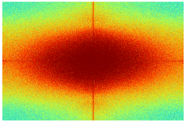


F.T. Original

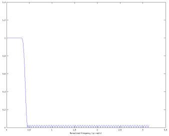
Original Image

LPF: the algorithm

1. Given an arbitrary image & skewing coefficients M_x & M_y.
2. Fetch a filter with cutoff $\frac{\pi}{M_y}$.



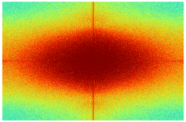
F.T. Original



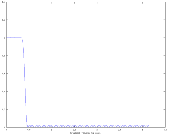
1D FIR, $\omega_c = \frac{\pi}{8}$

LPF: the algorithm

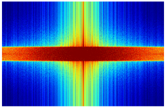
1. Given an arbitrary image & skewing coefficients M_x & M_y.
2. Fetch a filter with cutoff $\frac{\pi}{M_y}$.
3. Filter each column and store in memory.



F.T. Original

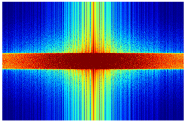


1D FIR, $\omega_c = \frac{\pi}{8}$

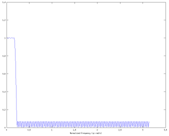


F.T. Filtered

1. Given an arbitrary image & skewing coefficients M_x & M_y.
2. Fetch a filter with cutoff $\frac{\pi}{M_y}$.
3. Filter each column and store in memory.
4. Fetch a filter with cutoff $\frac{\pi}{M_x}$.



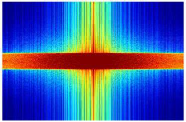
F.T. Filtered



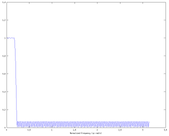
1D FIR, $\omega_c = \frac{\pi}{16}$

`LPF`: the algorithm

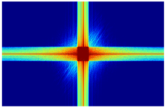
1. Given an arbitrary image & skewing coefficients M_x & M_y.
2. Fetch a filter with cutoff $\frac{\pi}{M_y}$.
3. Filter each column and store in memory.
4. Fetch a filter with cutoff $\frac{\pi}{M_x}$.
5. Filter each row and output to `projective_transform`.



F.T. Filtered



1D FIR, $\omega_c = \frac{\pi}{16}$

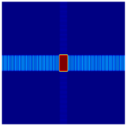


F.T. Output

LPF: the algorithm

1. Given an arbitrary image & skewing coefficients M_x & M_y.
2. Fetch a filter with cutoff $\frac{\pi}{M_y}$.
3. Filter each column and store in memory.
4. Fetch a filter with cutoff $\frac{\pi}{M_x}$.
5. Filter each row and output to `projective_transform`.
6. Repeat this process every refresh cycle.

Original



F.T. of Process

Output

memory_interface

- 1 image is a lot of data:
  $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB

- 1 image is a lot of data:
  $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB
- Total BRAM: 0.316MiB

memory_interface

- 1 image is a lot of data:
  $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB
- Total BRAM: 0.316MiB
- We need to store 4 images in memory!

memory_interface

- 1 image is a lot of data: $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB
- Total BRAM: 0.316MiB
- We need to store 4 images in memory!
- Let's use the ZBT RAM: $2 \cdot 2.25$MiB

memory_interface

- 1 image is a lot of data: $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB
- Total BRAM: 0.316MiB
- We need to store 4 images in memory!
- Let's use the ZBT RAM: $2 \cdot 2.25$MiB
- Not so fast: 1 clock cycle per memory access

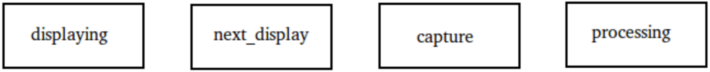
- 1 image is a lot of data: $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB
- Total BRAM: 0.316MiB
- We need to store 4 images in memory!
- Let's use the ZBT RAM: $2 \cdot 2.25$MiB
- Not so fast: 1 clock cycle per memory access
- 1 pixel per address would require a clock speed $> 100MHz$

`memory_interface`

- 1 image is a lot of data:
  $640 \cdot 480 \cdot 24$ bits ≈ 0.88MiB
- Total BRAM: 0.316MiB
- We need to store 4 images in memory!
- Let's use the ZBT RAM: $2 \cdot 2.25$MiB
- Not so fast: 1 clock cycle per memory access
- 1 pixel per address would require a clock speed $> 100MHz$
- Let's store store 18 bits per pixel or 2 per address

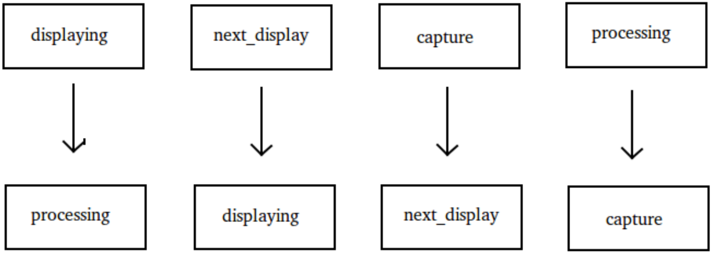
memory_interface: operation

Four images in memory:



memory_interface: operation

Four images in memory:



Shift every refresh cycle

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to `memory_interface`

system io: ntsc_capture & vga_write

ntsc_capture

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to memory_interface

vga_write

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to `memory_interface`

`vga_write`

- Image data streamed to monitor

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to `memory_interface`

`vga_write`

- Image data streamed to monitor
- New image every $\frac{1}{60}$ seconds

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to `memory_interface`

`vga_write`

- Image data streamed to monitor
- New image every $\frac{1}{60}$ seconds
- Module will be adapted from Lab 2 VGA code

system io: `ntsc_capture` & `vga_write`

`ntsc_capture`

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to `memory_interface`

`vga_write`

- Image data streamed to monitor
- New image every $\frac{1}{60}$ seconds
- Module will be adapted from Lab 2 VGA code
- Requires own clock (ISE)

system io: ntsc_capture & vga_write

ntsc_capture

- Image data streaming from camera
- New image every $\frac{1}{30}$ seconds
- Module will be adapted from NTSC code on 6.111 website
- Requires own clock (ISE)
- Outputs two pixels to memory_interface

vga_write

- Image data streamed to monitor
- New image every $\frac{1}{60}$ seconds
- Module will be adapted from Lab 2 VGA code
- Requires own clock (ISE)
- memory_interface will feed properly formatted pixels

timeline

11-11-2011 Finalized block diagram

11-18-2011 First drafts of `projective_transform` and `memory_interface` written

11-22-2011 First drafts of `object_recognition`, `LPF`, `vga_write`, and `ntsc_capture` first drafts written; `projective_transform` and `memory_interface` fully tested

11-28-2011 `ntsc_capture` and vga_write fully tested; start of basic integration

11-31-2011 `object_recognition` and `LPF` fully tested; start of full integration

12-05-2011 Full integration complete

12-12-2011 Final report due