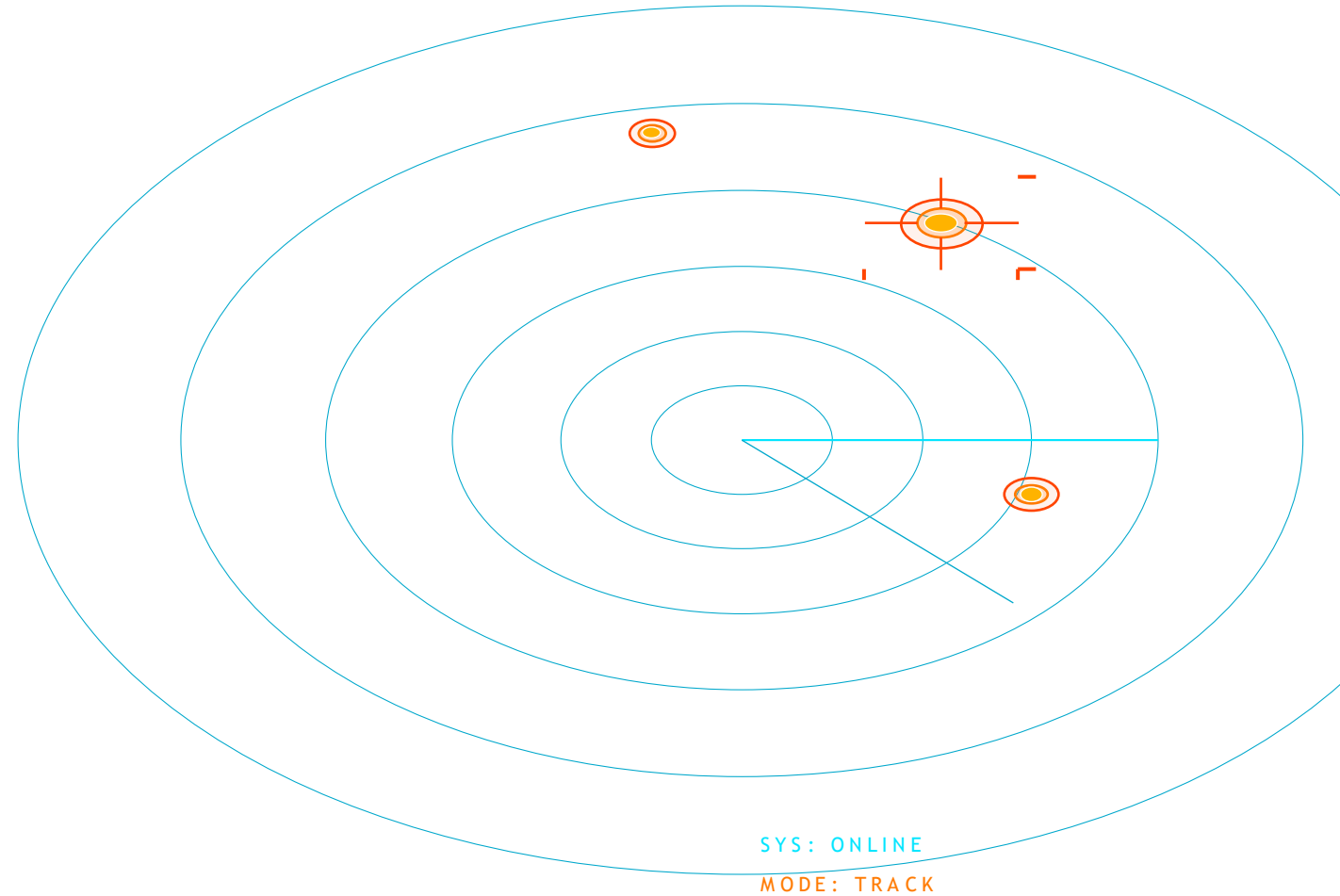


UNCALIBRATED STEREO MOTION TRACKING

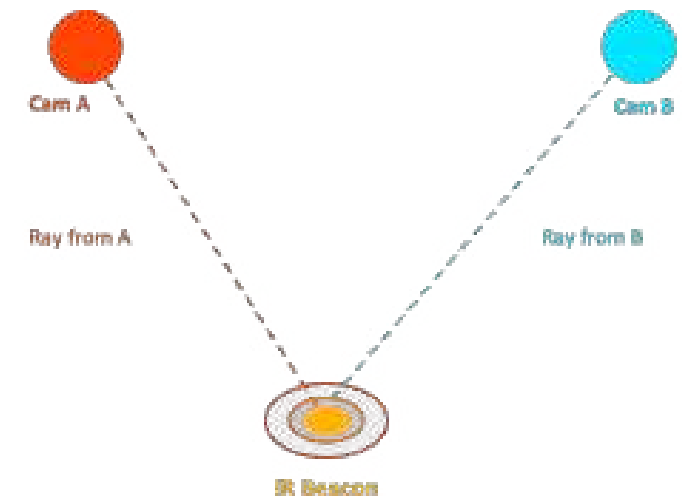
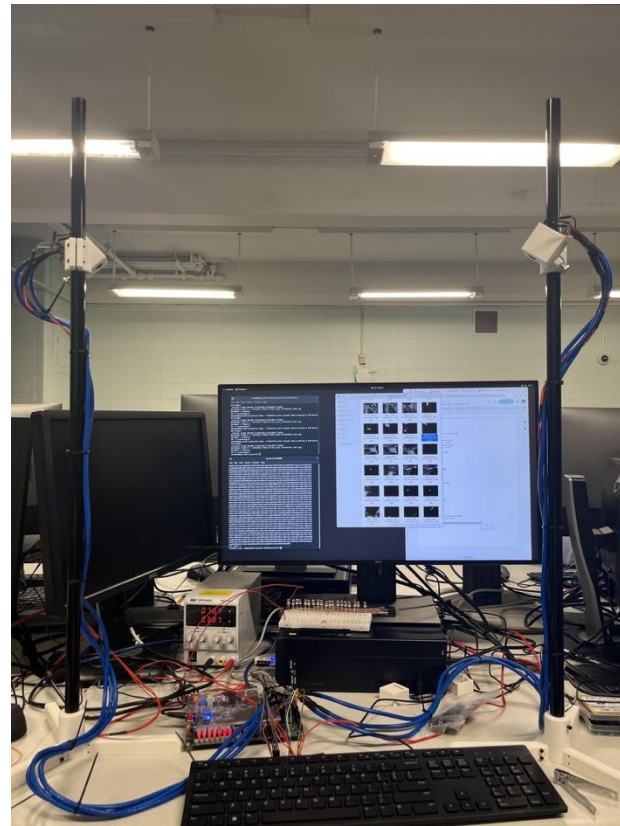
Leen Alshorafa & Kuan Zhang

Embedded Systems (CSEE4840)



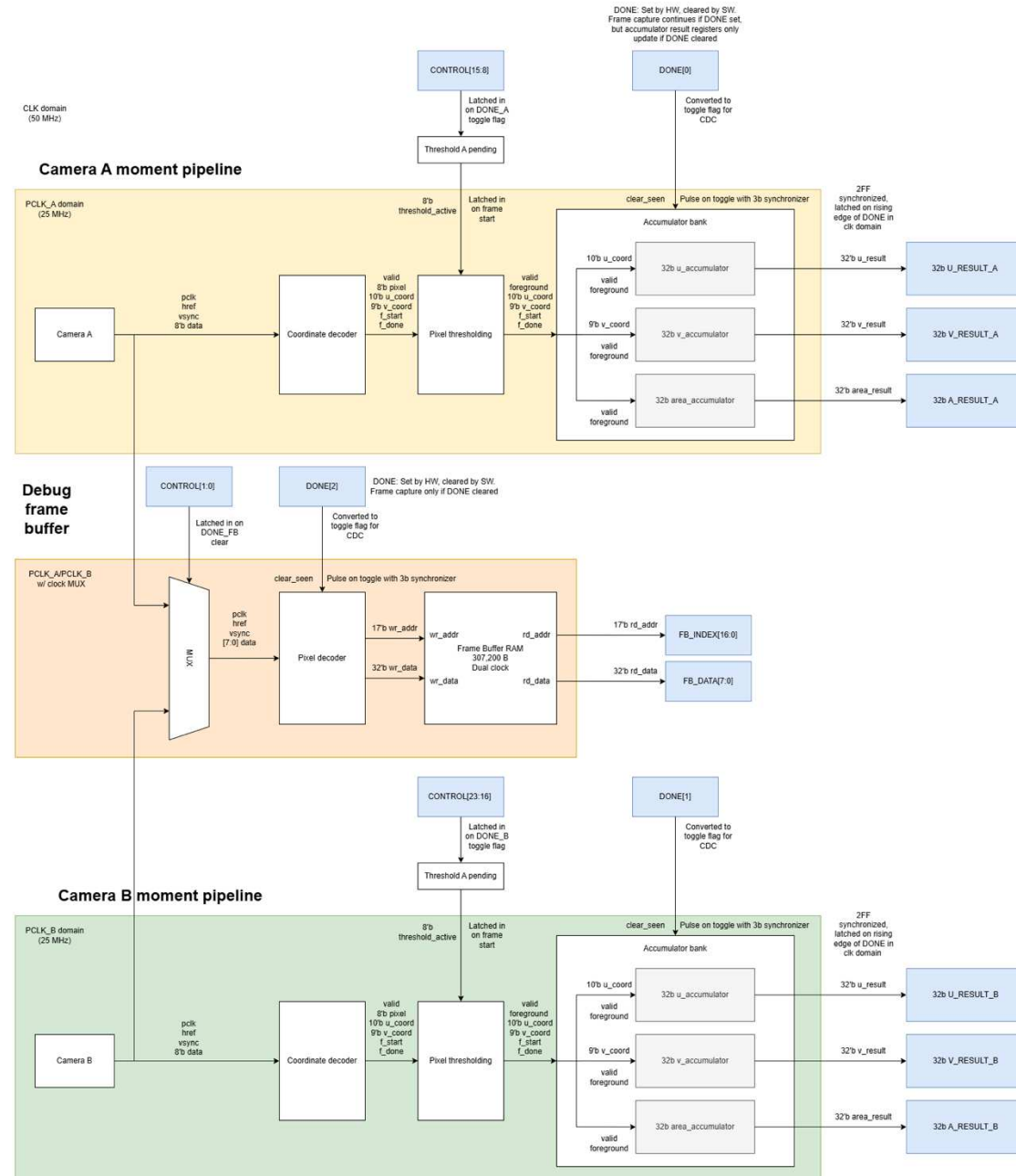
System Overview

- Image processing on FPGA: OV7670 data capture, pixel thresholding and IR beacon centroid detection
- Uncalibrated stereo in software: pre-calibrated camera intrinsics; everything else found dynamically.
- Functionality: Realtime 30 FPS IR beacon tracking with mm-scale precision



Hardware

- Two moment accumulation pipelines and a debug frame buffer for photo capture

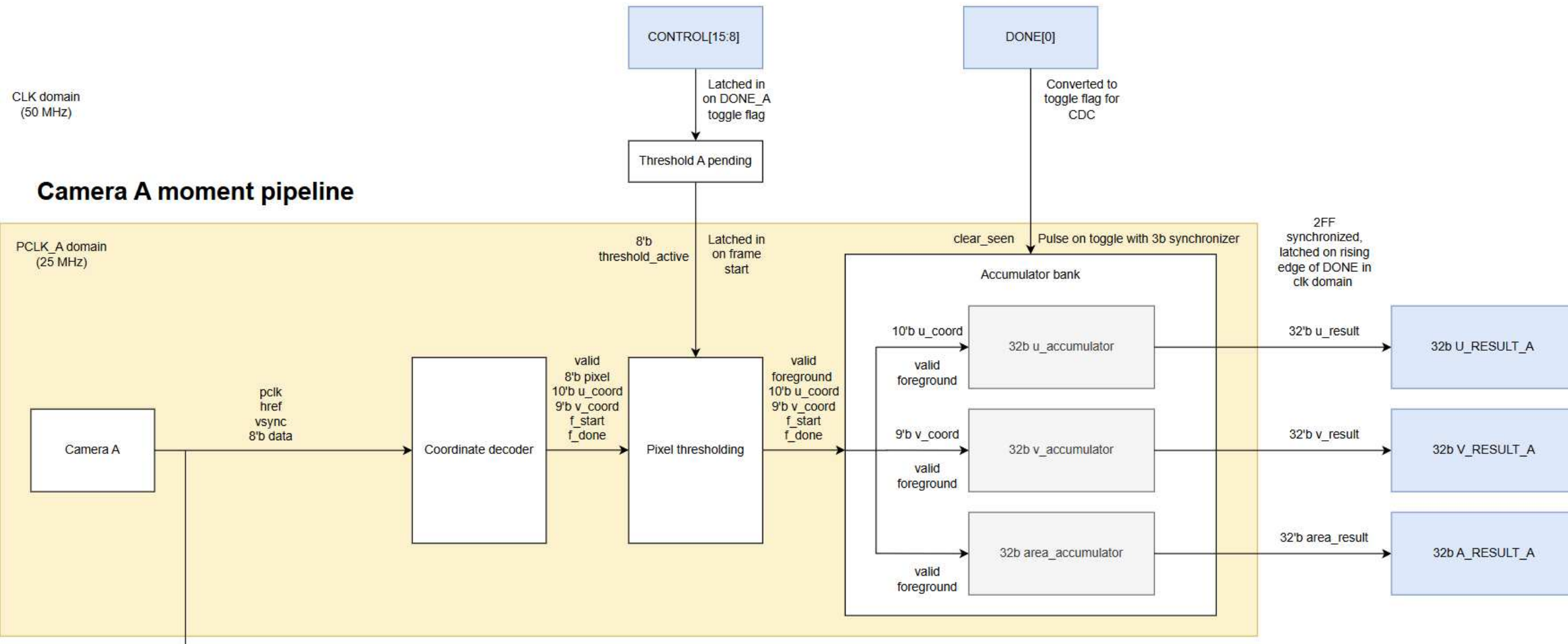


CLK domain
(50 MHz)

Camera A moment pipeline

PCLK_A domain
(25 MHz)

DONE: Set by HW, cleared by SW.
Frame capture continues if DONE set,
but accumulator result registers only
update if DONE cleared



Debug frame buffer

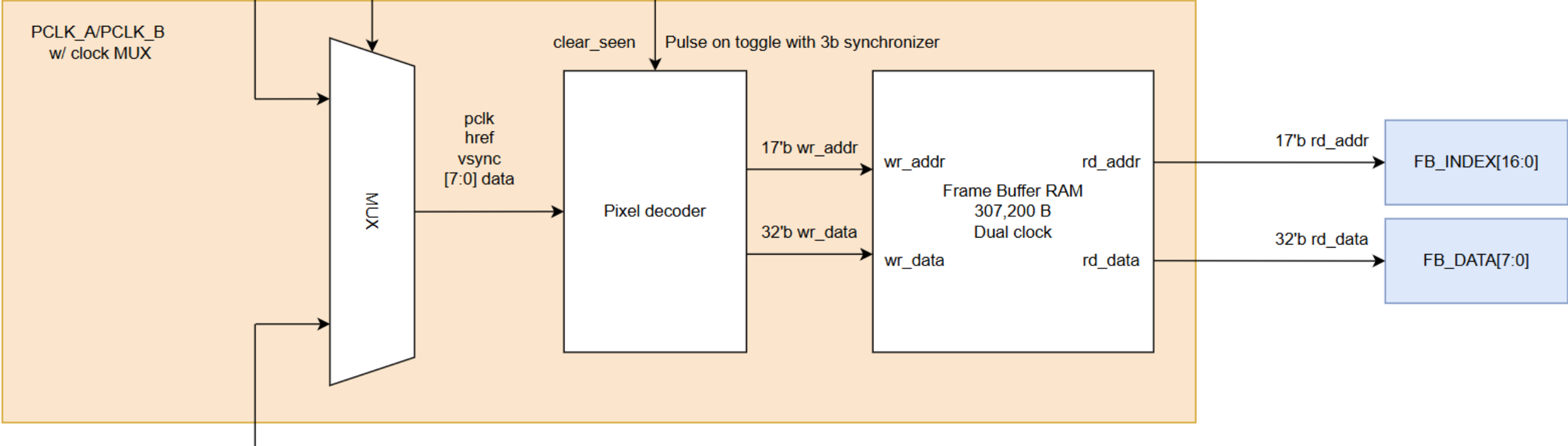
CONTROL[1:0]

Latched in on DONE_FB clear

DONE[2]

Converted to toggle flag for CDC

DONE: Set by HW, cleared by SW.
Frame capture only if DONE cleared



Pinout

Camera A:

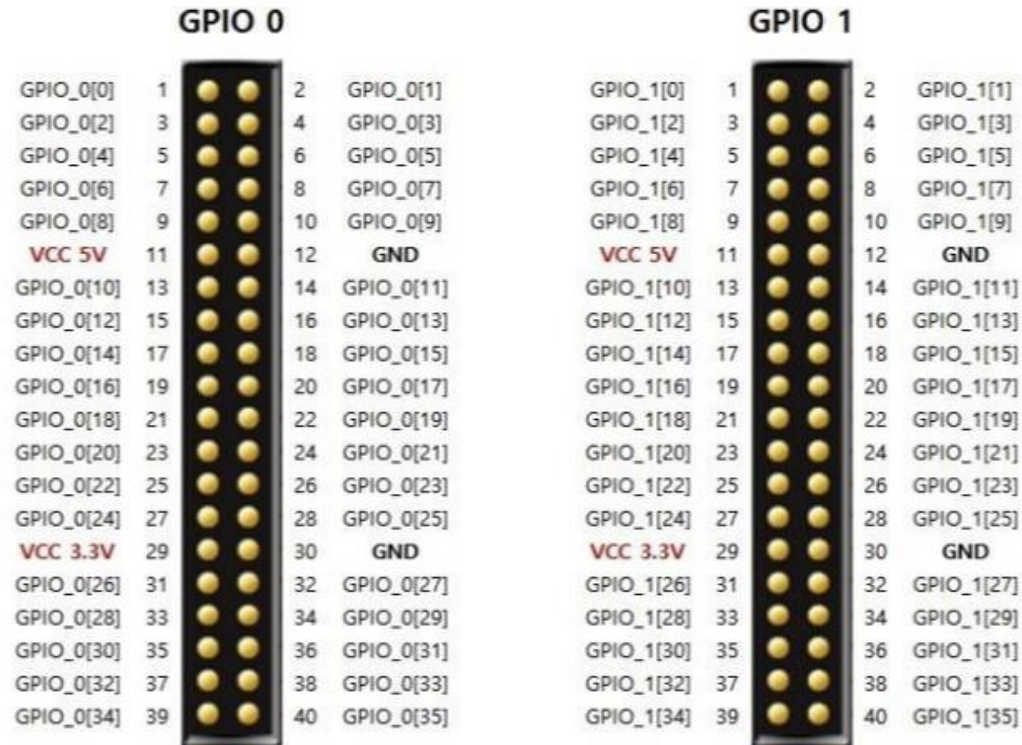
- GPIO_0[7:0] : DATA
- GPIO_0[8] : HREF
- GPIO_0[9]: VSYNC
- GPIO_0[10]: PCLK
- GPIO_0[26]: XCLK
- GPIO_0[35:27]: Software PIO
- GPIO_0[22:25]: Software I2C
- 22 = SCL
- 23 = SDA

Camera B:

- Mirrored on GPIO_1

LEDR:

- [9]: Unused
- [8]: Always on unless reset
- [7:6]: Frame capture select mode (00 = OFF, 01 = A, 10 = B)
- [5:3]: STATUS (whether camera in capture state)
- [2:0]: DONE (frame_done, b_done, a_done)



PIOs:

0x100

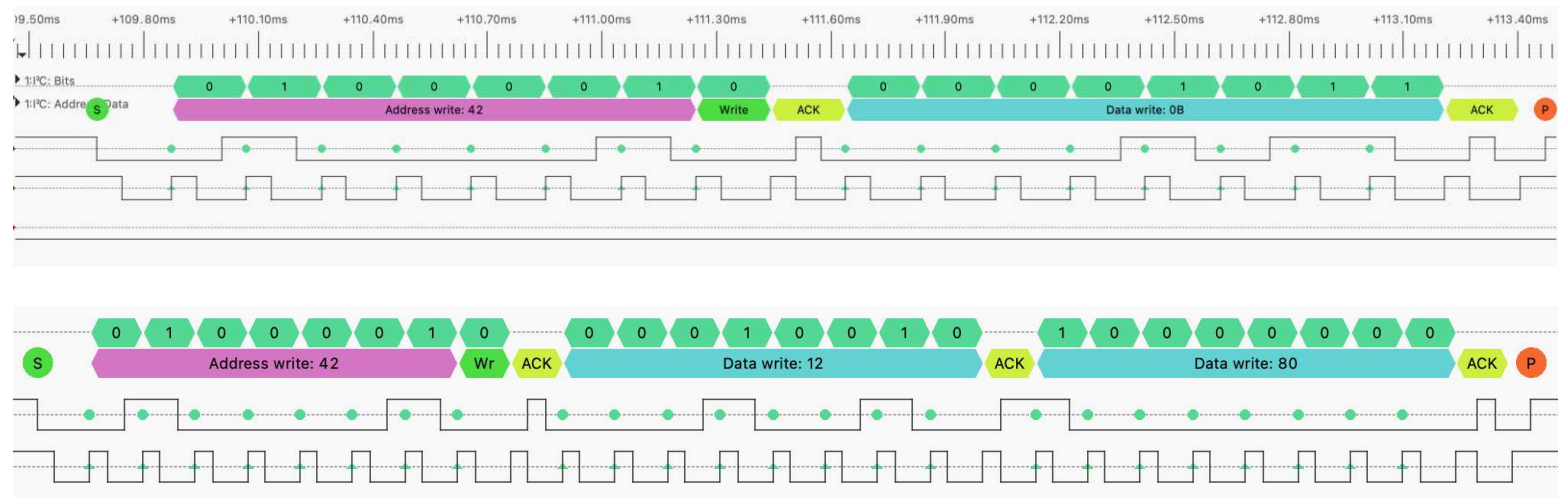
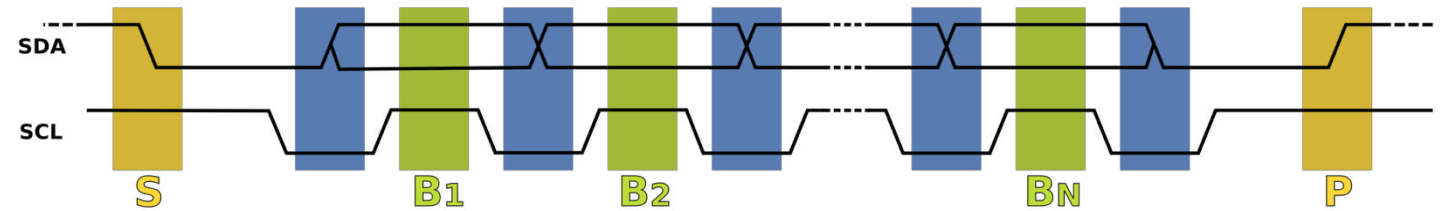
0x120

0x140

0x160

Camera Control

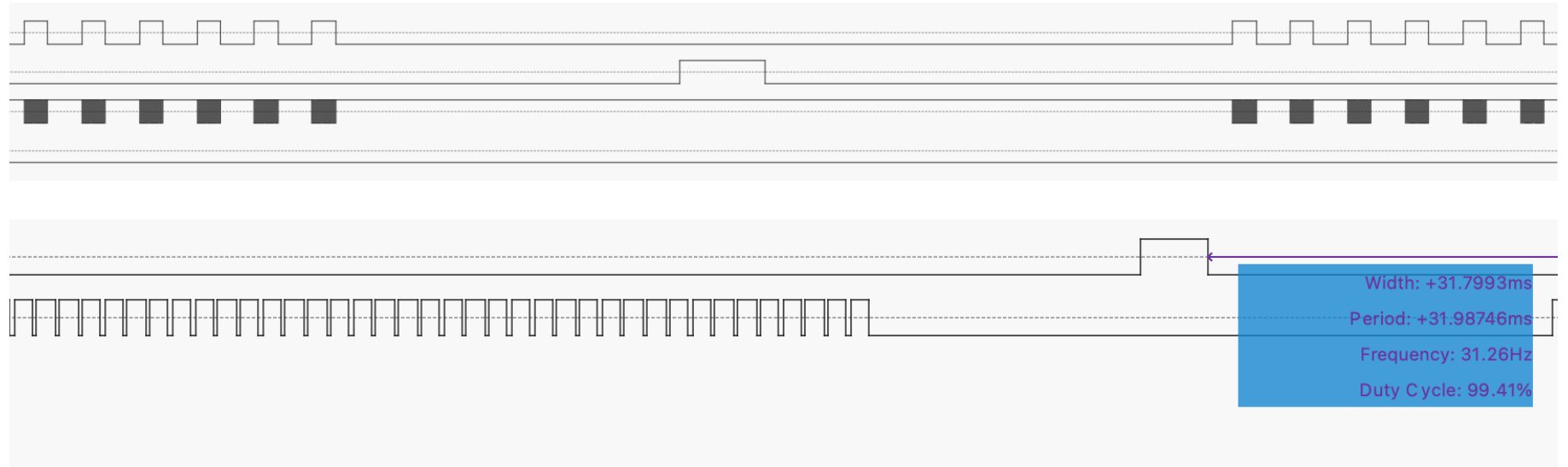
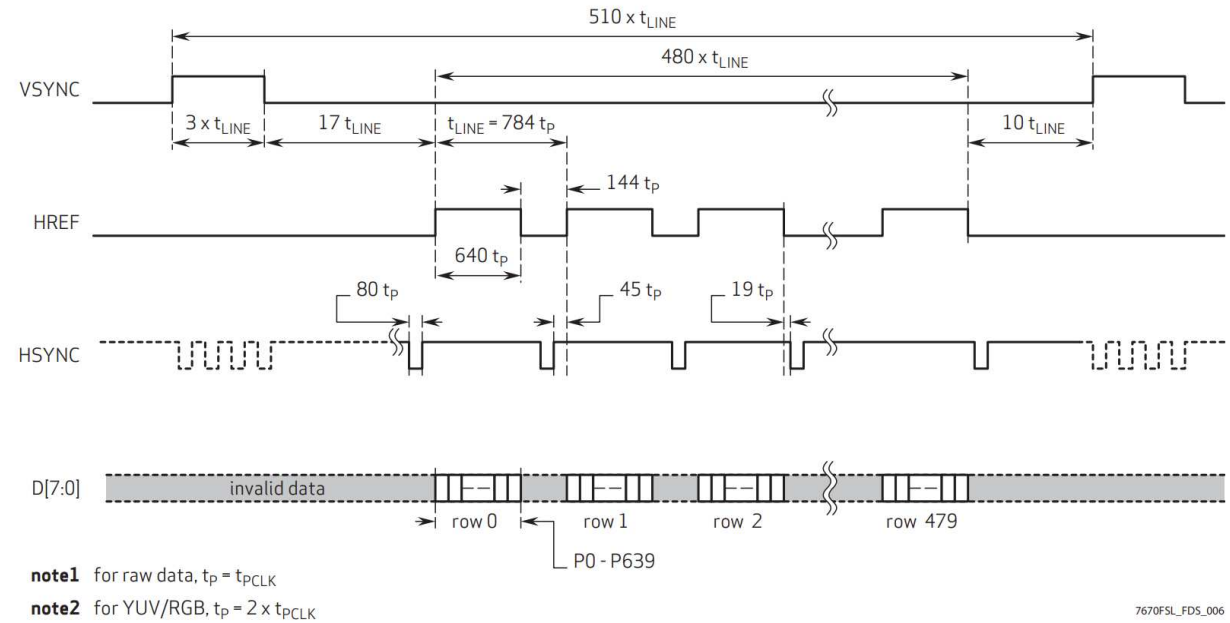
- Software bit-banged I2C using HPS-controlled PIO
- Device address 0x21
- R/W to control registers



VGA Timing

- YUYV format with full VGA
- 31.26 FPS achieved with PCLK = 25 MHz

Figure 6 VGA Frame Timing



Hardware/Software Interface (1/2)

Use	Connections	Name	Description	Export	Clock	Base	End
<input checked="" type="checkbox"/>		<input type="checkbox"/> gpio1_i2c	PIO (Parallel I/O) Intel FPGA IP				
		clk	Clock Input	<i>Double-click to</i>	clk_0		
		reset	Reset Input	<i>Double-click to</i>	[clk]		
		s1	Avalon Memory Mapped Slave	<i>Double-click to</i>	[clk]	0x0000_0160	0x0000_016f
	external_conne...	Conduit	gpio1_i2c				
<input checked="" type="checkbox"/>		<input type="checkbox"/> gpio1_upper	PIO (Parallel I/O) Intel FPGA IP				
		clk	Clock Input	<i>Double-click to</i>	clk_0		
		reset	Reset Input	<i>Double-click to</i>	[clk]		
		s1	Avalon Memory Mapped Slave	<i>Double-click to</i>	[clk]	0x0000_0140	0x0000_014f
	external_conne...	Conduit	gpio1_upper				
<input checked="" type="checkbox"/>		<input type="checkbox"/> gpio0_i2c	PIO (Parallel I/O) Intel FPGA IP				
		clk	Clock Input	<i>Double-click to</i>	clk_0		
		reset	Reset Input	<i>Double-click to</i>	[clk]		
		s1	Avalon Memory Mapped Slave	<i>Double-click to</i>	[clk]	0x0000_0120	0x0000_012f
	external_conne...	Conduit	gpio0_i2c				
<input checked="" type="checkbox"/>		<input type="checkbox"/> gpio0_upper	PIO (Parallel I/O) Intel FPGA IP				
		clk	Clock Input	<i>Double-click to</i>	clk_0		
		reset	Reset Input	<i>Double-click to</i>	[clk]		
		s1	Avalon Memory Mapped Slave	<i>Double-click to</i>	[clk]	0x0000_0100	0x0000_010f
	external_conne...	Conduit	gpio0_upper				
<input checked="" type="checkbox"/>		<input type="checkbox"/> clk_0	Clock Source	clk	exported		
		clk_in	Clock Input	<i>Double-click to</i>	reset	clk_0	
		clk_in_reset	Reset Input	<i>Double-click to</i>			
		clk	Clock Output	<i>Double-click to</i>			
		clk_reset	Reset Output	<i>Double-click to</i>			
<input checked="" type="checkbox"/>		<input type="checkbox"/> hps_0	Arria V/Cyclone V Hard Proce...	<i>Double-click to</i>	hps_0_h2...		
		h2f_user1_clock	Clock Output	<i>Double-click to</i>	hps_0_h2...		
		memory	Conduit	<i>Double-click to</i>	hps_0_h2...		
		hps_io	Conduit	<i>Double-click to</i>	hps_0_h2...		
		h2f_reset	Reset Output	<i>Double-click to</i>	hps_0_h2...		
		h2f_axi_clock	Clock Input	<i>Double-click to</i>	hps_0_h2...		
		h2f_axi_master	AXI Master	<i>Double-click to</i>	hps_0_h2...		
		f2h_axi_clock	Clock Input	<i>Double-click to</i>	hps_0_h2...		
		f2h_axi_slave	AXI Slave	<i>Double-click to</i>	hps_0_h2...		
		h2f_lw_axi_clock	Clock Input	<i>Double-click to</i>	hps_0_h2...		
	h2f_lw_axi_master	AXI Master	<i>Double-click to</i>	hps_0_h2...			
<input checked="" type="checkbox"/>		<input type="checkbox"/> imgproc_0	Image Processor	<i>Double-click to</i>	clk_0		
		clock	Clock Input	<i>Double-click to</i>	[clock]		
		reset	Reset Input	<i>Double-click to</i>	[clock]		
		avalon_slave_0	Avalon Memory Mapped Slave	<i>Double-click to</i>	[clock]	0x0000_0000	0x0000_003f
		camera_a	Conduit	<i>Double-click to</i>	[clock]		
		camera_b	Conduit	<i>Double-click to</i>	[clock]		
	status	Conduit	<i>Double-click to</i>	[clock]			

Hardware/Software Interface (2/2)

Register Map

Address	Register	Access	Meaning
0	AREA_A	R	Camera A foreground area
1	U_A	R	Camera A foreground u/x moment sum
2	V_A	R	Camera A foreground v/y moment sum
3	AREA_B	R	Camera B foreground area
4	U_B	R	Camera B foreground u/x moment sum
5	V_B	R	Camera B foreground v/y moment sum
6	DONE	R/W	bit 0: A, bit 1: B, bit 2: frame buffer
7	CONTROL	R/W	[1:0] frame source: 0 none, 1 A, 2 B; [15:8] threshold A, [23:16] threshold B
8	FB_INDEX	R/W	Frame buffer word index, 0 .. 76799
9	FB_DATA	R	Four pixels packed as {p3, p2, p1, p0}

Test captures:

- Frame buffer captures from select OV7670 camera via debug interface



Algorithms

Camera calibration

$$u = f_x \frac{x_c}{z_c} + o_x \quad v = f_y \frac{y_c}{z_c} + o_y$$

Homogenous coordinates of (u, v) :

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \equiv \begin{bmatrix} \tilde{u} \\ \tilde{v} \\ \tilde{w} \end{bmatrix} \equiv \begin{bmatrix} z_c u \\ z_c v \\ z_c \end{bmatrix} = \begin{bmatrix} f_x x_c + z_c o_x \\ f_y y_c + z_c o_y \\ z_c \end{bmatrix} = \begin{bmatrix} f_x & 0 & o_x & 0 \\ 0 & f_y & o_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_c \\ y_c \\ z_c \\ 1 \end{bmatrix}$$

where: $(u, v) = (\tilde{u}/\tilde{w}, \tilde{v}/\tilde{w})$

Image
Coordinates

$$\mathbf{u} = \begin{bmatrix} u \\ v \end{bmatrix}$$



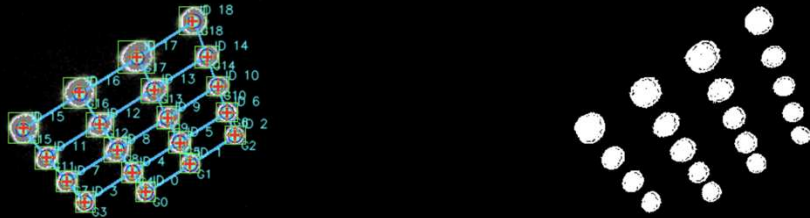
Perspective
Projection

Camera
Coordinates

$$\mathbf{x}_c = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix}$$

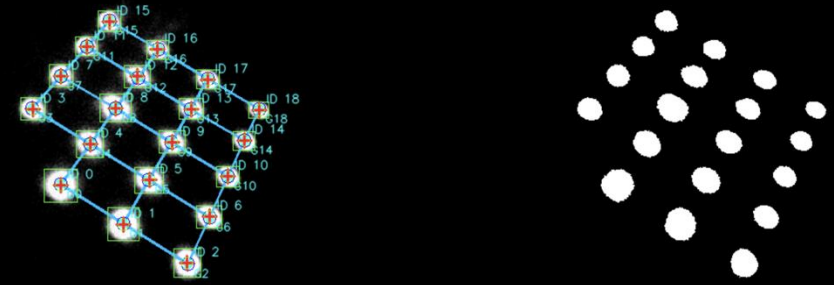
Camera calibration

14/31 CAM_A/frame_camA_1778493212_1787.pgm threshold=121 blobs=19 target 19 exact



Click beacon, type ID, Enter saves. x clears. [/]: fit strength. m model. s saves grid. n/p image. q quits.
Selected: none Assigned: 19/19 Grid: homography, strength=1.00, missing=top-left
Saving to: beacon_labels.json

30/31 CAM_B/frame_camB_1778493524_1798.pgm threshold=140 blobs=19 target 19 exact



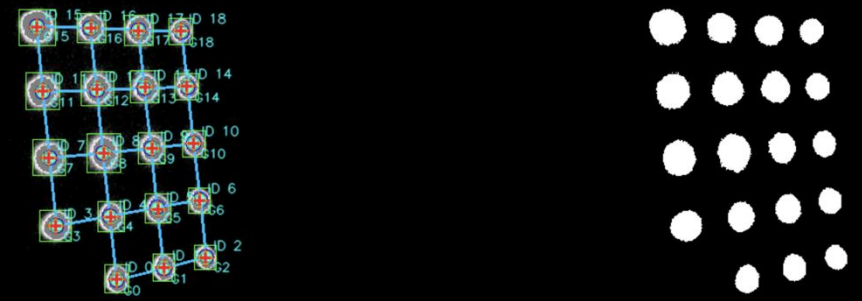
Click beacon, type ID, Enter saves. x clears. [/]: fit strength. m model. s saves grid. n/p image. q quits.
Selected: none Assigned: 19/19 Grid: homography, strength=1.00, missing=top-left
Saving to: beacon_labels.json

3/31 CAM_A/frame_camA_1778487379_1705.pgm threshold=85 blobs=19 target 19 exact



Click beacon, type ID, Enter saves. x clears. [/]: fit strength. m model. s saves grid. n/p image. q quits.
Selected: none Assigned: 19/19 Grid: homography, strength=1.00, missing=top-left
Saving to: beacon_labels.json

4/31 CAM_A/frame_camA_1778487581_1711.pgm threshold=96 blobs=19 target 19 exact

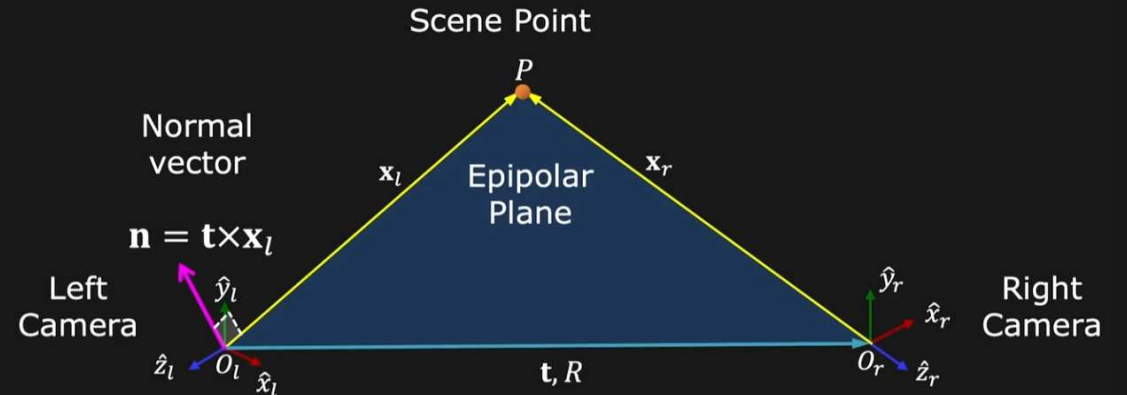
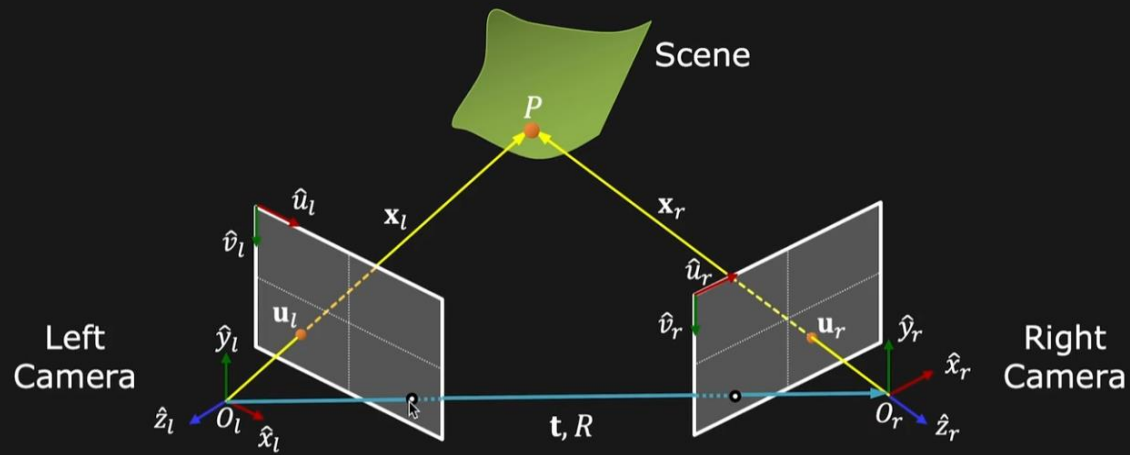


Click beacon, type ID, Enter saves. x clears. [/]: fit strength. m model. s saves grid. n/p image. q quits.
Selected: none Assigned: 19/19 Grid: homography, strength=1.00, missing=top-left
Saving to: beacon_labels.json

Camera calibration

$$K_A = \begin{bmatrix} 879.693451 & 0 & 365.717241 \\ 0 & 879.693451 & 241.590062 \\ 0 & 0 & 1 \end{bmatrix}, \quad K_B = \begin{bmatrix} 900.939218 & 0 & 307.065820 \\ 0 & 900.939218 & 218.219419 \\ 0 & 0 & 1 \end{bmatrix}.$$

Epipolar geometry



Vector normal to the epipolar plane: $\mathbf{n} = \mathbf{t} \times \mathbf{x}_l$

Dot product of \mathbf{n} and \mathbf{x}_l (perpendicular vectors) is zero:

$$\mathbf{x}_l \cdot (\mathbf{t} \times \mathbf{x}_l) = 0$$

$$[x_l \quad y_l \quad z_l] \left(\begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} + \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix} \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \right) = 0$$

Essential and Fundamental Matrices

$$[x_l \quad y_l \quad z_l] \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} = 0$$

$$[u_l \quad v_l \quad 1] \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix} \begin{bmatrix} u_r \\ v_r \\ 1 \end{bmatrix} = 0$$

Fundamental Matrix F

Fundamental Matrix Estimation

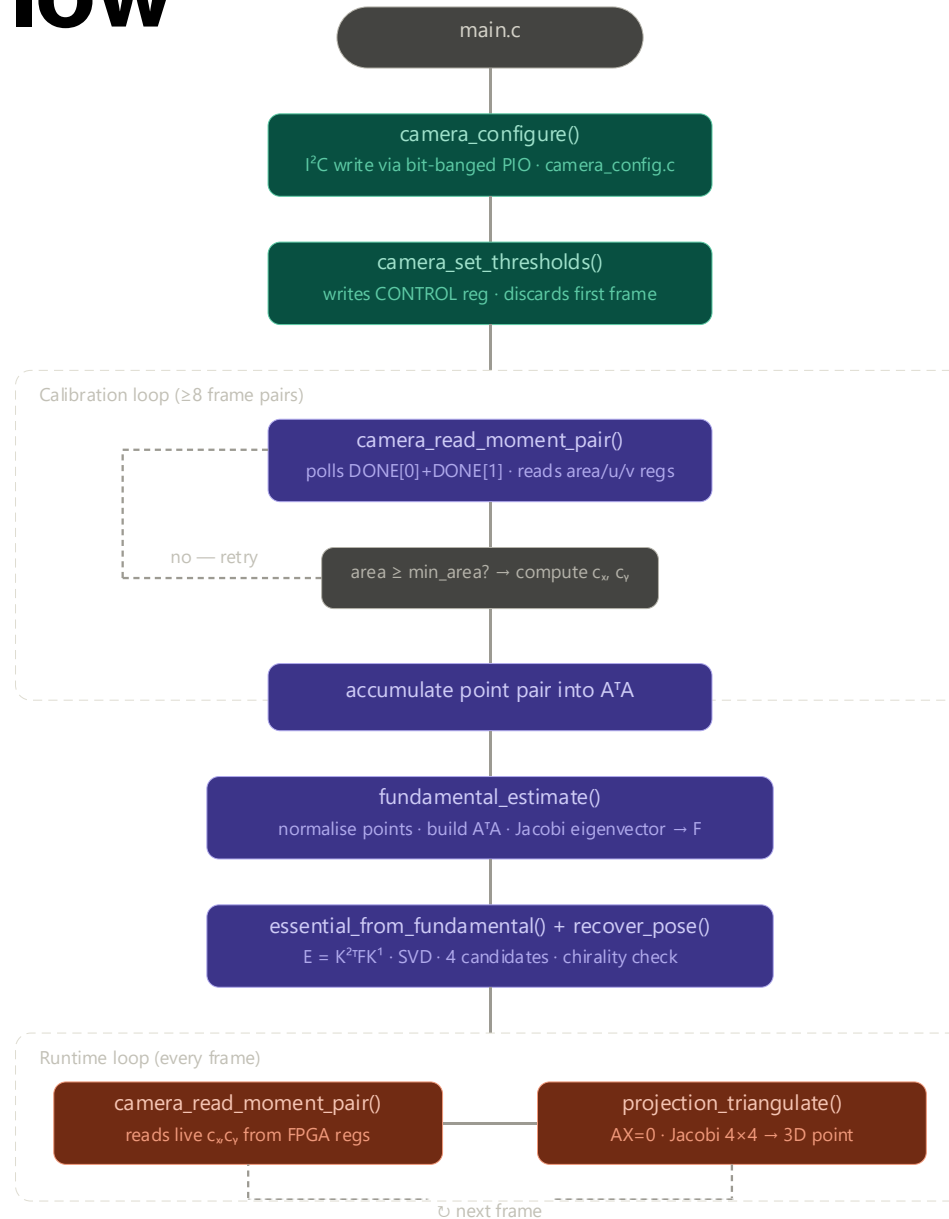
$$\begin{array}{c}
 \left[\begin{array}{cccccccc|c}
 u_l^{(1)} & u_r^{(1)} & u_l^{(1)} v_r^{(1)} & u_l^{(1)} & v_l^{(1)} u_r^{(1)} & v_l^{(1)} v_r^{(1)} & v_l^{(1)} & u_r^{(1)} & v_r^{(1)} & 1 \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 u_l^{(i)} & u_r^{(i)} & u_l^{(i)} v_r^{(i)} & u_l^{(i)} & v_l^{(i)} u_r^{(i)} & v_l^{(i)} v_r^{(i)} & v_l^{(i)} & u_l^{(i)} & u_r^{(i)} & 1 \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 u_l^{(m)} & u_r^{(m)} & u_l^{(m)} v_r^{(m)} & u_l^{(m)} & v_l^{(m)} u_r^{(m)} & v_l^{(m)} v_r^{(m)} & v_l^{(m)} & u_l^{(m)} & u_r^{(m)} & 1
 \end{array} \right]
 \begin{array}{c}
 \left[\begin{array}{c}
 f_{11} \\
 f_{21} \\
 f_{31} \\
 f_{21} \\
 f_{22} \\
 f_{23} \\
 f_{31} \\
 f_{32} \\
 f_{33}
 \end{array} \right]
 = \left[\begin{array}{c}
 0 \\
 \vdots \\
 0 \\
 \vdots \\
 0
 \end{array} \right]
 \end{array}
 \end{array}$$

A
 (Known)

\mathbf{f}
 (Unknown)

$$\min_{\mathbf{f}} \|\mathbf{A}\mathbf{f}\|^2 \quad \text{such that } \|\mathbf{f}\|^2 = 1$$

Code Control Flow



Jacobi Least-Squares Solver

Goal: Estimate the fundamental matrix F from stereo correspondences.

Epipolar constraint:

$$x_2^T F x_1 = 0$$

Each matched point pair contributes one row:

$$[x_2x_1, x_2y_1, x_2, y_2x_1, y_2y_1, y_2, x_1, y_1, 1]$$

All rows form the homogeneous system:

$$Af \approx 0$$

Convert into eigenvalue problem:

$$A^T A f = \lambda f$$

The desired solution is the eigenvector corresponding to the smallest eigenvalue.

Jacobi Least-Squares Solver

1. Construct symmetric matrix:

$$A^T A$$

2. Find largest off-diagonal element:

$$a_{pq}$$

3. Compute Jacobi rotation:

$$\tau = \frac{a_{qq} - a_{pp}}{2a_{pq}}$$

$$t = \frac{\text{sign}(\tau)}{|\tau| + \sqrt{1 + \tau^2}}$$

4. Rotate rows and columns to eliminate a_{pq}
5. Repeat until matrix becomes diagonal
6. Extract eigenvector with smallest eigenvalue
7. Reshape into the 3×3 fundamental matrix F

Jacobi SVD

The estimated fundamental matrix is converted into an essential matrix:

$$E = K_2^T F K_1$$

A valid essential matrix must satisfy:

$$E = U \Sigma V^T$$

with constrained singular values:

$$\Sigma = \text{diag}(s, s, 0)$$

The algorithm computes:

$$E^T E$$

and applies Jacobi diagonalization again.

Eigenvalues correspond to:

$$\sigma_i^2$$

while eigenvectors form:

$$V$$

Singular values are recovered through:

$$\sigma_i = \sqrt{\lambda_i}$$

and left singular vectors are computed using:

$$U_i = \frac{E V_i}{\sigma_i}$$

Pose Recovery

1. Compute candidate rotations:

$$R_1 = UWV^T$$

$$R_2 = UW^T V^T$$

2. Extract translation vector:

$$t = U[\cdot \ 0]$$

3. Generate four possible camera poses:

$$(R_1, +t), (R_1, -t), (R_2, +t), (R_2, -t)$$

4. Perform chirality check using triangulated 3D points

5. Select physically valid pose where:

$$z_1 > 0$$

$$z_2 > 0$$

for both cameras

Credits:

- Prof. Stephen Edwards
- TA : Xiaoyang Liu
- Graphics and equations
from <https://www.youtube.com/playlist?list=PL2zRqk16wsdoCCLpou-dGo7QQNks1Ppzo>