Simple Parallel Calibration and 3D Reconstruction in Real-Timefor RGB-D Cameras

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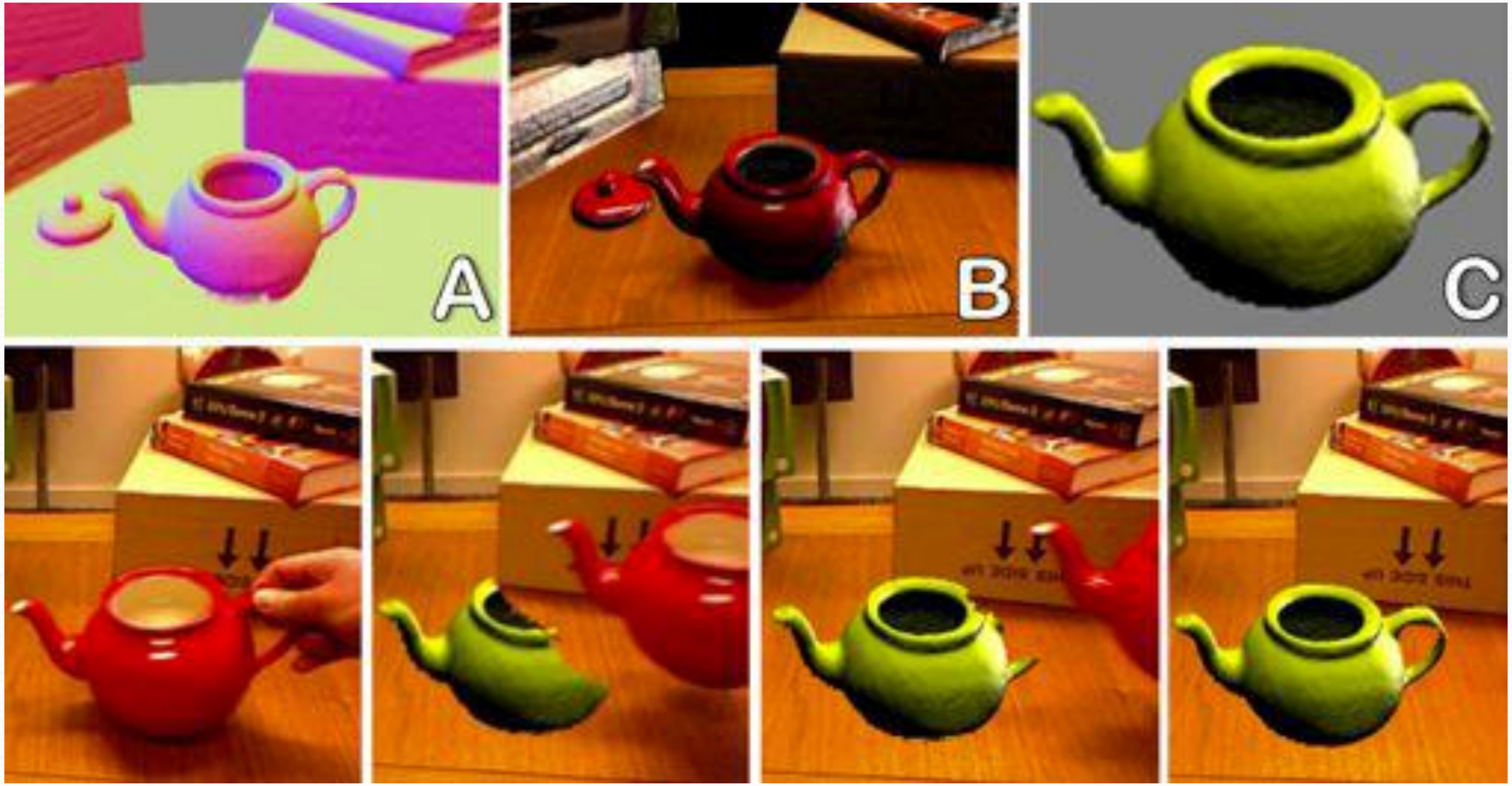
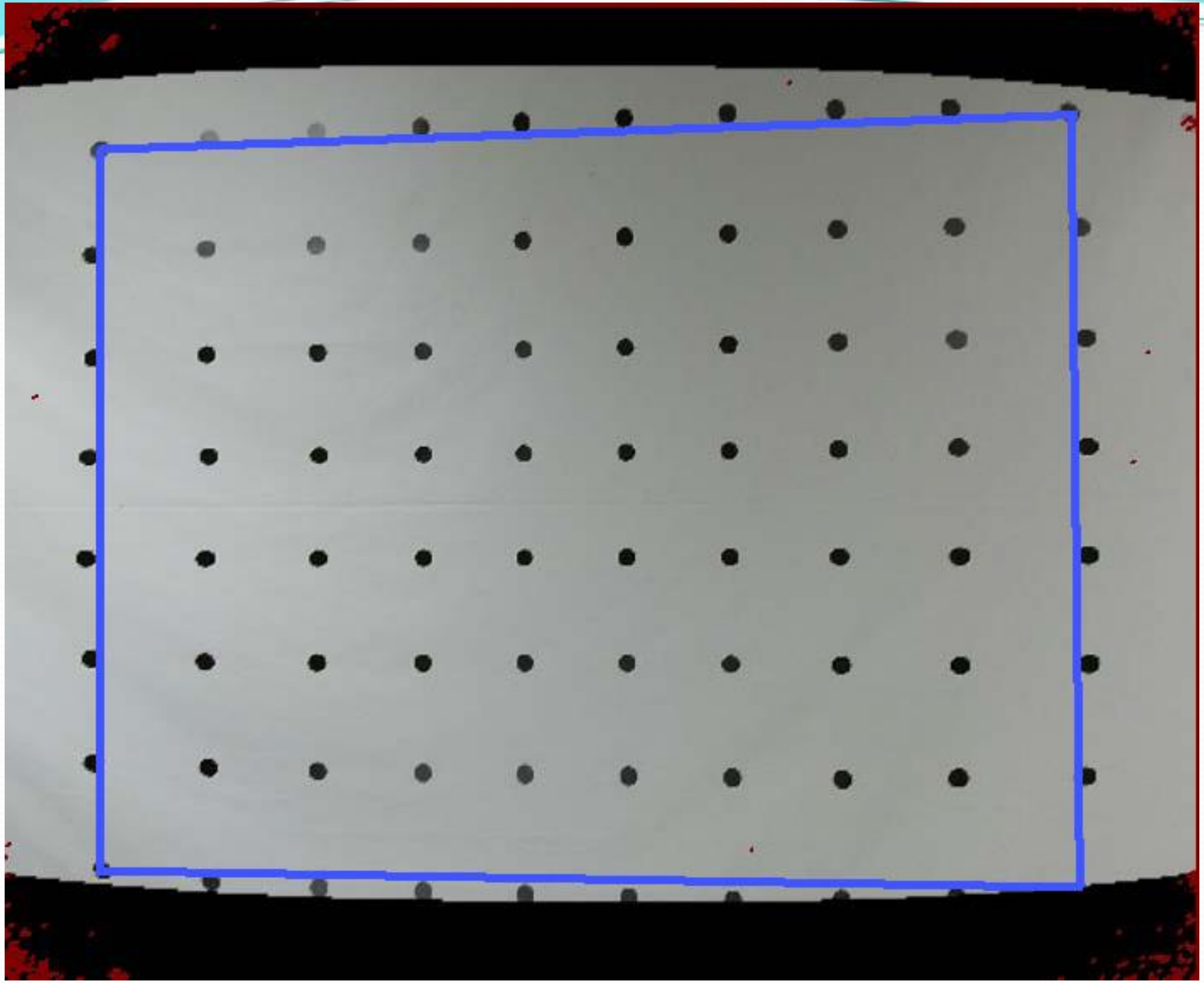
Outline

- Introduction
- Academic Background:
  - Pinhole Camera Model (Camera calibration / 3D reconstruction)
  - Kai's per-pixel 3D reconstruction on GPU
  - Inspiration
- Natural GPU Calibration and Reconstruction Method:
  - Calibration system
  - Calibration procedures
  - Undistorted 3D Reconstruction
- Conclusion

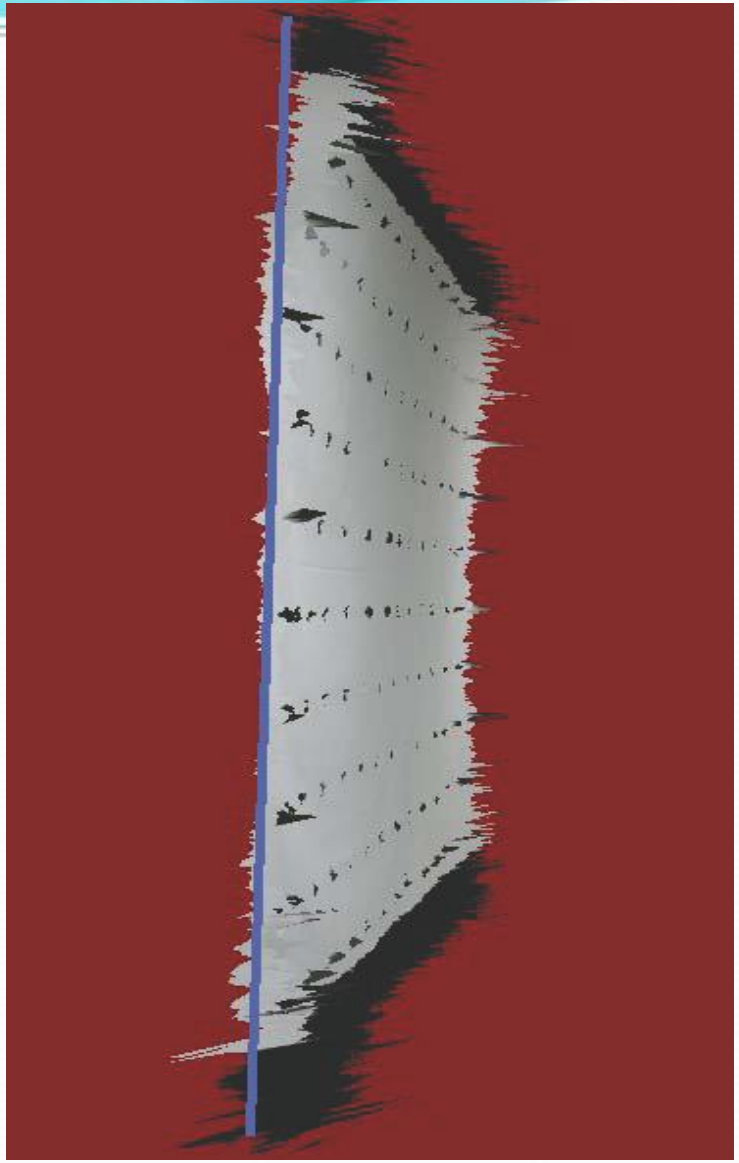
Object Segmentation in KinectFusion



Raw Camera Space 3D Reconstruction



lens Distortion



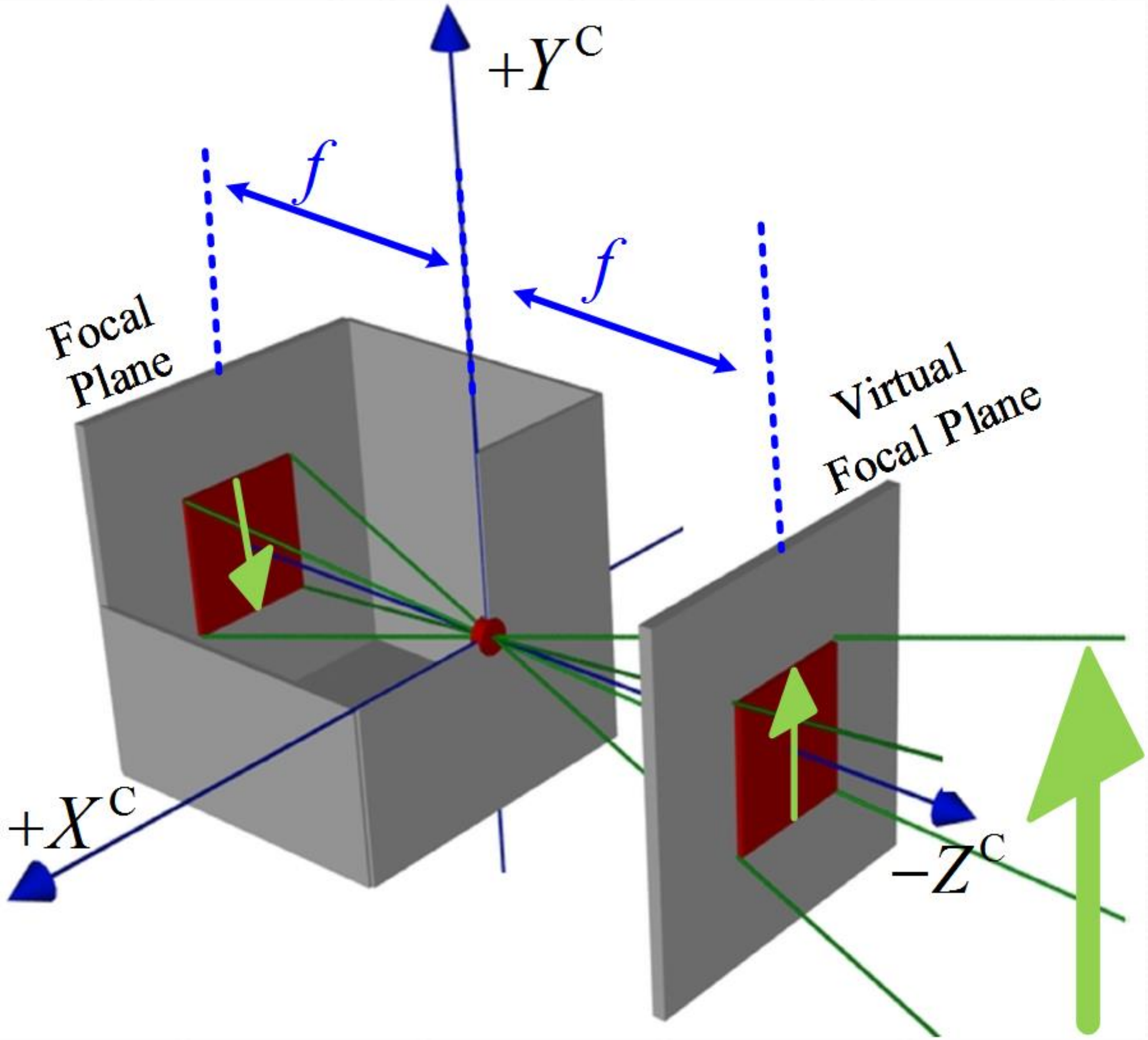
Depth Distortion

Introduction

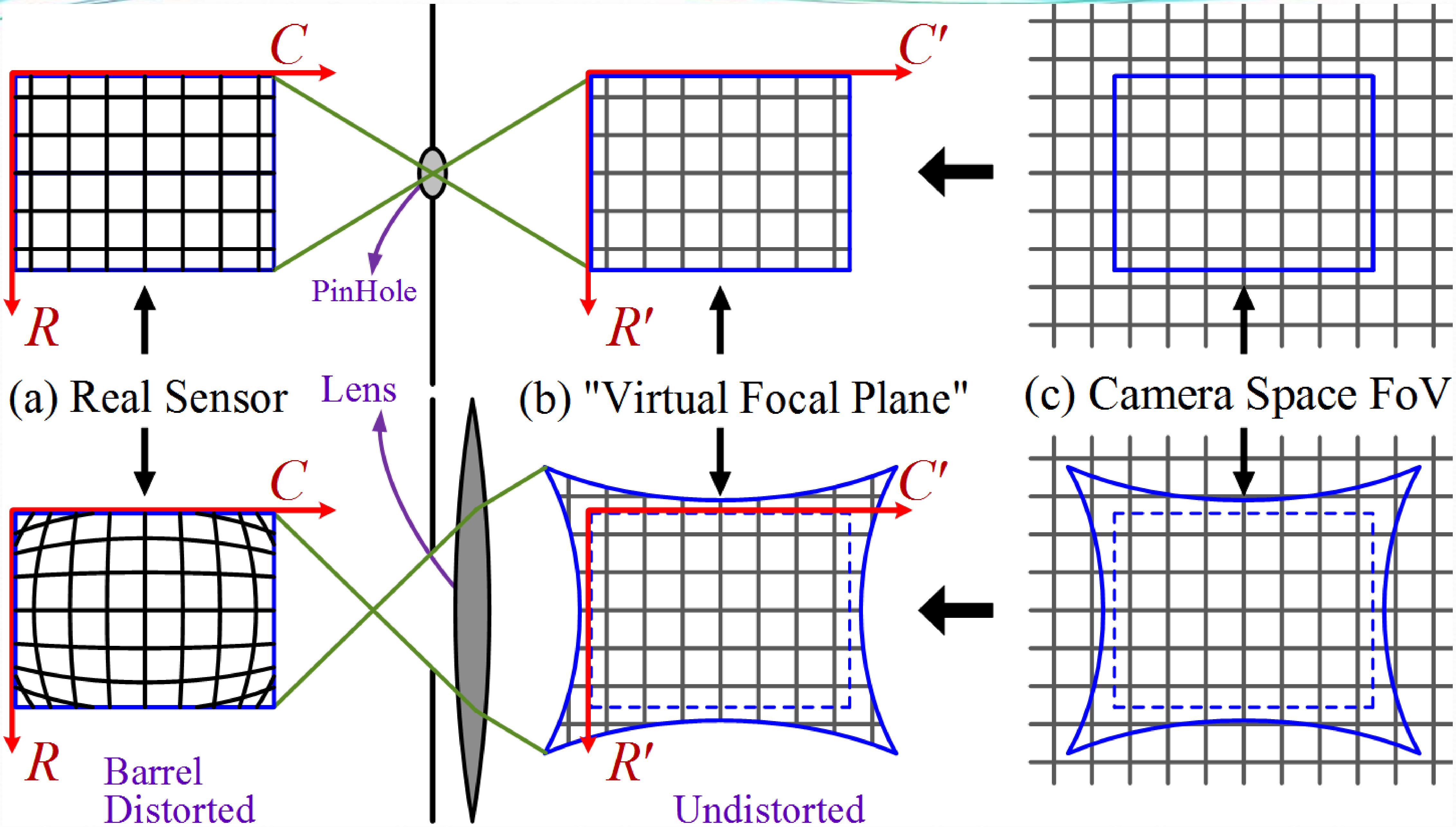
- Goal: given a RGB-D camera, show undistorted 3D reconstruction with color (RGB) on GPU
- Camera: KinectV2
- Streams:

  Depth, NearIR: 424 * 512 ; RGB : 1080 * 1920
- Plan:
  - determine best-fit calibration system
  - choose corresponding parallel (on GPU) calibration method
  - build models in demand
  - calibrate and reconstruct

Pinhole-Camera Model

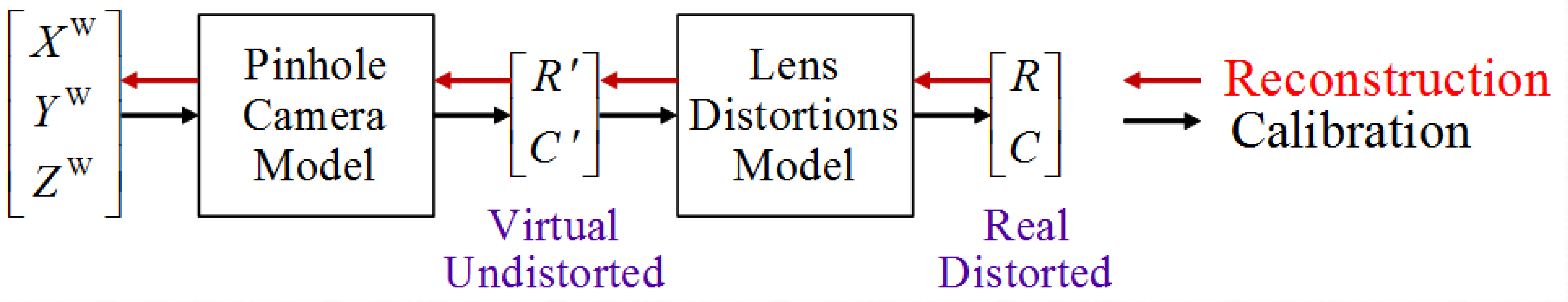


- From Camera Space to Image Space with Lens Distortions



Academic Background

- Pinhole-Camera Model (Reconstruction and Calibration)



Intrinsic Matrix $K = \begin{bmatrix} f_c & s & t_c \\ 0 & f_r & t_r \\ 0 & 0 & 1 \end{bmatrix}$

Extrinsic Matrix $\begin{bmatrix} R_{3*3} & T_{3*1} \end{bmatrix}$

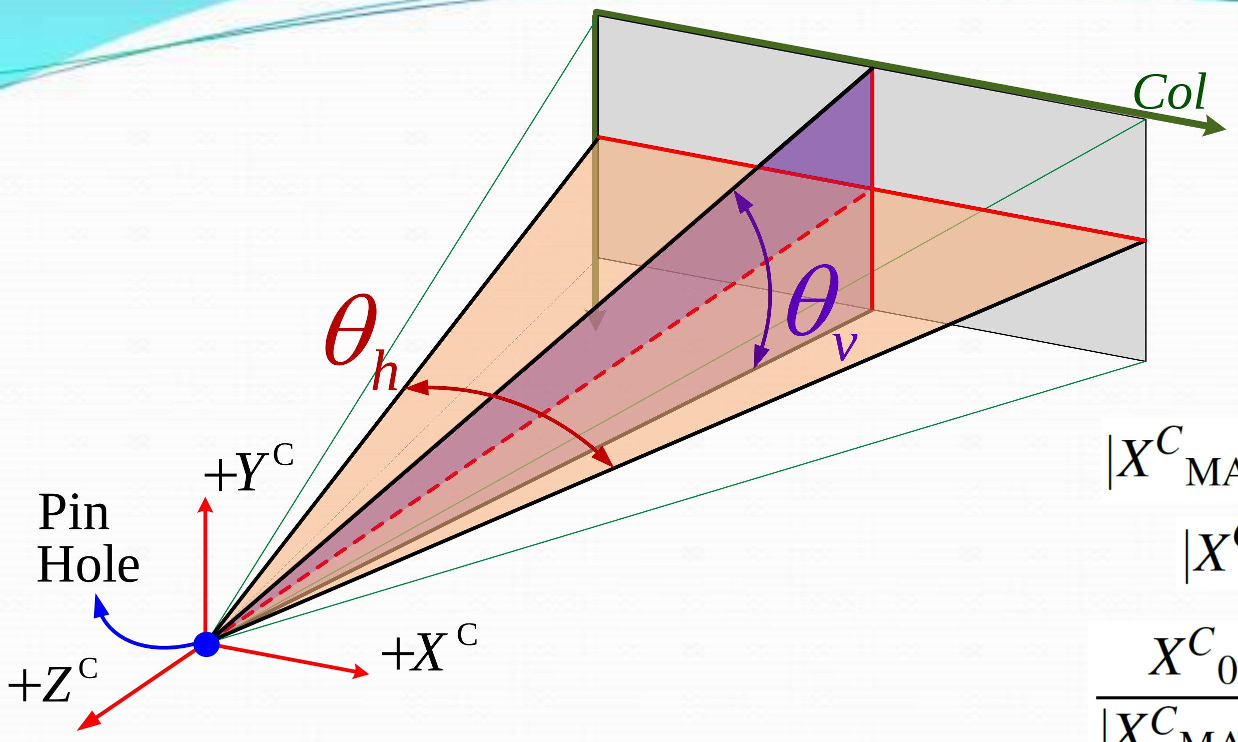
Pinhole Camera Matrix :

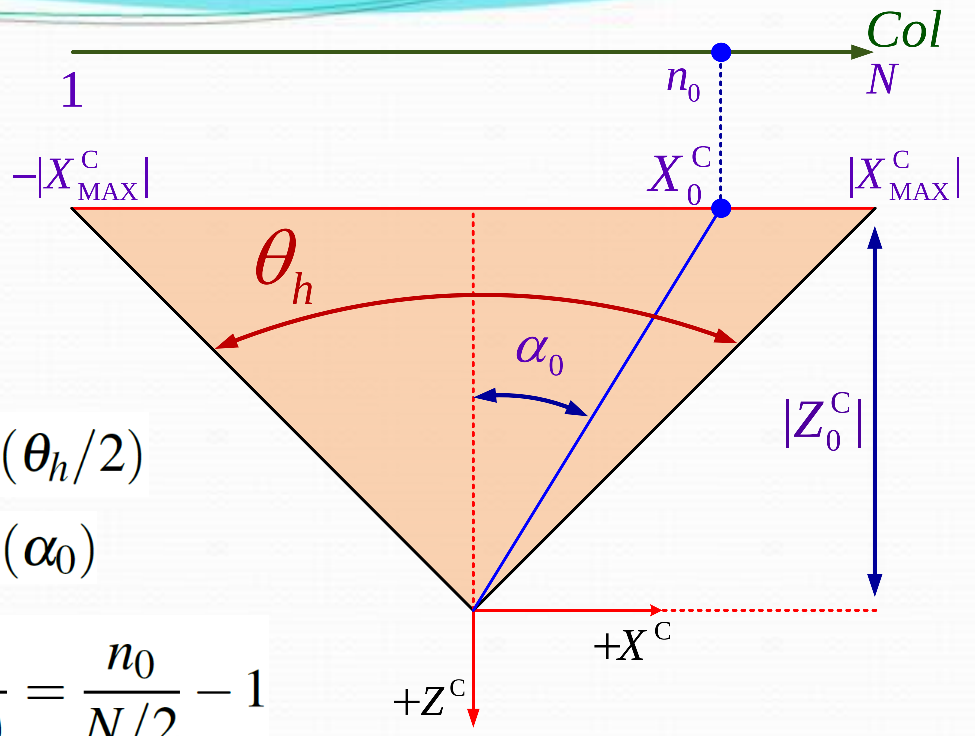
$$M = K\begin{bmatrix} R_{3*3} & T_{3*1} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix}$$

$$C' = C(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + [p_1(r^2 + 2C^2) + 2p_2 CR]$$
$$R' = R(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + [p_2(r^2 + 2R^2) + 2p_1 CR]$$

Distortion Parameters: $k_1/k_2/k_3/p_1/p_2$

Raw Camera Space 3D Reconstruction





$$|X^C{}_{\mathrm{MAX}}| = |Z^C{}_0| \cdot tan(\theta_h/2)$$

$$|X^C{}_0| = |Z^C{}_0| \cdot tan(\alpha_0)$$

$$\frac{X^C{}_0}{|X^C{}_{\mathrm{MAX}}|} = \frac{tan(\alpha_0)}{tan(\theta_h/2)} = \frac{n_0}{N/2} - 1$$

$$X^C[m,n] = tan(\theta_h/2) \cdot (\frac{n}{N/2} - 1) \cdot |Z^C[m,n]|$$

$$Y^C[m,n] = tan(\theta_v/2) \cdot (\frac{m}{M/2} - 1) \cdot |Z^C[m,n]|$$

$$Z^C[m,n] = -\beta D[m,n]$$

65535.0

$$a[m,n] = tan(\theta_h/2) \cdot (\frac{n}{N/2} - 1)$$

$$b[m,n] = tan(\theta_v/2) \cdot (\frac{m}{M/2} - 1)$$

$$X^C[m,n] = a[m,n] \cdot |Z^C[m,n]|$$

$$Y^C[m,n] = b[m,n] \cdot |Z^C[m,n]|$$

- Pinhole-Camera Model (Reconstruction and Calibration)

$$M = K\begin{bmatrix} R_{3*3} & T_{3*1} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix}$$

Distortion Parameters: $k_1/k_2/k_3/p_1/p_2$

- Raw Camera Space 3D Reconstruction on GPU

$$Z^C[m,n] = -\beta D[m,n]$$

65535.0

$$X^C[m,n] = a[m,n] \cdot |Z^C[m,n]|$$

$$Y^C[m,n] = b[m,n] \cdot |Z^C[m,n]|$$

- Kai's [1] : A Natural Parallel Reconstruction

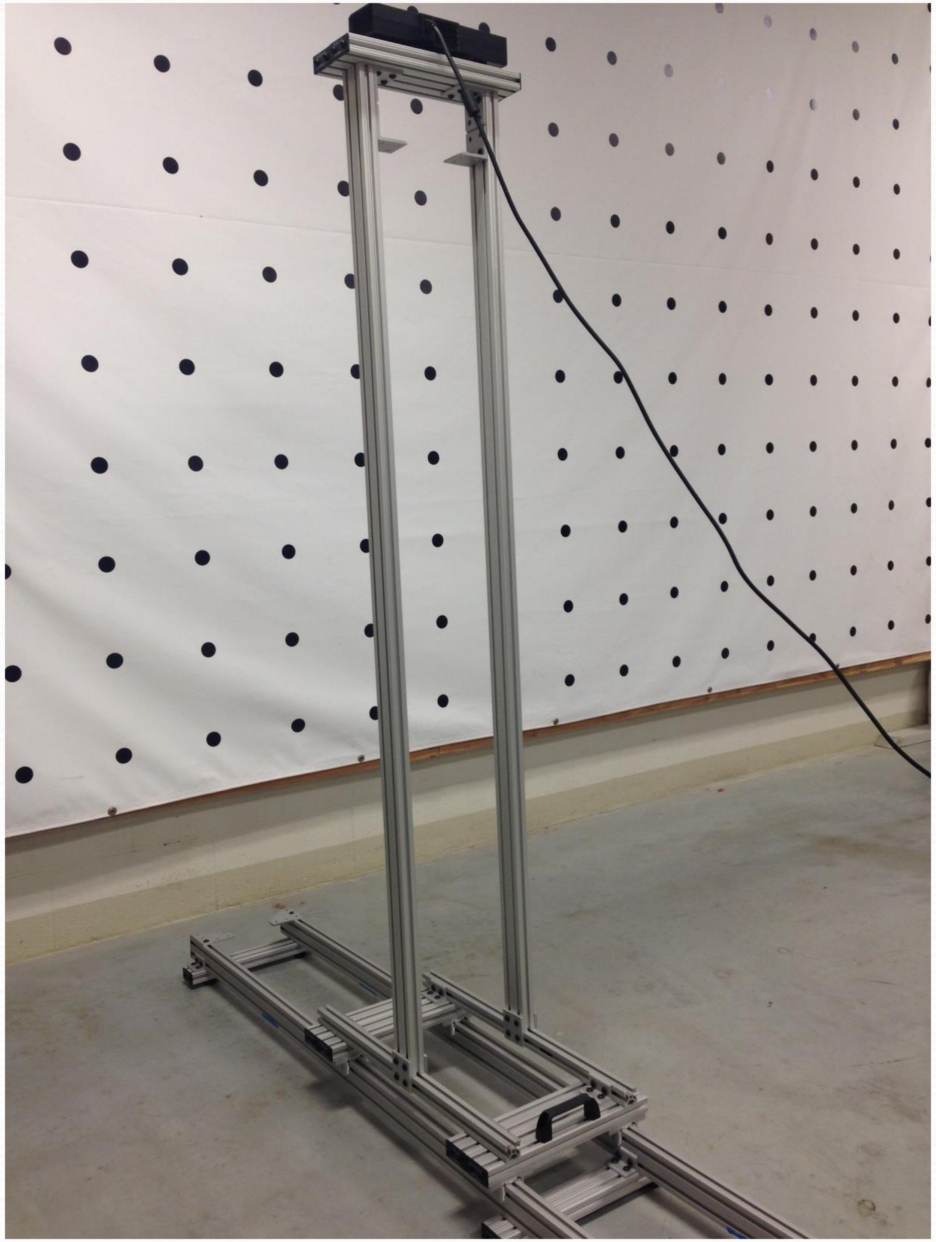
Pinhole Camera Model $M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix}$ $\rightarrow$

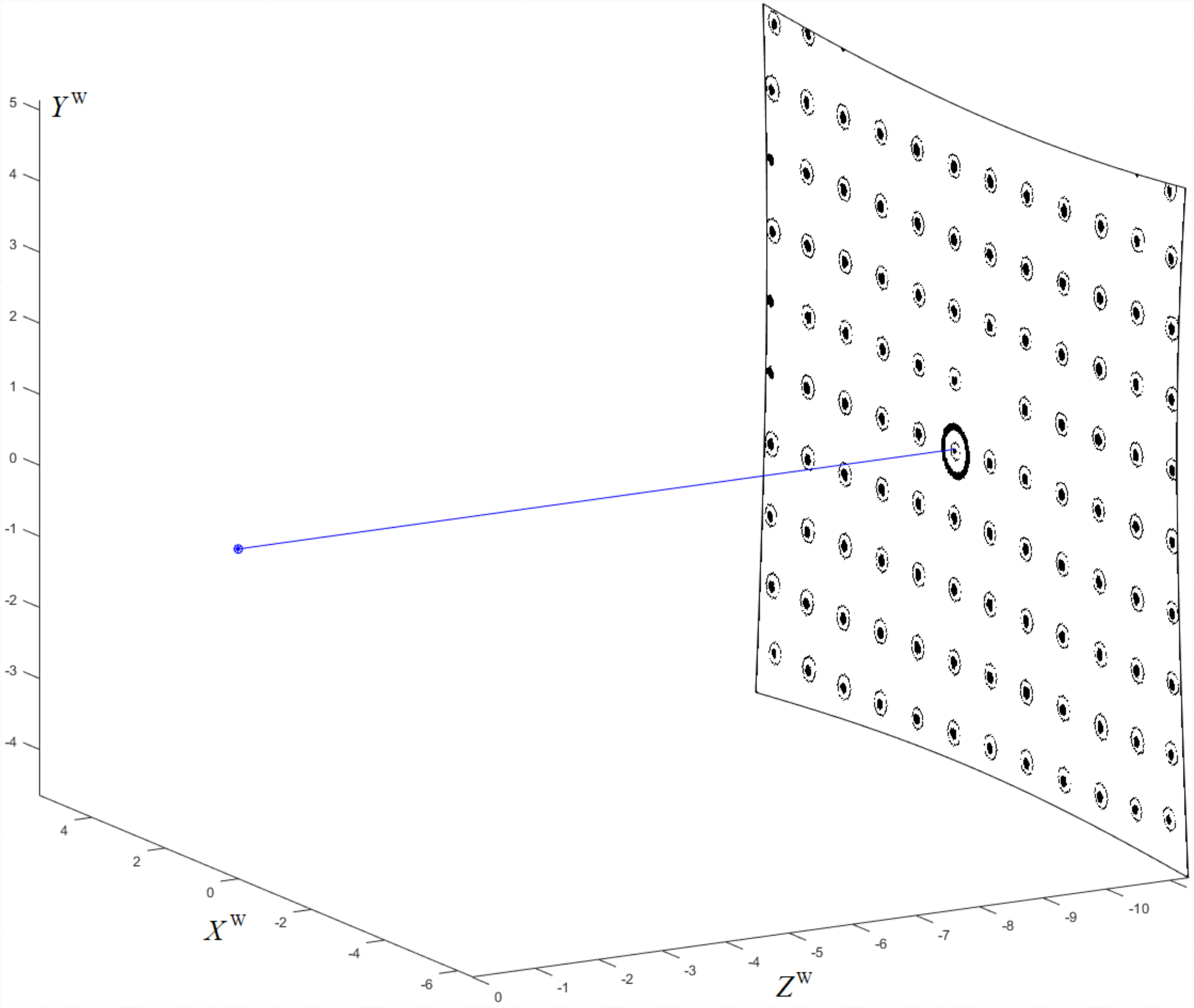
$$X^W[m,n] = a[m,n]Z^W[m,n] + b[m,n]$$

$$Y^W[m,n] = c[m,n]Z^W[m,n] + d[m,n]$$

- Inspiration: find a way to get per-pixel Z^W

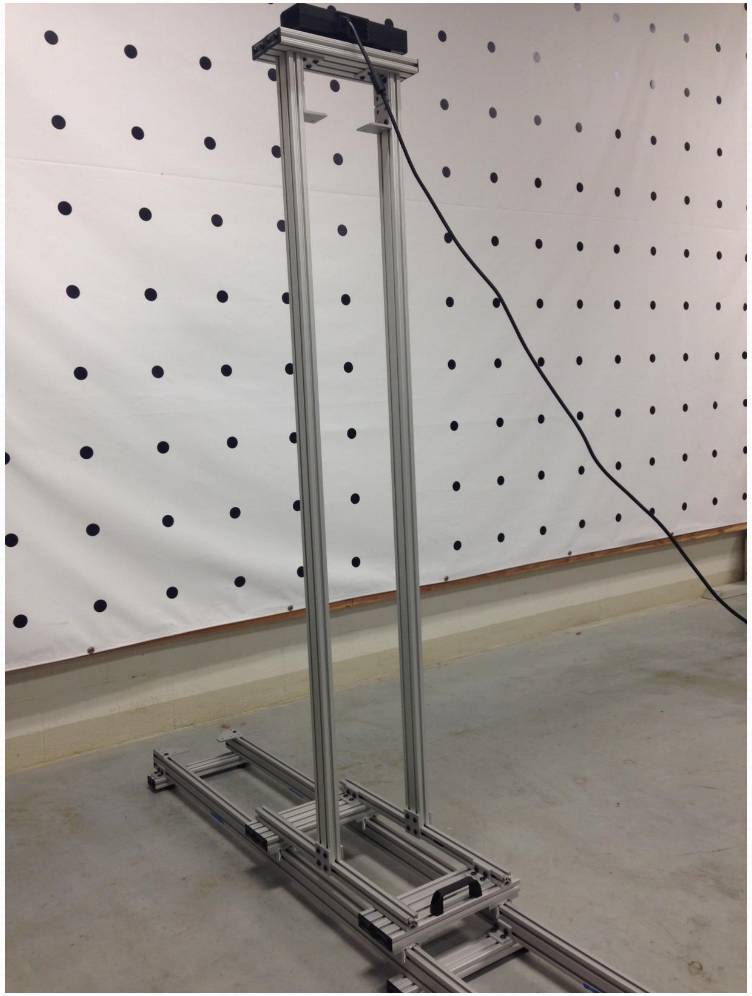
Rail Calibration System





Data Collection

- Mount: camera and laser distance measurer
- Want:
  - NIR: $X^W Y^W Z^W ID$
  - RGB: $X^W Y^W Z^W RGBD$
- Bound:
  - Z^W: Laser Distance Measurer
  - $X^W Y^W$: Uniform Round Dot Pattern
- Found (algorithms):
  - Calibration Points (*Row*, *Col*)s Extraction;
  - Corresponding World Space Address Assignment;
  - Non-Linear Dense Transformation



Calibration Points (*Row, Col*) Extraction;

- Gray-Scaling

$$I_0[m,n] = 0.21R[m,n] + 0.72G[m,n] + 0.07B[m,n]$$

- Histogram Equalization

$$I_1[m,n] = \frac{I_0[m,n] - I_{\mathrm{MIN}}}{I_{\mathrm{MAX}} - I_{\mathrm{MIN}}}$$

- Adaptive Thresholding

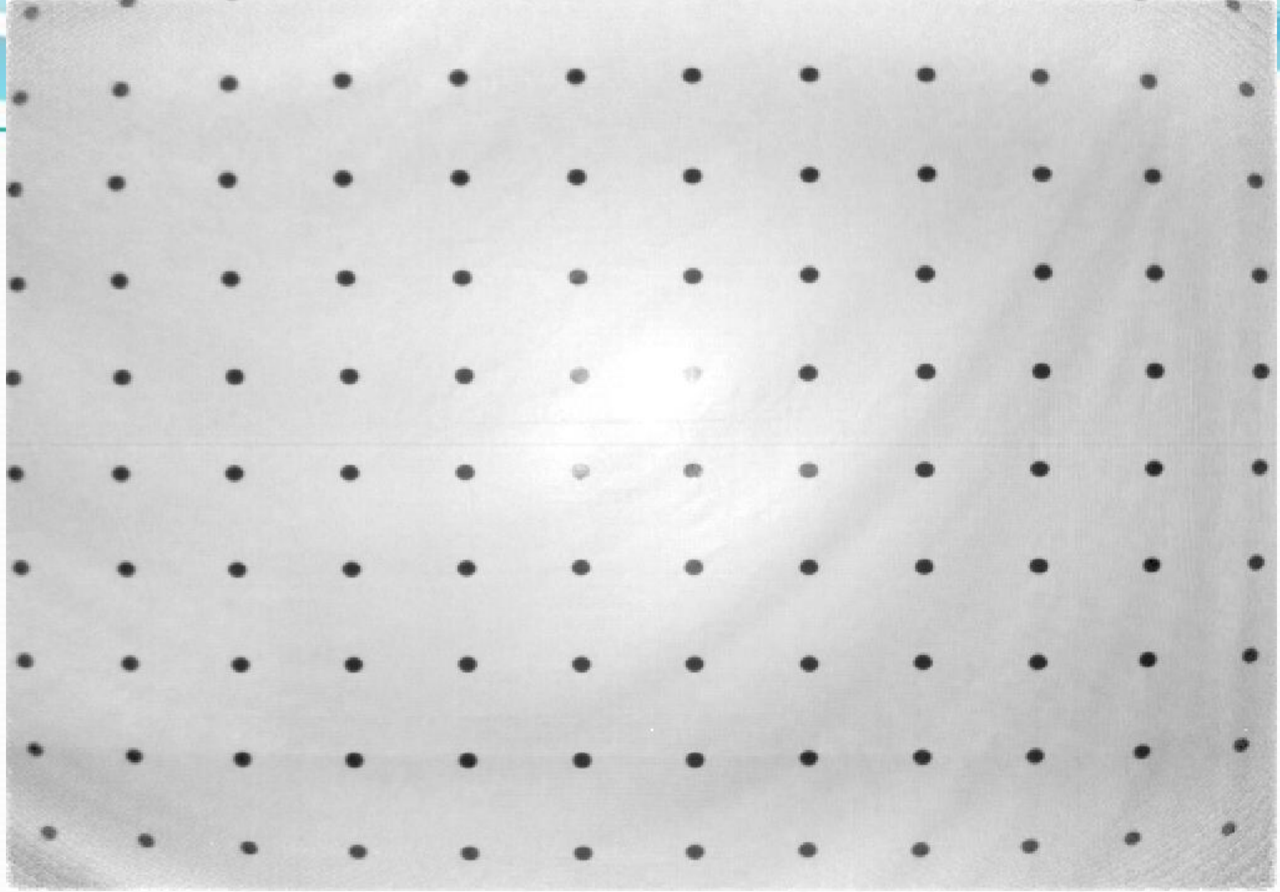
$$I_2[m,n] = \begin{cases} 1, & I_1[m,n] - I_{\mathrm{b}}[m,n] - C_0 > 0 \\ 0, & else \end{cases}$$

- Round Dot Tracking

E	*A*	*F*
B	*O*	*C*
G	*D*	*H*

$$I_3[m,n] = I_2[m,n] * \frac{(128I_{\mathrm{A}} + 64I_{\mathrm{B}} + 32I_{\mathrm{C}} + 16I_{\mathrm{D}} + 8I_{\mathrm{E}} + 4I_{\mathrm{F}} + 2I_{\mathrm{G}} + I_{\mathrm{H}})}{255}$$

Raw NIR Image



After Historgram Equalization

$$I_0[m,n] = \frac{g[m,n]}{G} * (1.0 - 0.0) + 0.0 = \frac{g[m,n]}{G}$$

$$CDF(g) = \frac{\sum_{l=1}^{g} PMF[l]}{M \times N}$$

$$CDF(g_{\min}) = 0.01$$

$$CDF(g_{\max}) = 0.99$$

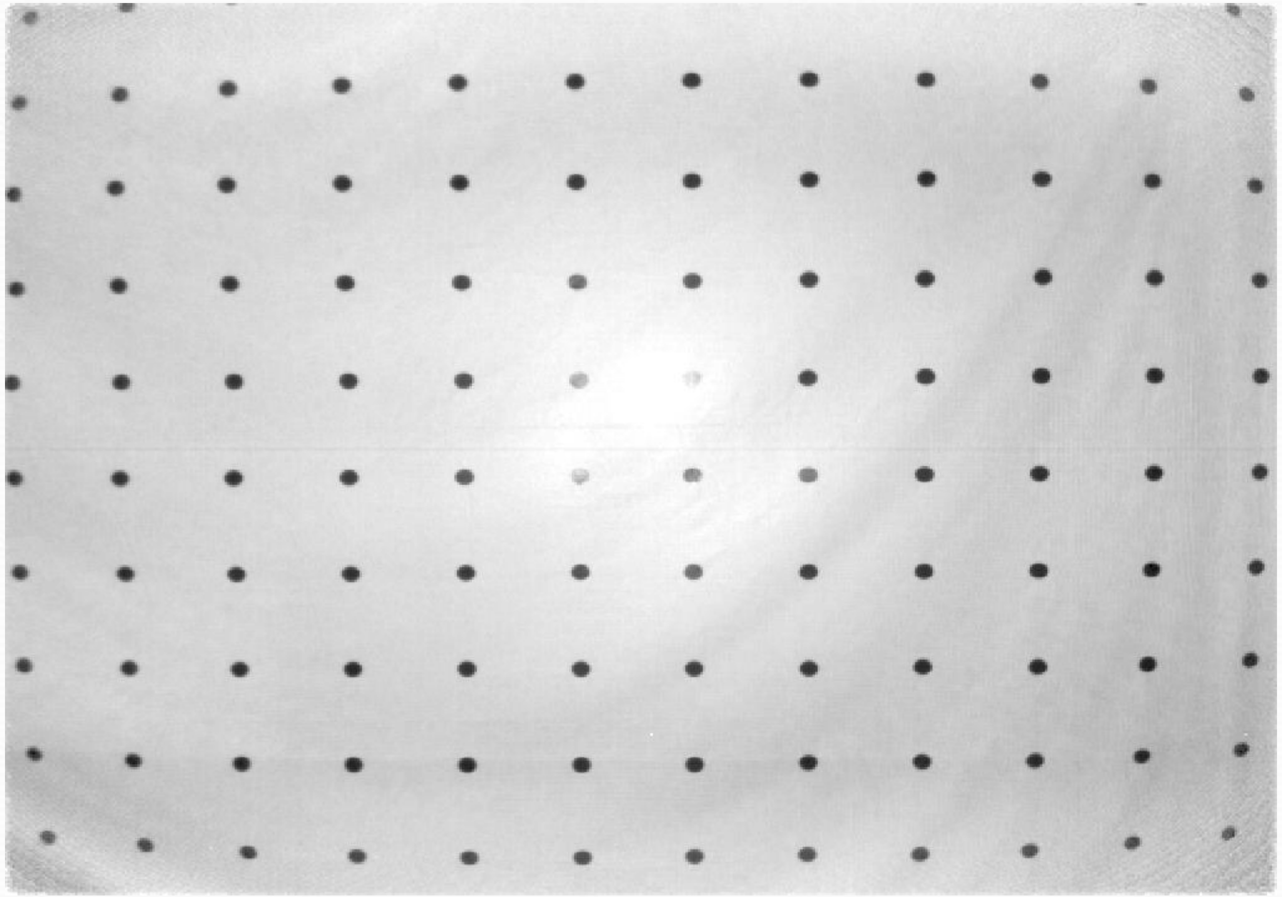
$$I_{\mathrm{MIN}} = g_{\min} / G$$

$$I_{\mathrm{MAX}} = g_{\max} / G$$

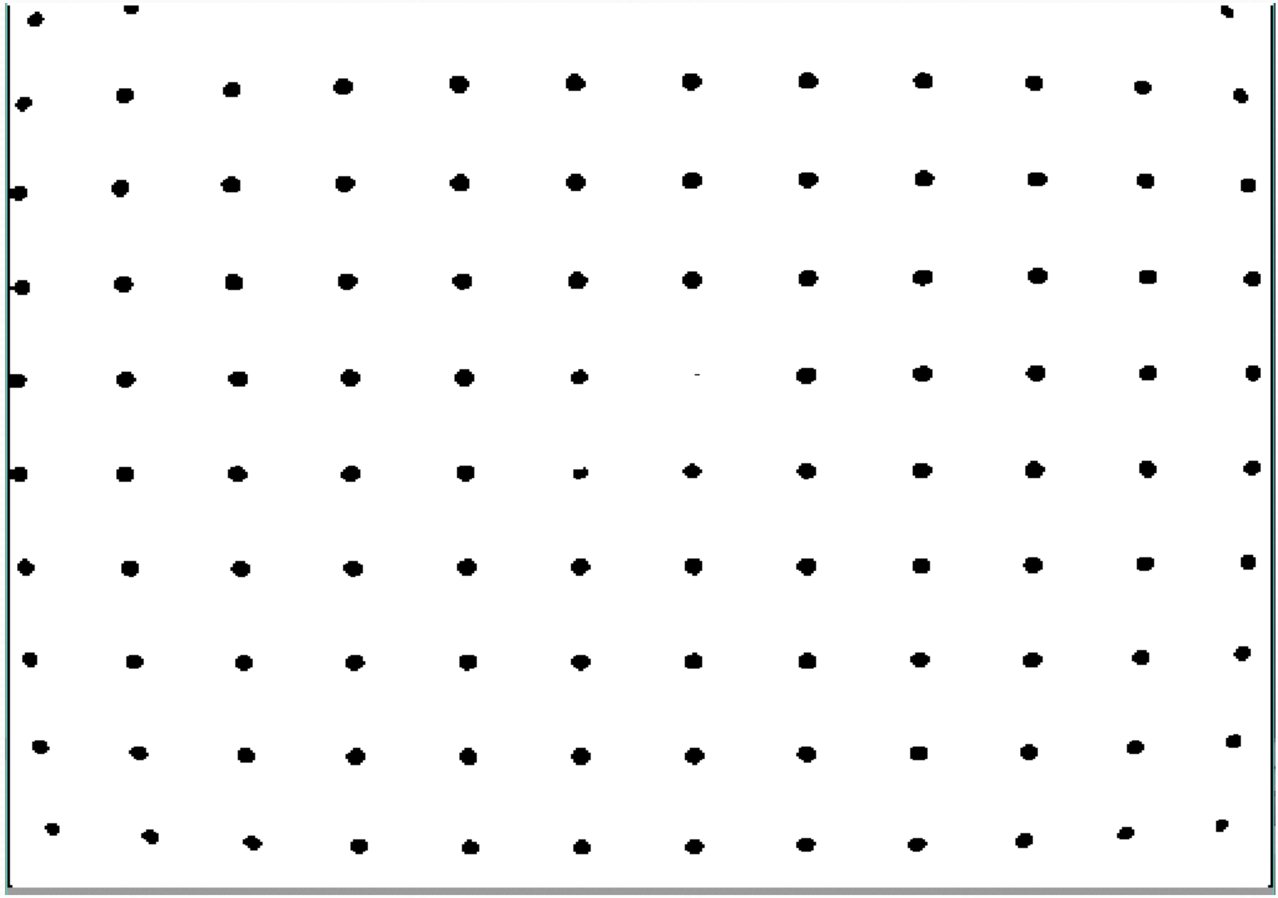
$$I_1[m,n] = \frac{I_0[m,n] - I_{\mathrm{MIN}}}{I_{\mathrm{MAX}} - I_{\mathrm{MIN}}}$$

- Adaptive Thresholding

$$I_2[m,n] = \begin{cases} 1, & I_1[m,n] - I_b[m,n] - C_0 > 0 \\ 0, & else \end{cases}$$



Historgram Equalized



Binarized

- Round Dot Tracking

E	A	F
B	O	C
G	D	H

$$I_3[m,n] = I_2[m,n] * \frac{(128I_{\mathrm{A}} + 64I_{\mathrm{B}} + 32I_{\mathrm{C}} + 16I_{\mathrm{D}} + 8I_{\mathrm{E}} + 4I_{\mathrm{F}} + 2I_{\mathrm{G}} + I_{\mathrm{H}})}{255}$$

$$if\ (I_{\mathrm{O}}\ \&\ 0\mathrm{x}80 == 1), \quad then, \quad \text{marker } A \text{ is valid} \quad (\text{ go Up })$$

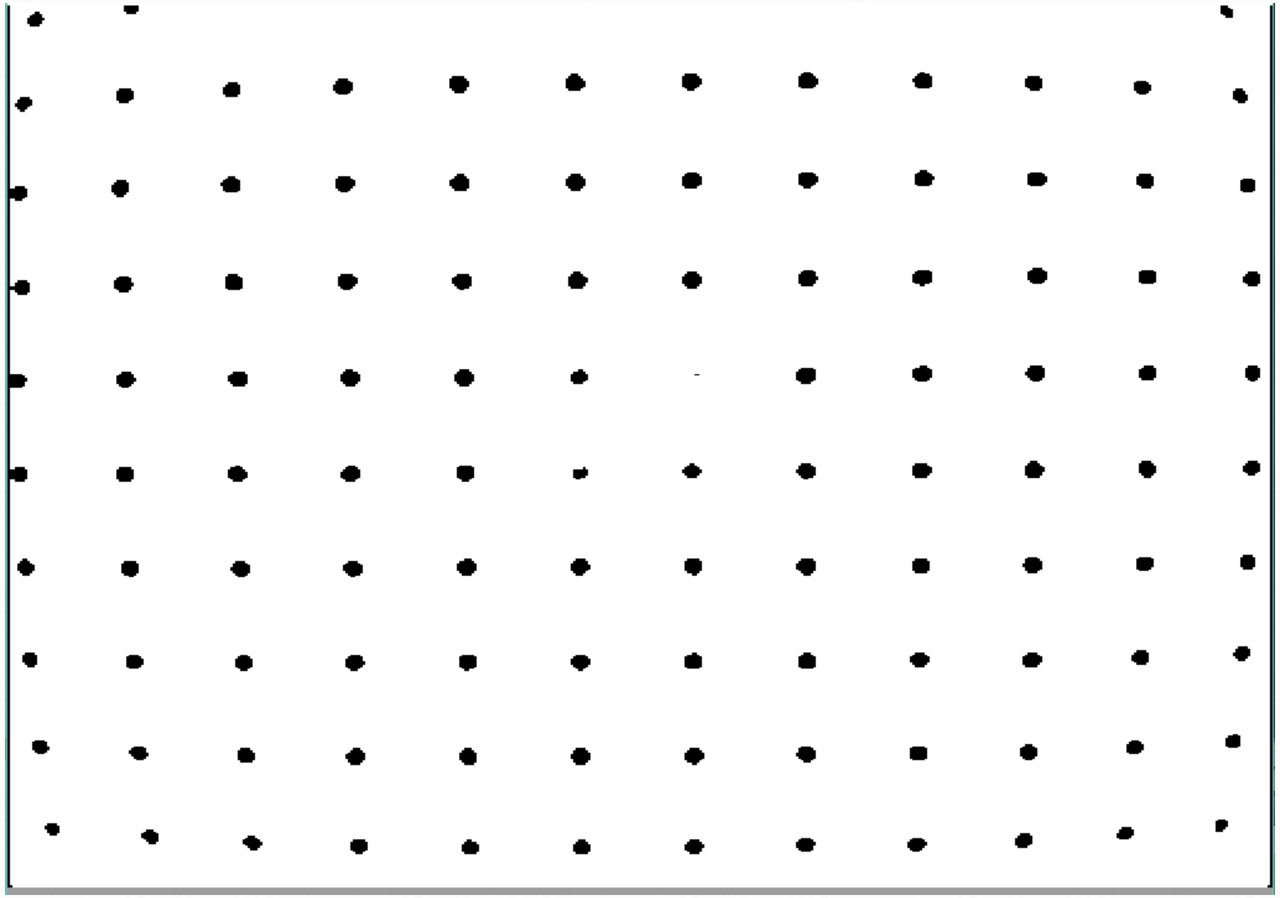
$$if\ (I_{\mathrm{O}}\ \&\ 0\mathrm{x}40 == 1), \quad then, \quad \text{marker } B \text{ is valid} \quad (\text{ go Left})$$

$$if\ (I_{\mathrm{O}}\ \&\ 0\mathrm{x}20 == 1), \quad then, \quad \text{marker } C \text{ is valid} \quad (\text{ go Right })$$

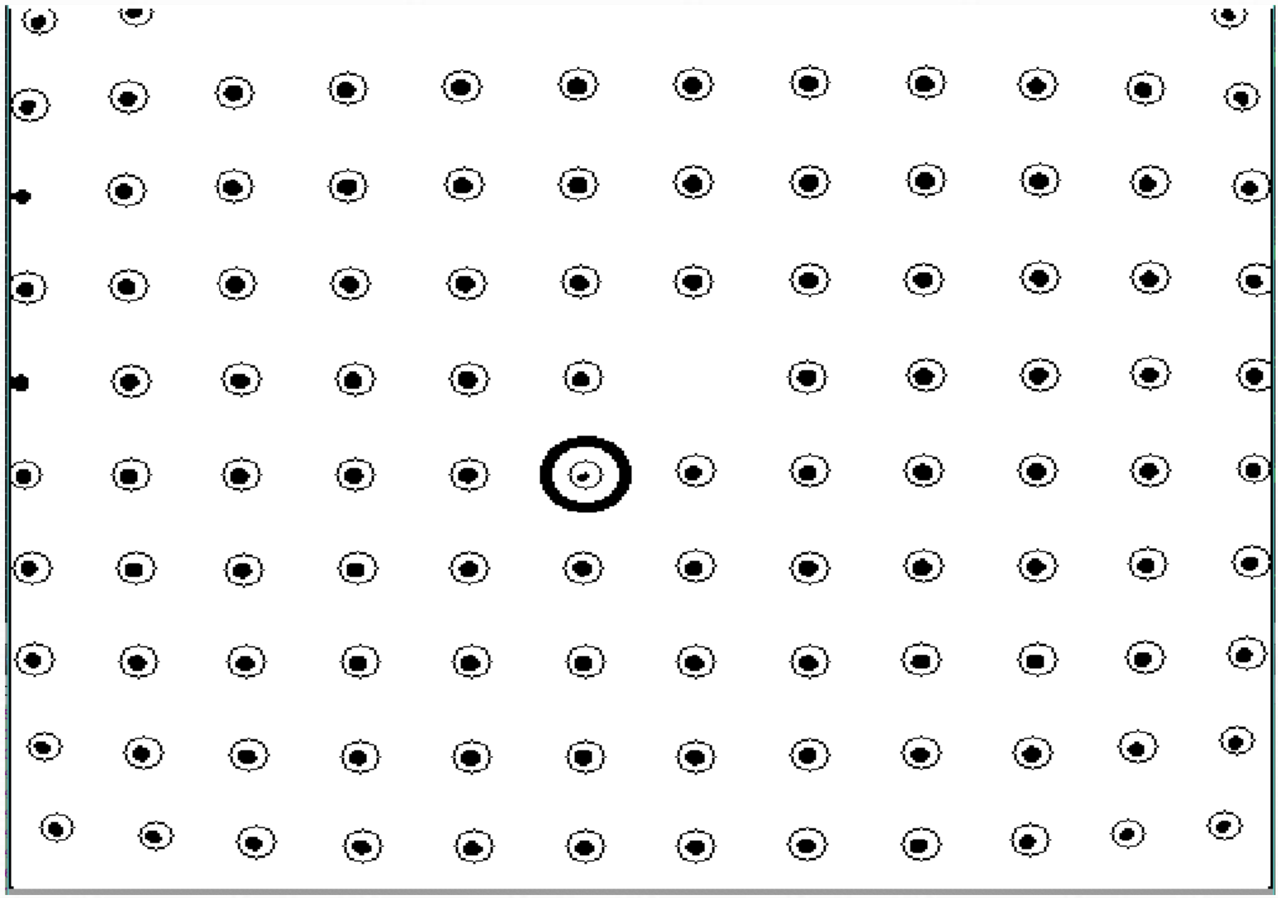
$$if\ (I_{\mathrm{O}}\ \&\ 0\mathrm{x}10 == 1), \quad then, \quad \text{marker } D \text{ is valid} \quad (\text{ go Down })$$

Anchor !=0 → Detect Valid → Flip Valid → Get Area + Bounding Box

Traverse and Extract on CPU



Binarized Image

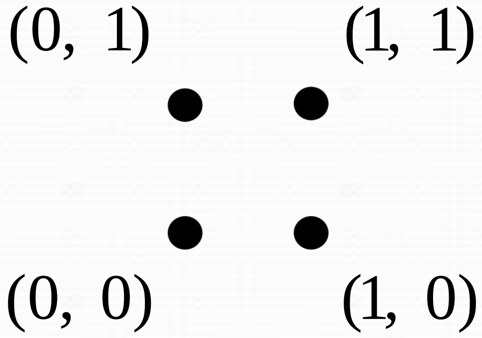


Dots’ Centers Extracted

World Space Address Assignment

- Travers every 4 Square-Shaped points and find best $\boldsymbol{A_0}$, which corresponds to the best-fit “Unit One” (228mm) in Image Space:

Get Linear Mapping matrix $\boldsymbol{A_0}$ → Transform all (R, C) to (X^W, Y^W) → Count (N_v) valid points with integer X^W/Y^W → Find best $\boldsymbol{A_0}$ who generates the largest N_v.



$$\begin{bmatrix} zX^W \\ zY^W \\ z \end{bmatrix} = \boldsymbol{A}_0 \begin{bmatrix} C \\ R \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} C \\ R \\ 1 \end{bmatrix}$$

- Translate Origin to the Center Dot

$$c_h = (512-1)/2 = 255.5$$
$$r_h = (424-1)/2 = 211.5$$

$$\begin{bmatrix} zx_h \\ zy_h \\ z \end{bmatrix} = \boldsymbol{A}_0 \cdot \begin{bmatrix} c_h \\ r_h \\ 1 \end{bmatrix}$$

$$c_h = round(c_h)$$
$$r_h = round(r_h)$$

$$\boldsymbol{A}_1 = \boldsymbol{T} \cdot \boldsymbol{A}_0 = \begin{bmatrix} 1 & 0 & -x_h \\ 0 & 1 & -y_h \\ 0 & 0 & 1 \end{bmatrix} \cdot \boldsymbol{A}_0$$

World Space Address Assignment

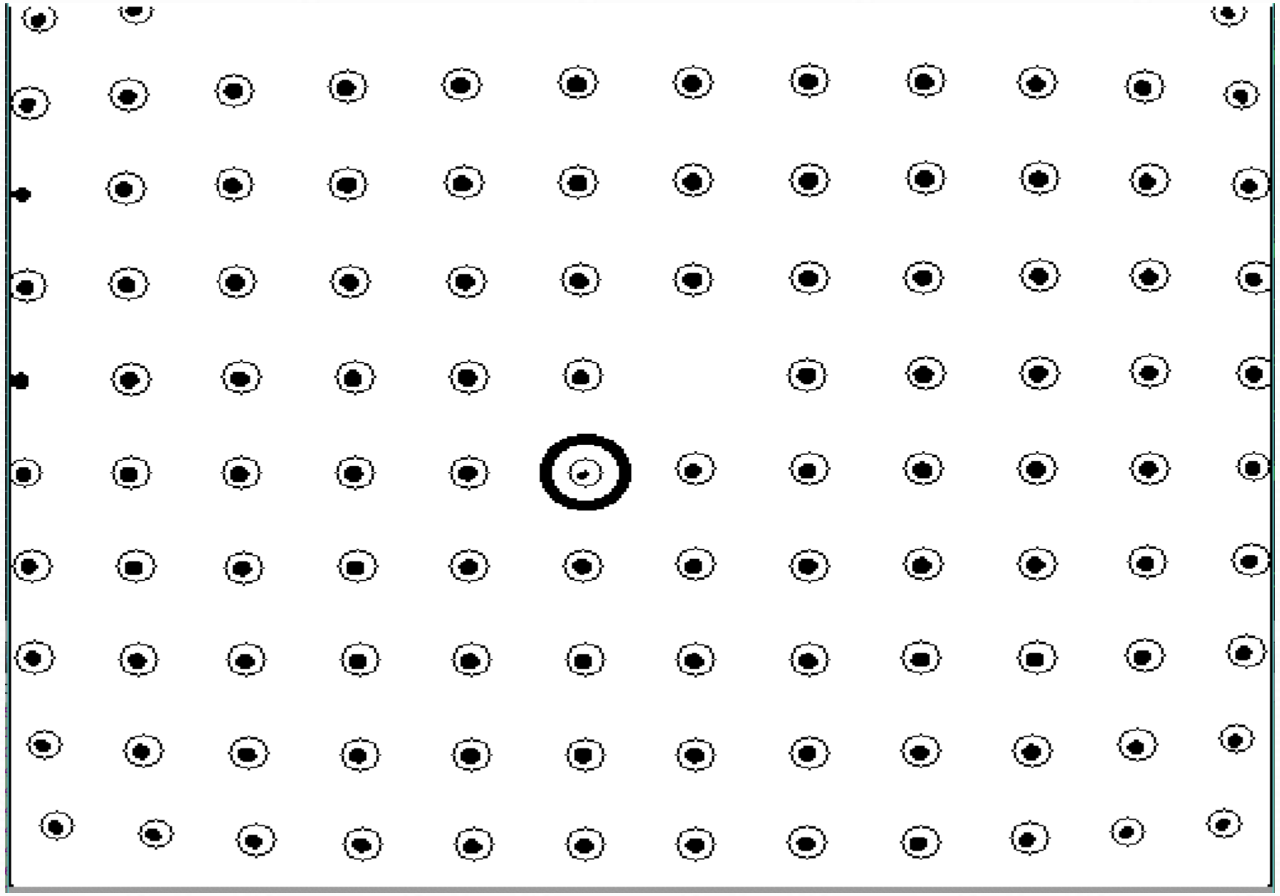
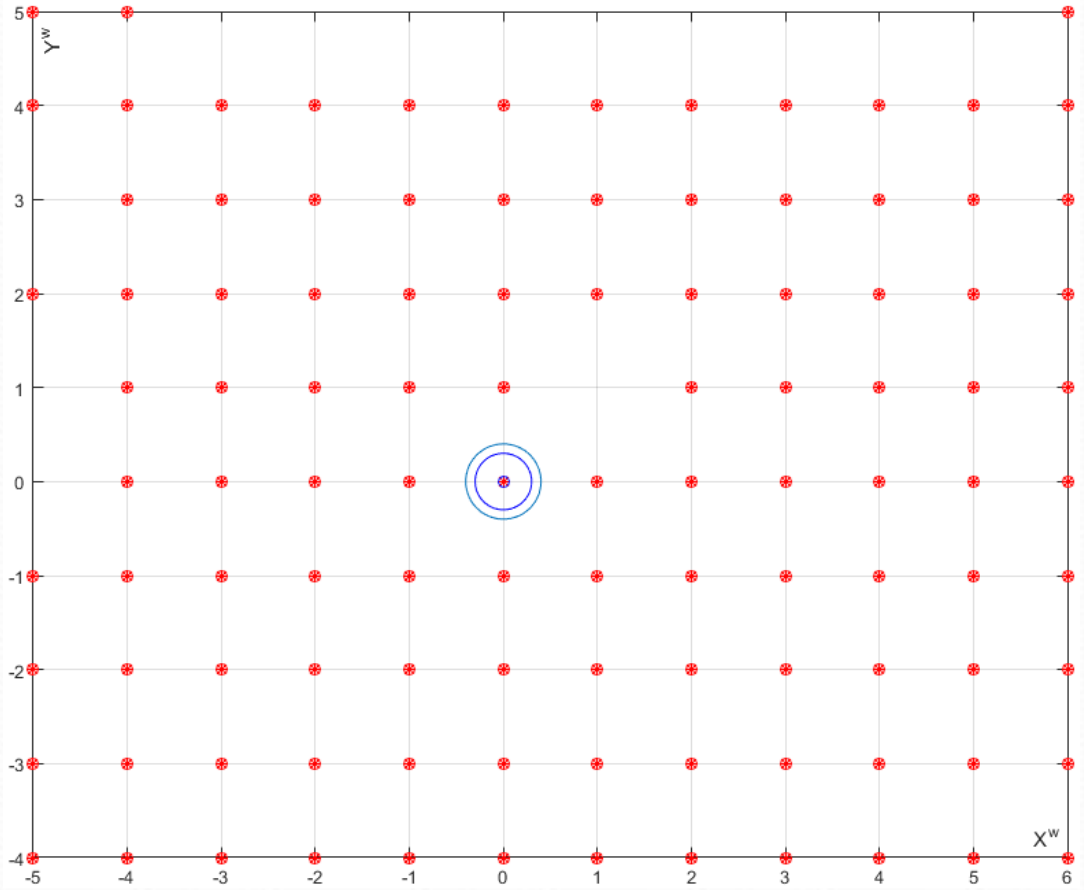


Image Space Calibration Points



Assigned World Space $X^w Y^w$

Two Dimensional Polynomial Mapping

- (First Order Perspective Transformation)

$$\begin{bmatrix} zX^W \\ zY^W \\ z \end{bmatrix} = \boldsymbol{A}_0 \begin{bmatrix} C \\ R \\ 1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} C \\ R \\ 1 \end{bmatrix}$$

- Second Order

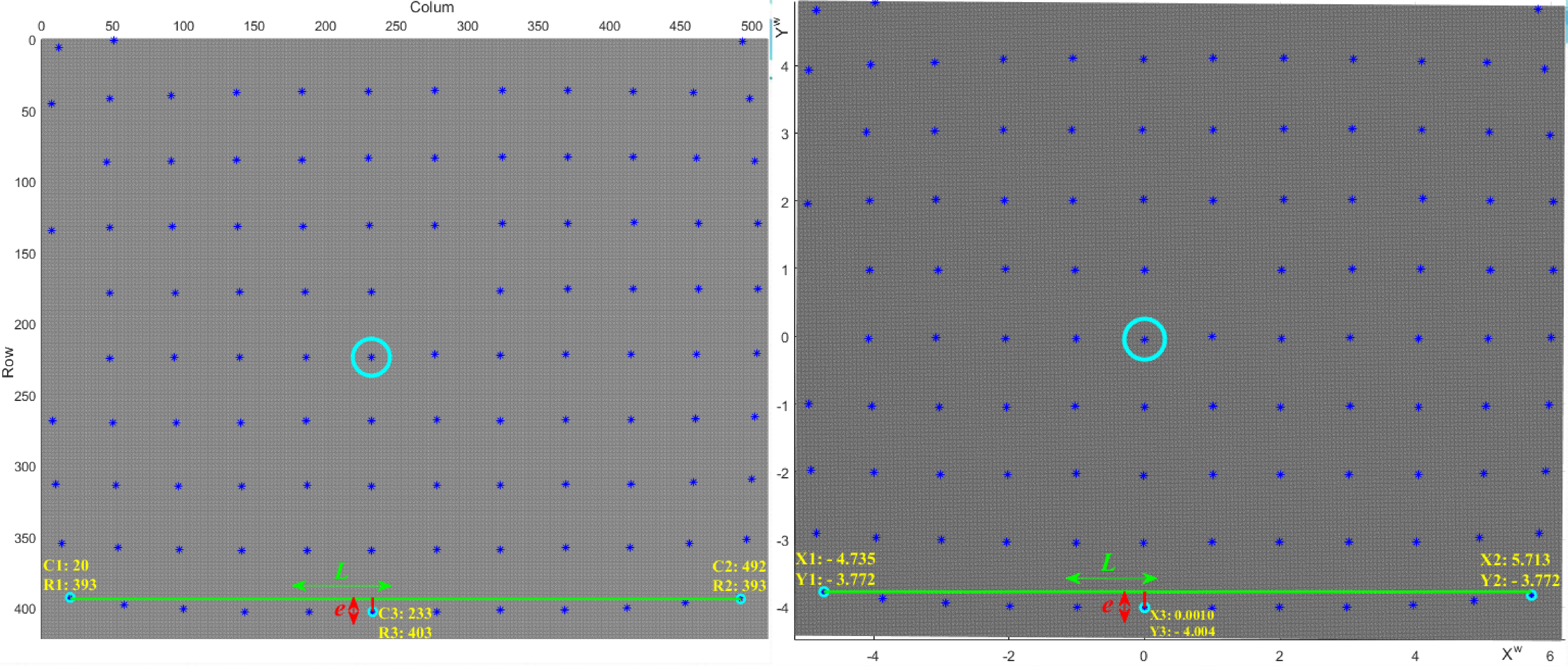
$$X^W = a_{11}C^2 + a_{12}CR + a_{13}R^2 + a_{14}C + a_{15}R + a_{16}$$

$$Y^W = a_{21}C^2 + a_{22}CR + a_{23}R^2 + a_{24}C + a_{25}R + a_{26}$$

- Fourth Order

$$X^W = a_{11}C^4 + a_{12}C^3R + a_{13}C^2R^2 + a_{14}CR^3 + a_{15}R^4 + a_{16}C^3 + a_{17}C^2R \quad \ldots$$
$$+ a_{18}CR^2 + a_{19}R^3 + a_{110}C^2 + a_{111}CR + a_{112}R^2 + a_{113}C + a_{114}R + a_{115}$$

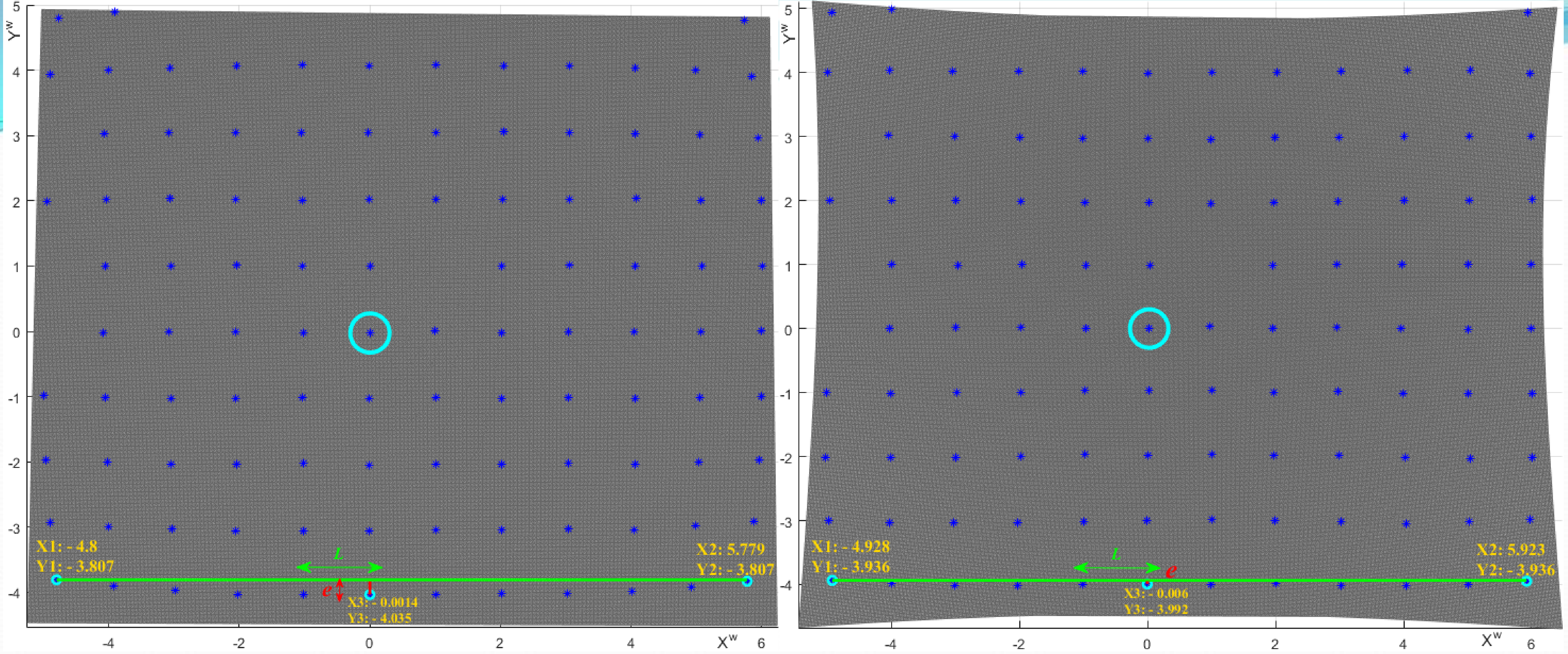
$$Y^W = a_{21}C^4 + a_{22}C^3R + a_{23}C^2R^2 + a_{24}CR^3 + a_{25}R^4 + a_{26}C^3 + a_{27}C^2R \quad \ldots$$
$$+ a_{28}CR^2 + a_{29}R^3 + a_{210}C^2 + a_{211}CR + a_{212}R^2 + a_{213}C + a_{214}R + a_{215}$$



$$d(\%) = e / L$$

$$d_0 = (\mathrm{R3} - \mathrm{R1}) / (\mathrm{C2} - \mathrm{C1}) = (403 - 393) / (492 - 20) = 2.1\%$$

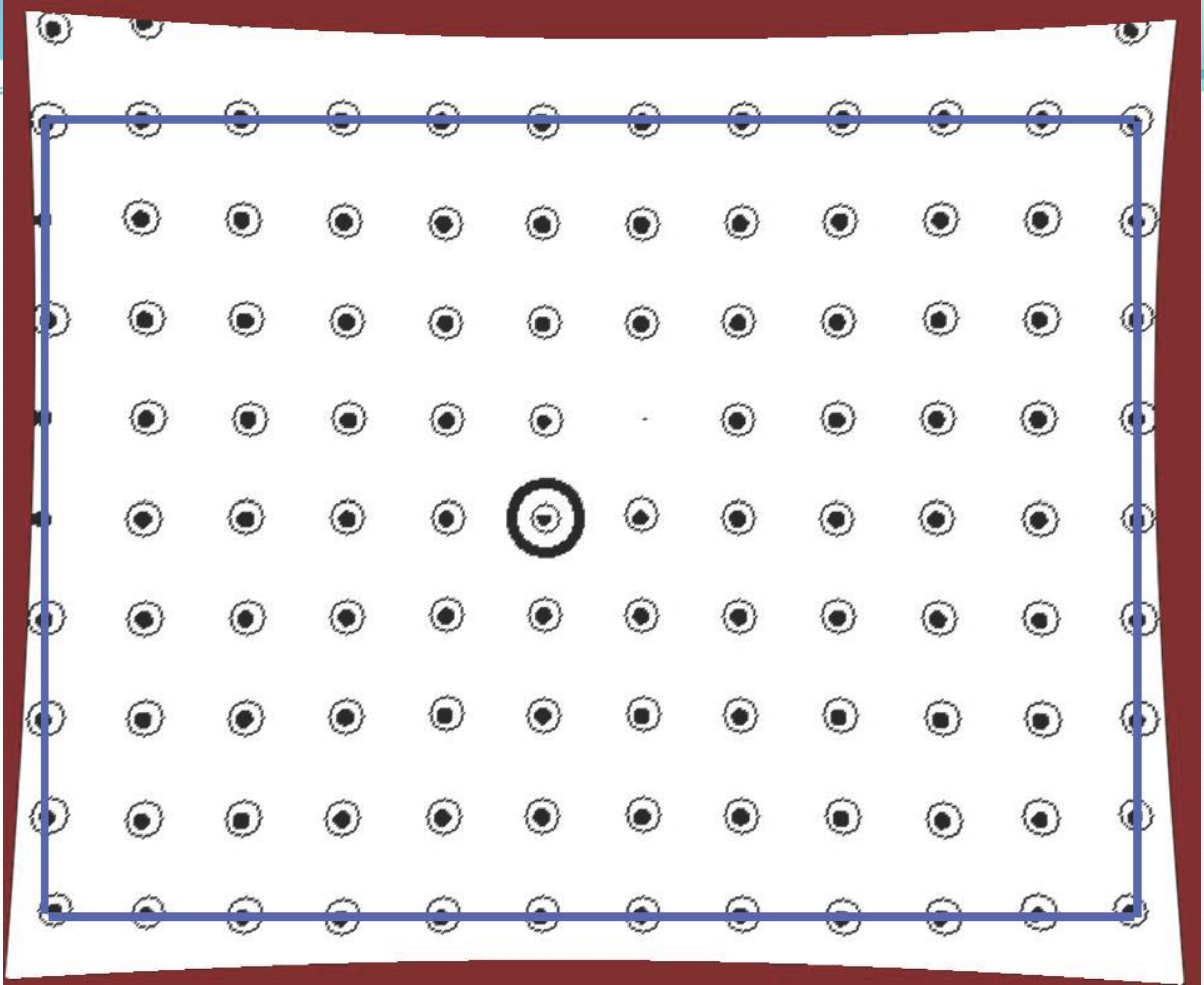
$$d_1 = (\mathrm{Y1} - \mathrm{Y3}) / (\mathrm{X2} - \mathrm{X1}) = [-3.772 + 4.004] / [5.713 + 4.735] = 2.2\%$$



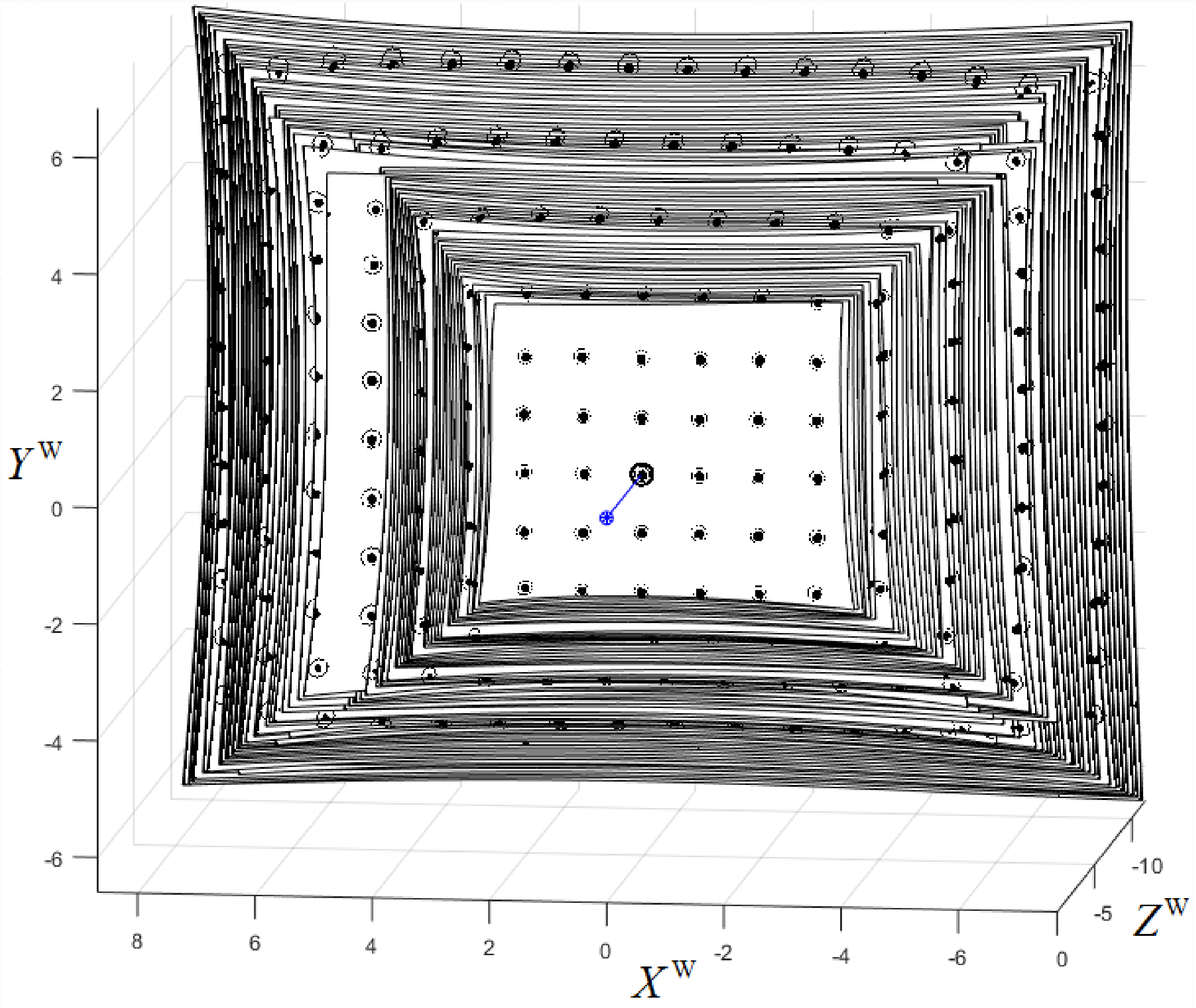
$$d(\%) = e / L$$

$$d_2 = [-3.807 - (-4.035)] = [5.779 - (-4.8)] = 2.1\%$$

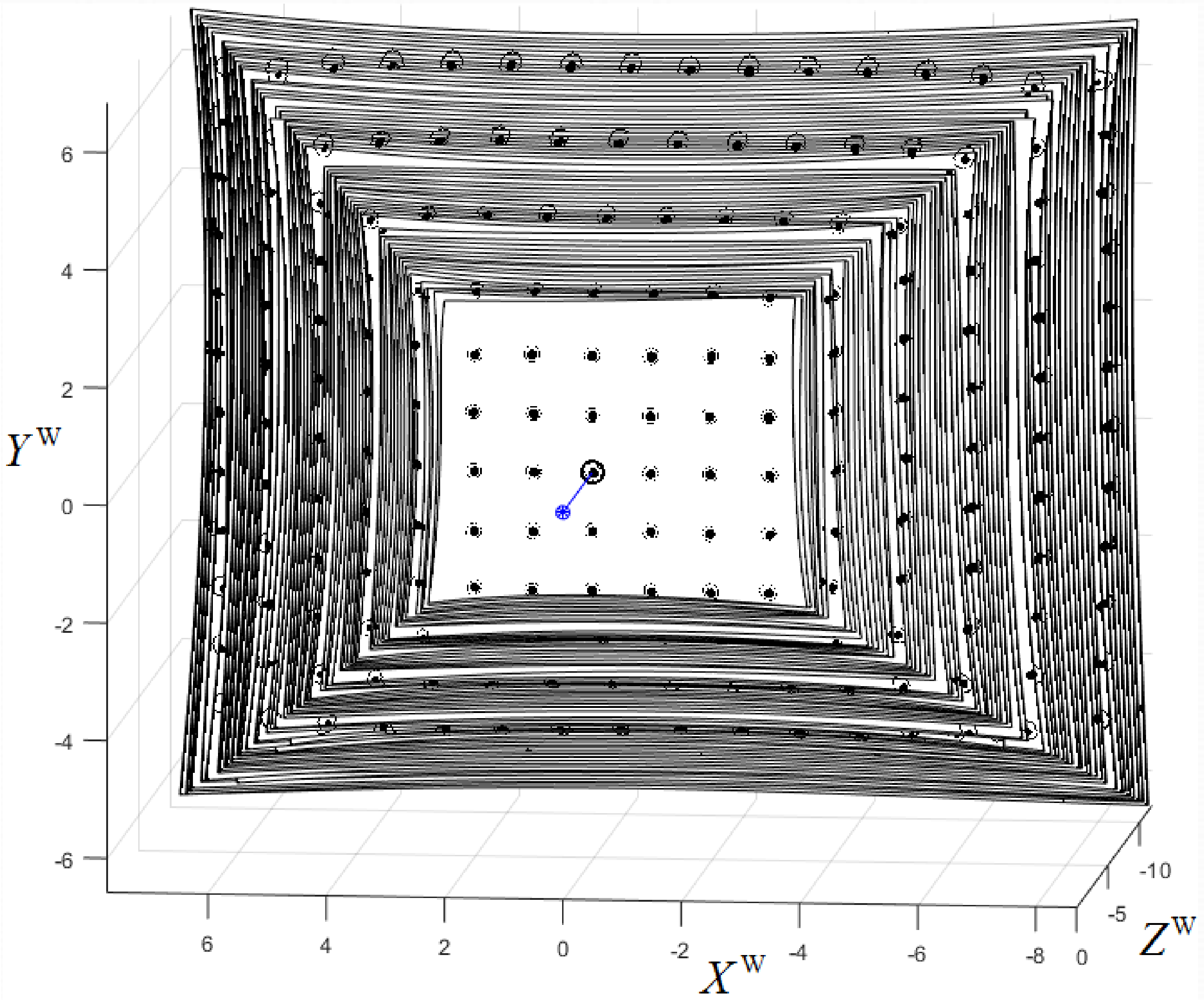
$$d_4 = [-3.936 - (-3.992)] = [5.923 - (-4.928)] \ = \ 0.516\%$$



63 frames from 1.165m to 2.565m, 25mm / frame

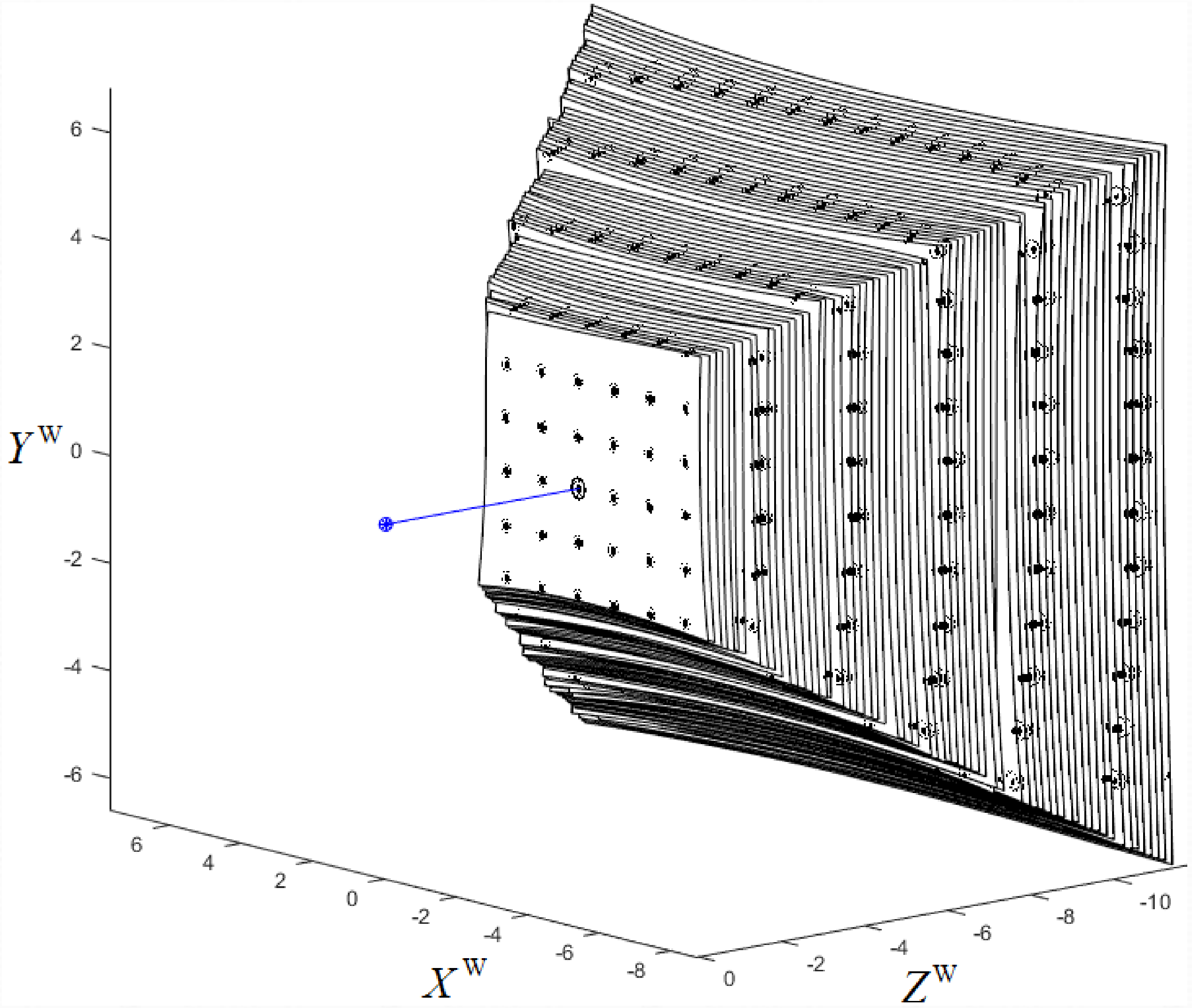


Staggered

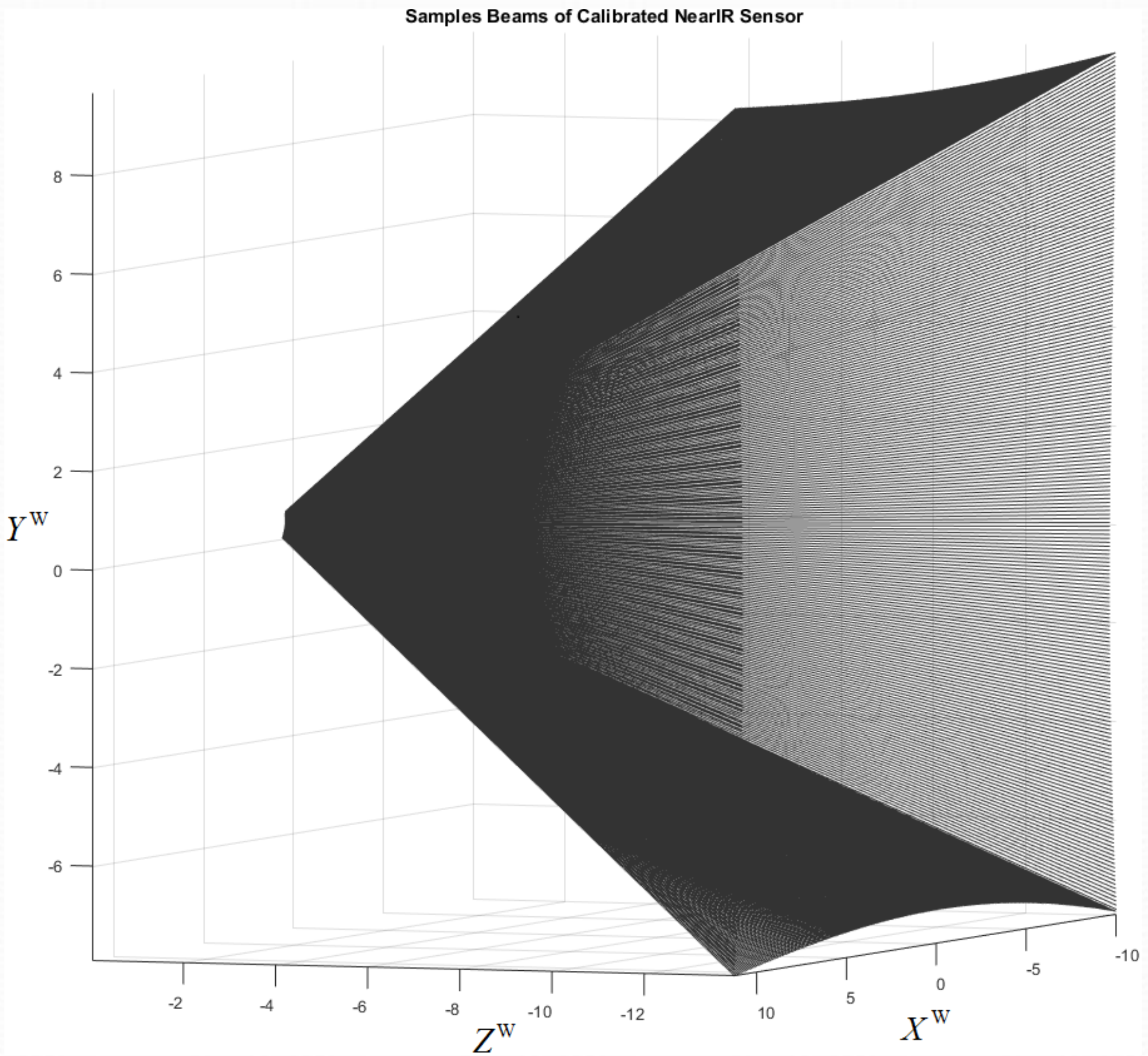


Unified

63 frames, generate Pixels' Beam Equations

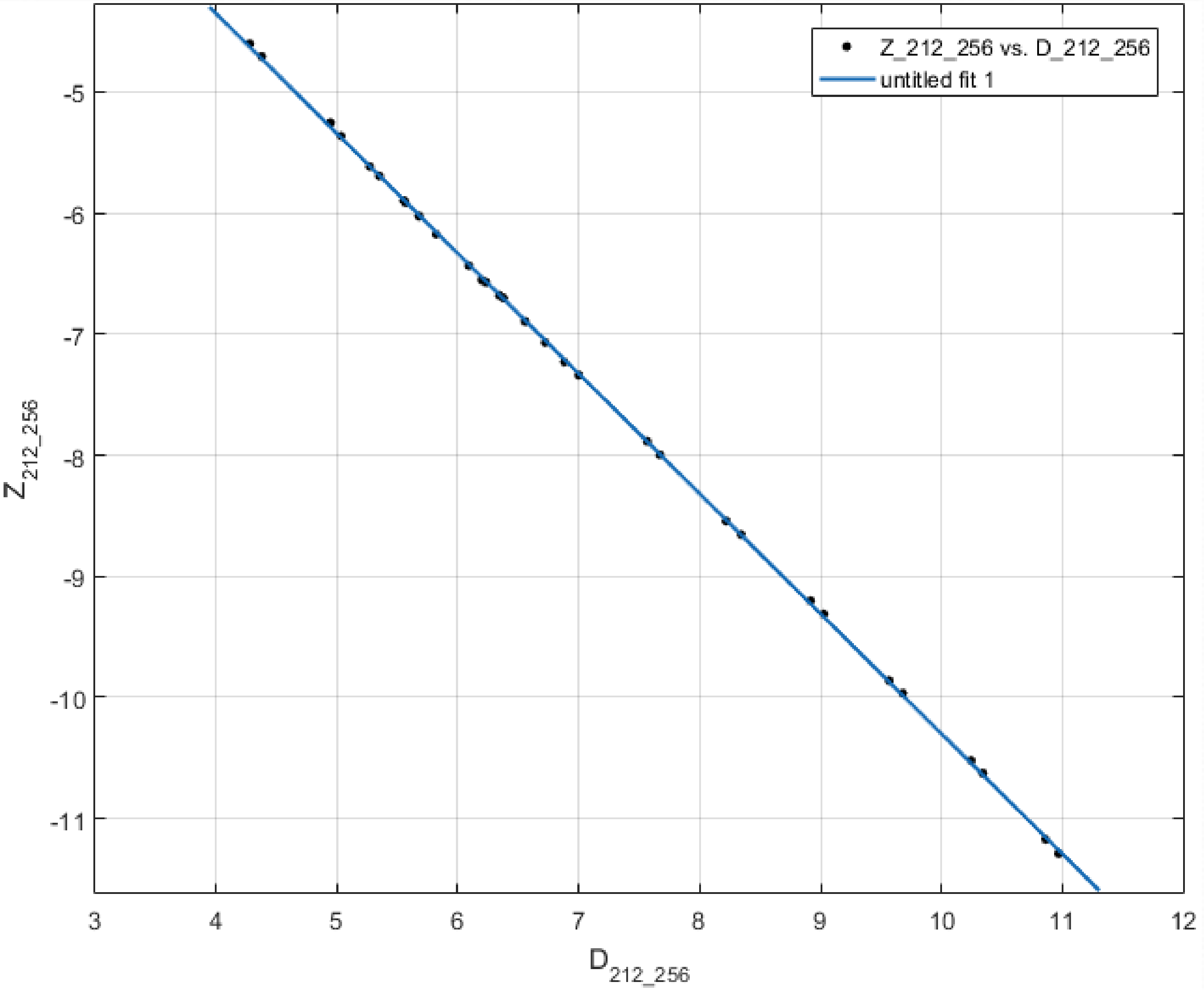


Frustum



Linear Z^W to $X^W Y^W$: Pixels' View

Per-Pixel D to Z^{W} mapping



D to Z^{W} Polynomial Fit

Data at pixel (212, 256) from 32 frames

↓

Linear

↓

$$Z^{W}[m,n] = e[m,n]D[m,n] + f[m,n]$$

Generate Look-Up Table

- Size: *Width* - *Height* - 6 (512*424*6)
- Data: $X^{W}Y^{W}Z^{W}D$
- Pre-Process: (for every frame)
  - Find best-fit plane equation $D = aX^{W} + bY^{W} + c$
  - Throw away 10% pixels of worst D
- Mappings:

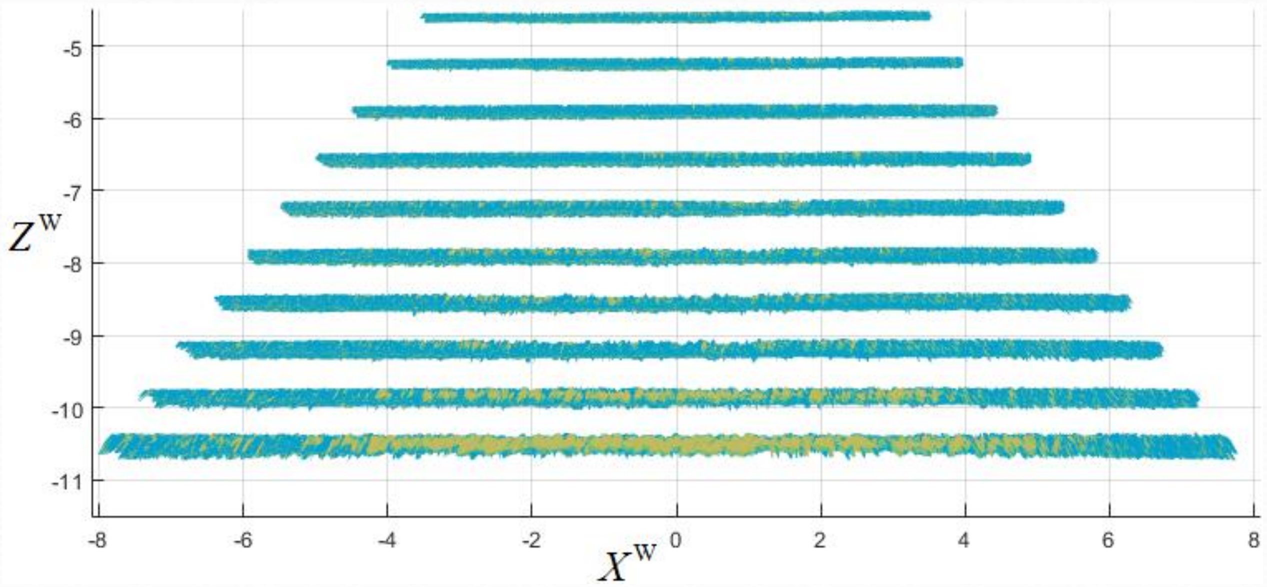
  Fragment Shader: 3 per-pixel linear mappings, 6 parameters

$$X^{W}[m,n] = a[m,n]Z^{W}[m,n] + b[m,n]$$

$$Y^{W}[m,n] = c[m,n]Z^{W}[m,n] + d[m,n]$$

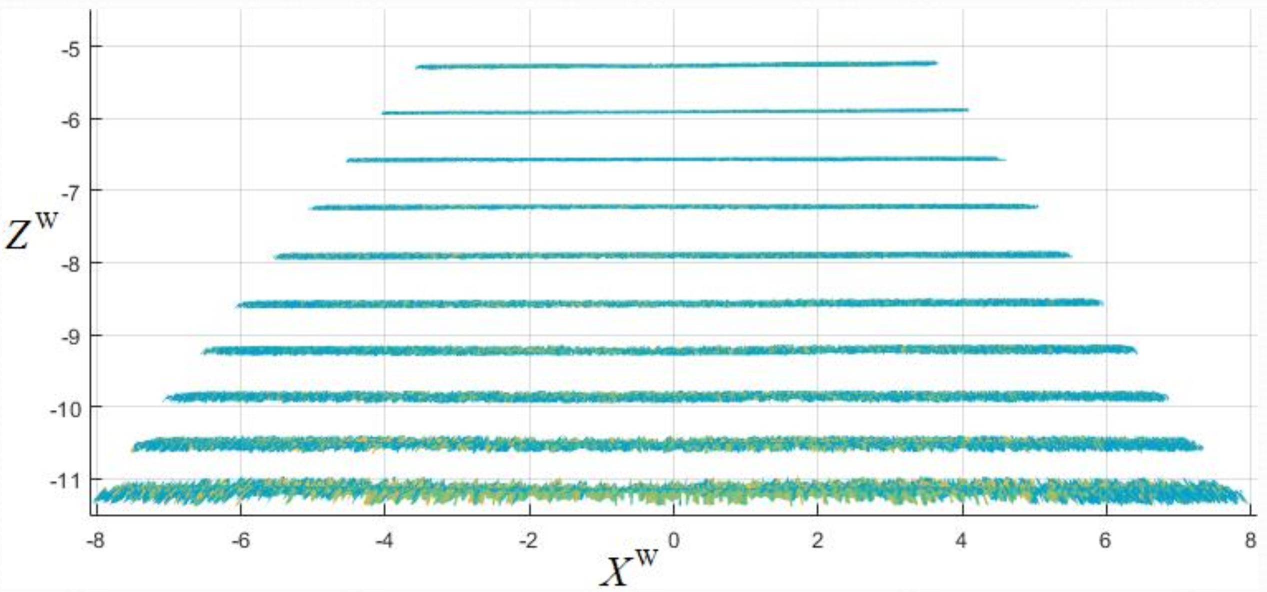
$$Z^{W}[m,n] = e[m,n]D[m,n] + f[m,n]$$

Depth Distortion Correction

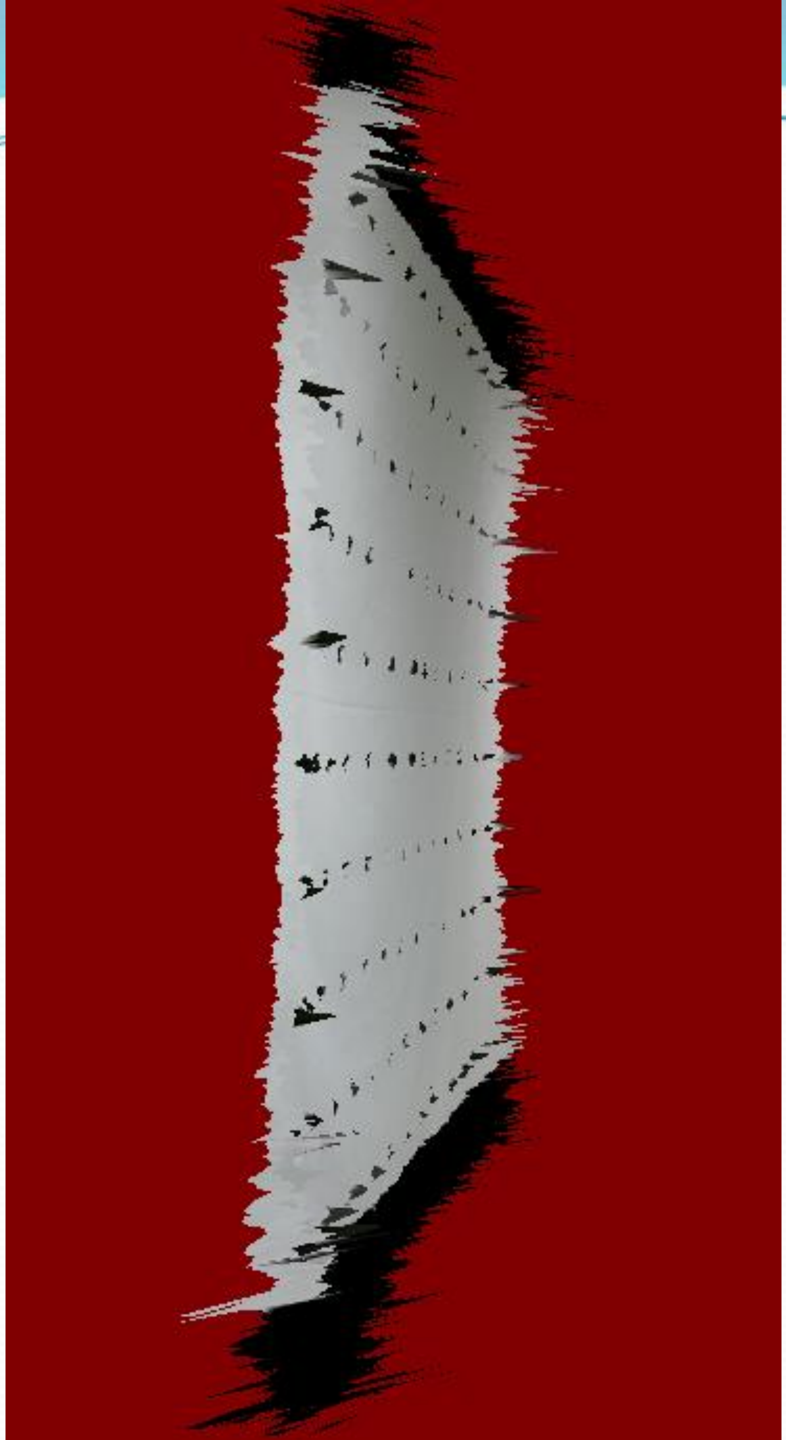


Raw Pin-Hole Reconstructions

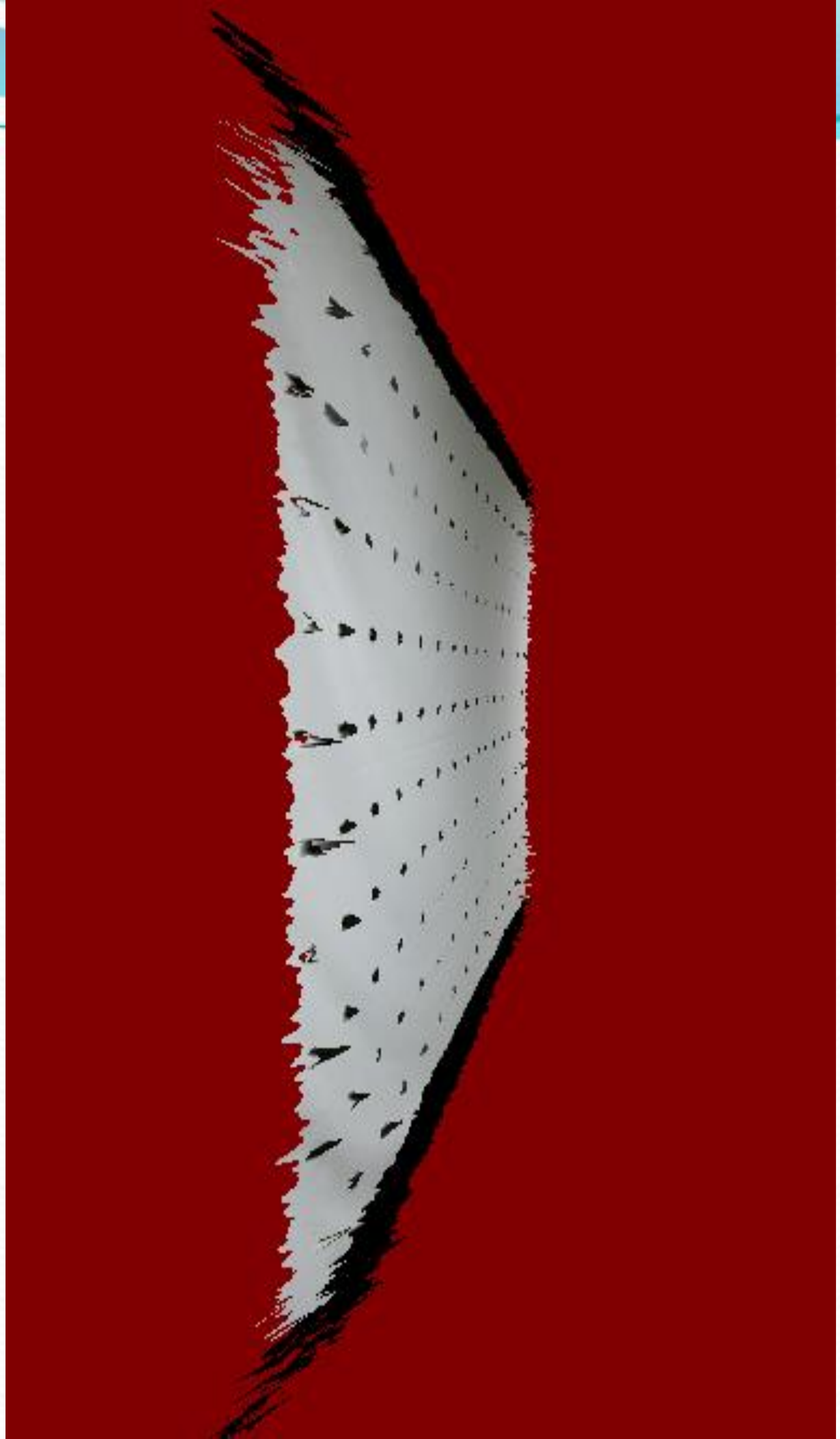
Transformed
into World Space
By
Best-Fit *Rotation* and *Translation*



Calibrated LUT Reconstructions

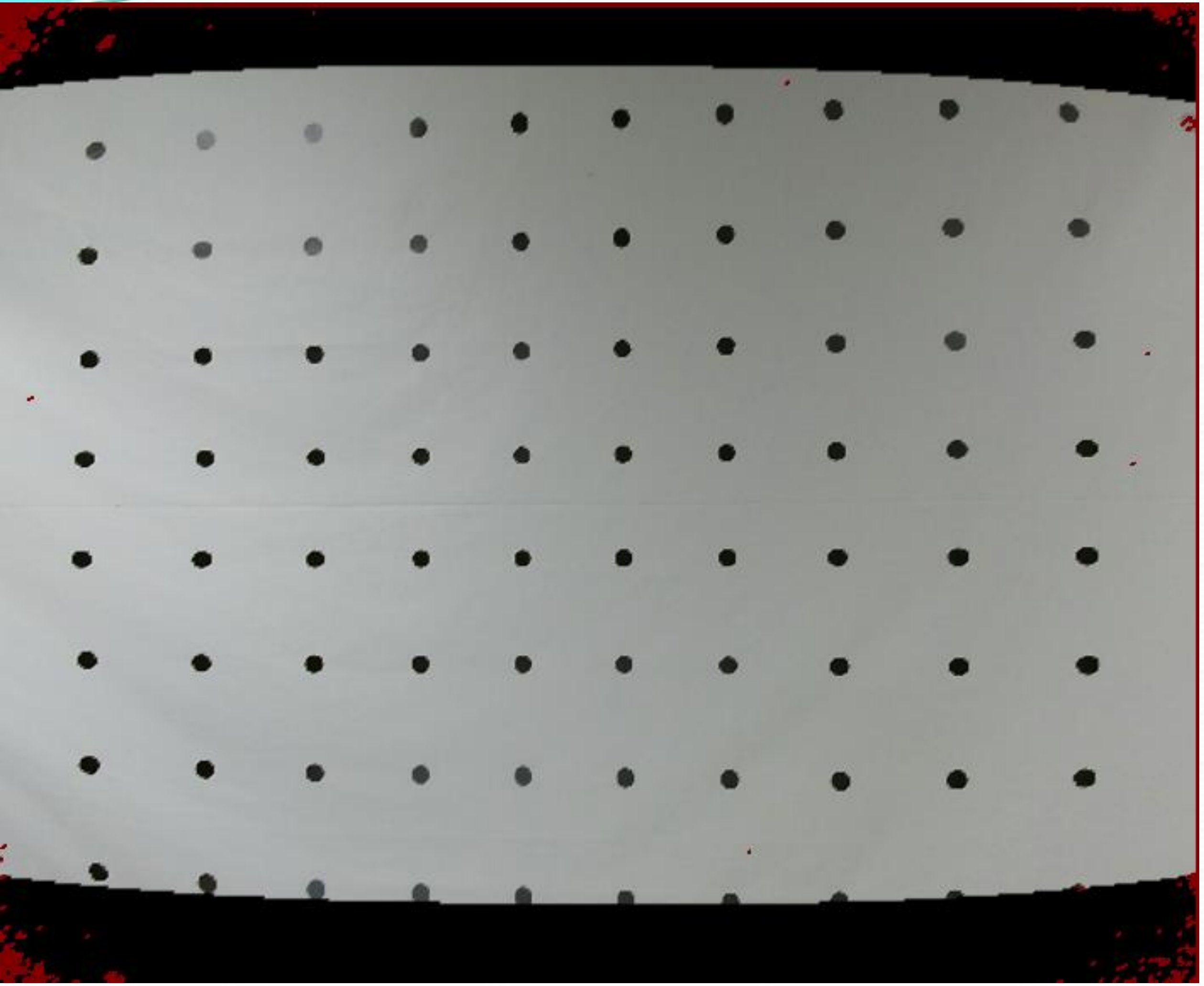


Before Calibration

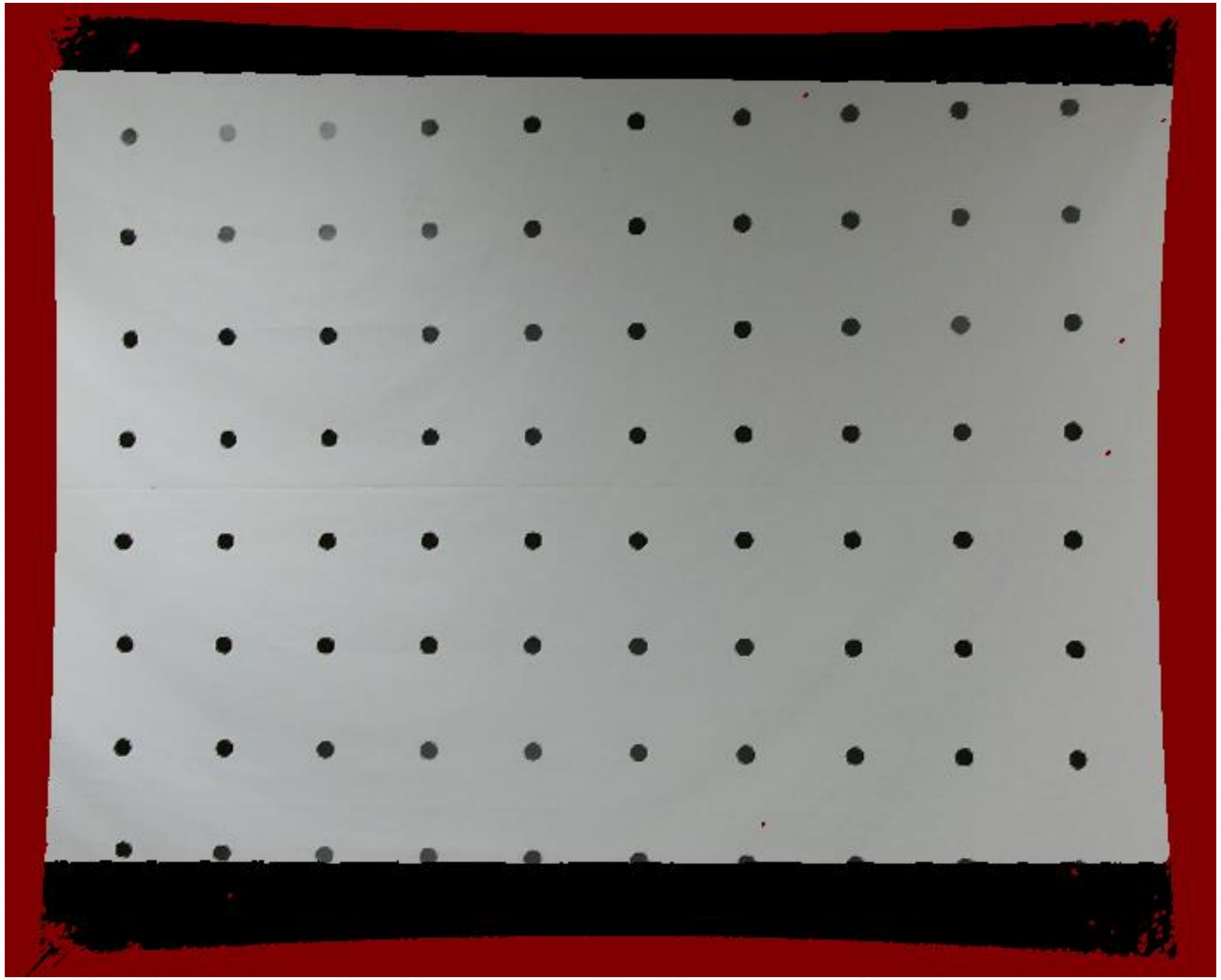


Calibrated

Lens Distortion Correction



Before Calibration



Calibrated

Conclusion

- Rail System

  Infinite frames of data, dense calibration points, per-pixel D to Z^W mapping
- Data Collection (Per-Frame)
  - Get Z^W from laser distance measurer ;
  - Robust calibration points' extraction ;

    Histogram Equalization, Adaptive Thresholding, Round Dots' Tracking
  - Assign world space coordinates to calibration points ;
  - Determine two-dimensional fourth order polynomial mapping ;
  - Generate dense undistorted $X^W Y^W$.
- Pre-Process
  - Unify staggered frames
  - Throw away 10% noise pixels
- Generate LUT: *Width* - *Height* - 6 (512*424*6)
- 3D Reconstruction: Undistorted 3D Reconstruction

Future Works

- Hard Ware
  - Longer rail: singular D to Z^W linear mapping to segmented mapping ;
  - Pattern Size and Distribution: based on resolution ;
  - 2D pattern to 3D pattern: in case NIR streams cannot be used, 3D pattern for depth streams analysis ;
  - Tracking module on rail: to substitute laser distance measure, such that it is possible to input Z^W record frames automatically.
- Software
  - Better DIP techniques ;
  - Higher order polynomial Z^W to $X^W Y^W$ mapping.

Questions?