

# Camera Model and Calibration

# Camera Calibration

- Determine extrinsic and intrinsic parameters of camera
  - Extrinsic
    - 3D location and orientation of camera
  - Intrinsic
    - Focal length
    - The size of the pixels

# Application: Object Transfer

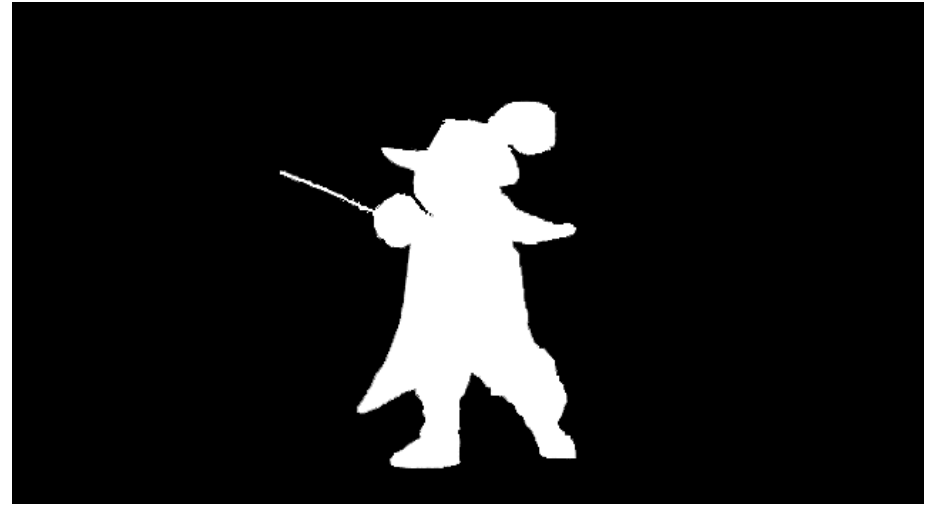


Source Image



Target Image

# More Results



# Pose Estimation

- Given 3D model of object, and its image (2D projection) determine the location and orientation (translation & rotation) of object such that when projected on the image plane it will match with the image.

<http://www.youtube.com/watch?v=ZNHRH00UMvk>

# Transformations

# 3-D Translation

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} + \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix}$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \\ 1 \end{bmatrix} = T \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ 1 \end{bmatrix}$$

$$T = \begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{ Translation Matrix}$$

$$T^{-1} = \begin{bmatrix} 1 & 0 & 0 & -d_x \\ 0 & 1 & 0 & -d_y \\ 0 & 0 & 1 & -d_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$TT^{-1} = T^{-1}T = I$$

$$\begin{bmatrix} 1 & 0 & 0 & d_x \\ 0 & 1 & 0 & d_y \\ 0 & 0 & 1 & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -d_x \\ 0 & 1 & 0 & -d_y \\ 0 & 0 & 1 & -d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_1 \times S_x \\ Y_1 \times S_y \\ Z_1 \times S_z \end{bmatrix}$$

# Scaling

$$S^{-1} = \begin{bmatrix} 1/S_x & 0 & 0 & 0 \\ 0 & 1/S_y & 0 & 0 \\ 0 & 0 & 1/S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$SS^{-1} = S^{-1}S = I$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \\ 1 \end{bmatrix} = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \\ 1 \end{bmatrix} = S \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ 1 \end{bmatrix}$$

$$S = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{Scaling Matrix}$$

$$\begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1/S_x & 0 & 0 & 0 \\ 0 & 1/S_y & 0 & 0 \\ 0 & 0 & 1/S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



$$X = R \cos \phi$$

$$Y = R \sin \phi$$

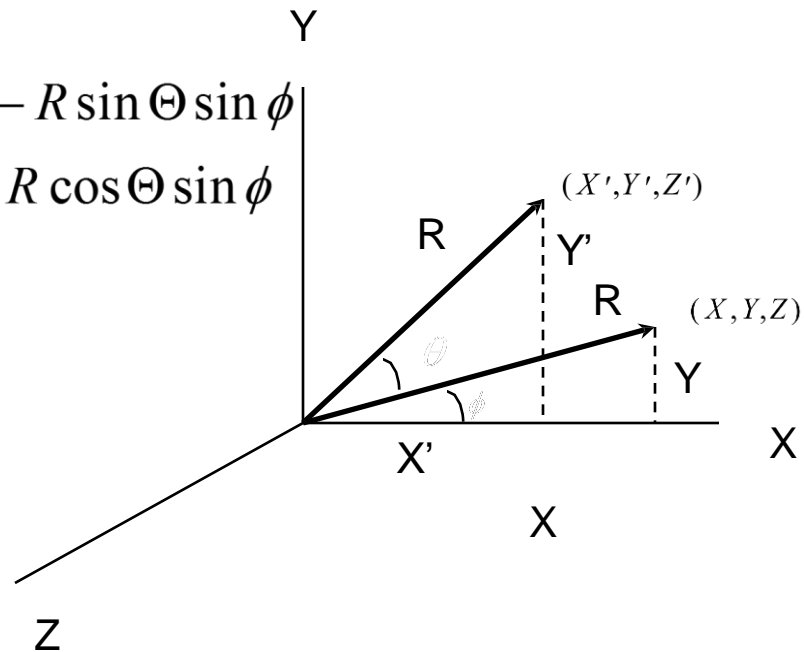
# Rotation

$$X' = R \cos(\Theta + \phi) = R \cos \Theta \cos \phi - R \sin \Theta \sin \phi$$

$$Y' = R \sin(\Theta + \phi) = R \sin \Theta \cos \phi + R \cos \Theta \sin \phi$$

$$X' = X \cos \Theta - Y \sin \Theta$$

$$Y' = X \sin \Theta + Y \cos \Theta$$



$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} \cos \Theta & -\sin \Theta & 0 \\ \sin \Theta & \cos \Theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$(R_\theta^Z)^{-1} = \begin{bmatrix} \cos \Theta & \sin \Theta & 0 \\ -\sin \Theta & \cos \Theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

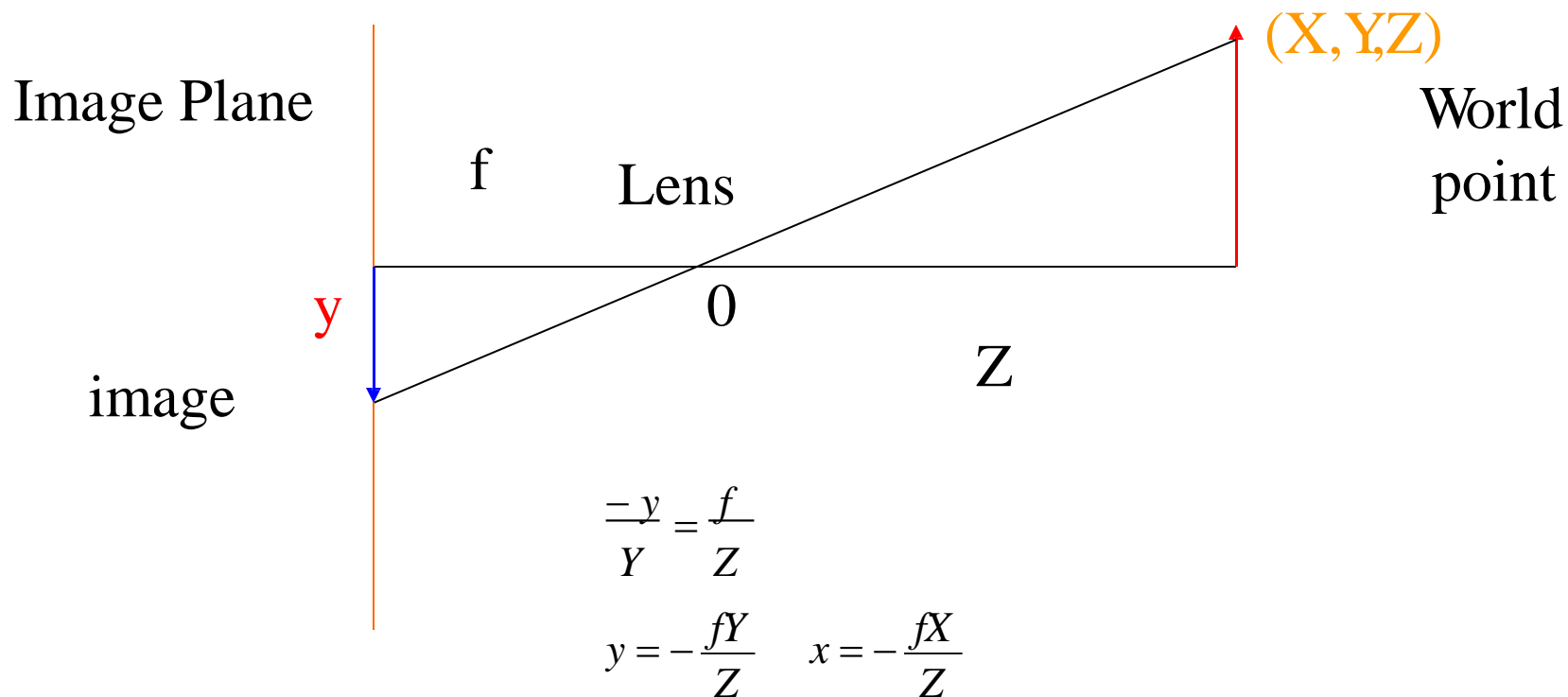
$$\begin{bmatrix} \cos \Theta & \sin \Theta & 0 \\ -\sin \Theta & \cos \Theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \Theta & -\sin \Theta & 0 \\ \sin \Theta & \cos \Theta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$(R_\theta^Z)^{-1} = (R_\theta^Z)^T \quad \text{Rotation matrices are orthonormal matrices}$$

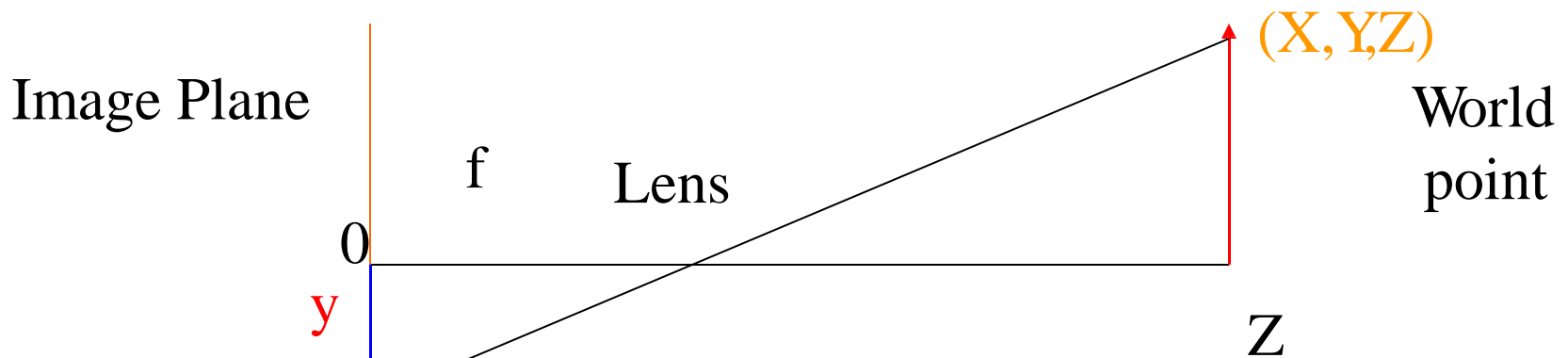
$$(R_\theta^Z)(R_\theta^Z)^T = I$$

$$r_i \cdot r_j = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

## Perspective Projection (origin at the lens center)



# Perspective Projection (origin at image center)



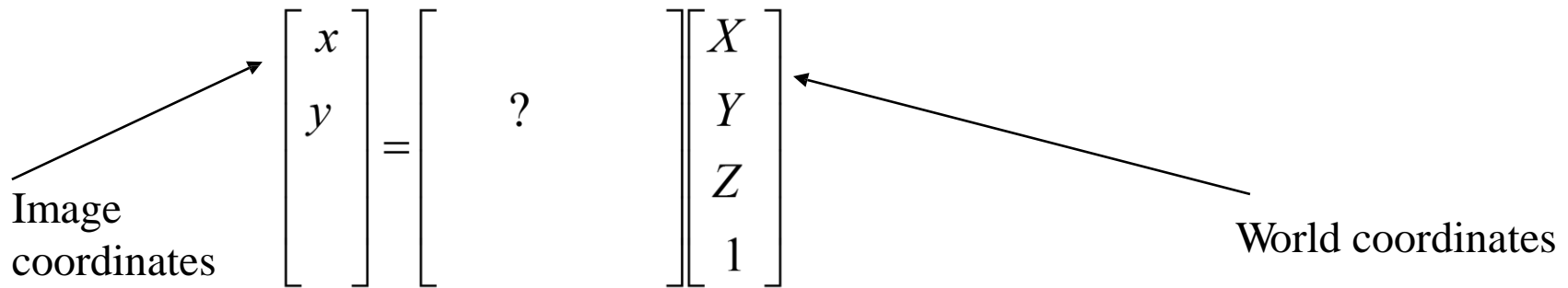
image

$$\frac{-y}{Y} = \frac{f}{Z - f}$$

$$y = -\frac{fY}{Z - f} \quad x = -\frac{fX}{Z - f}$$

$$y = \frac{fY}{f - Z} \quad x = \frac{fX}{f - Z}$$

# Perspective



$(X, Y, Z) \rightarrow \rightarrow \rightarrow (kX, kY, kZ, k)$ , Homogenous transformation

$(C_{h1}, C_{h2}, C_{h3}, C_{h4}) \rightarrow (\frac{C_{h1}}{C_{h4}}, \frac{C_{h2}}{C_{h4}}, \frac{C_{h3}}{C_{h4}})$ , Inverse homogenous

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{-1}{f} & 1 \end{bmatrix}$$

# Perspective

$$\begin{bmatrix} C_{h1} \\ C_{h2} \\ C_{h3} \\ C_{h4} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{-1}{f} & 1 \end{bmatrix} \begin{bmatrix} kX \\ kY \\ kZ \\ k \end{bmatrix}$$

$$x = \frac{C_{h1}}{C_{h4}} = \frac{kX}{k - \frac{kZ}{f}} = \frac{fX}{f - Z}$$

$$y = \frac{C_{h2}}{C_{h4}} = \frac{kY}{k - \frac{kZ}{f}} = \frac{fY}{f - Z}$$

$$\begin{bmatrix} C_{h1} \\ C_{h2} \\ C_{h3} \\ C_{h4} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{-1}{f} & 1 \end{bmatrix} \begin{bmatrix} kX \\ kY \\ kZ \\ k \end{bmatrix} = \begin{bmatrix} kX \\ kY \\ kZ \\ k - \frac{kZ}{f} \end{bmatrix}$$

# Camera Model

- Camera is at the origin of the world coordinates first
- Then translated by some amount(G),
- Then rotated around Z axis in counter clockwise direction,
- Then rotated again around X in counter clockwise direction, and
- Then translated by C.

$$C_h = PCR_{-\phi}^X R_{-\theta}^Z GW_h$$

Since we are moving the camera instead of object we need to use inverse transformations

# Camera Model

$$C_h = PCR_{-\phi}^X R_{-\theta}^Z GW_h$$

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{-1}{f} & 1 \end{bmatrix}, R_{-\theta}^Z = \begin{bmatrix} \cos \theta & \sin \theta & 0 & 0 \\ -\sin \theta & \cos \theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{-\phi}^X = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \phi & \sin \phi & 0 \\ 0 & -\sin \phi & \cos \phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, G = \begin{bmatrix} 1 & 0 & 0 & -X_0 \\ 0 & 1 & 0 & -Y_0 \\ 0 & 0 & 1 & -Z_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & -r_1 \\ 0 & 1 & 0 & -r_2 \\ 0 & 0 & 1 & -r_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



# Camera Model

$$C_h = PCR_{-\phi}^X R_{-\theta}^Z G W_h$$

$$x = f \frac{(X - X_0) \cos \theta + (Y - Y_0) \sin \theta - r_1}{-(X - X_0) \sin \theta \sin \phi + (Y - Y_0) \cos \theta \sin \phi - (Z - Z_0) \cos \phi + r_3 + f}$$
$$y = f \frac{(X - X_0) \sin \theta \cos \phi + (Y - Y_0) \cos \theta \cos \phi + (Z - Z_0) \sin \phi - r_2}{-(X - X_0) \sin \theta \sin \phi + (Y - Y_0) \cos \theta \sin \phi - (Z - Z_0) \cos \phi + r_3 + f}$$

# Camera Model

$$C_h = PCR_{-\phi}^X R_{-\theta}^Z GW_h$$

$$x = \frac{C_{h1}}{C_{h4}}$$

$$y = \frac{C_{h2}}{C_{h4}}$$

$$C_h = AW_h$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_3 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$Ch_1 = a_{11}X + a_{12}Y + a_{13}Z + a_{14} = Ch_4x$$

$$Ch_2 = a_{21}X + a_{22}Y + a_{23}Z + a_{24} = Ch_4y$$

$$Ch_4 = a_{41}X + a_{42}Y + a_{43}Z + a_{44}$$

$Ch_3$  is not needed, we have 12 unknowns.

# Camera Model

- How to determine camera matrix?
- Select some known 3D points  $(X, Y, Z)$ , and find their corresponding image points  $(x, y)$ .
- Solve for camera matrix elements using least squares fit.

# Camera Model

$$C_h = PCR_{-\phi}^X R_{-\theta}^Z GW_h$$

$$x = \frac{C_{h1}}{C_{h4}}$$

$$y = \frac{C_{h2}}{C_{h4}}$$

$$C_h = AW_h$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_3 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$Ch_1 = a_{11}X + a_{12}Y + a_{13}Z + a_{14} = Ch_4x$$

$$Ch_2 = a_{21}X + a_{22}Y + a_{23}Z + a_{24} = Ch_4y$$

$$Ch_4 = a_{41}X + a_{42}Y + a_{43}Z + a_{44}$$

$Ch_3$  is not needed, we have 12 unknowns.

# Camera Model

$$Ch_1 = a_{11}X + a_{12}Y + a_{13}Z + a_{14} = Ch_4x$$

$$Ch_2 = a_{21}X + a_{22}Y + a_{23}Z + a_{24} = Ch_4y$$

$$Ch_4 = a_{41}X + a_{42}Y + a_{43}Z + a_{44}$$

$$a_{11}X + a_{12}Y + a_{13}Z + a_{14} - a_{41}Xx - a_{42}Yx - a_{43}Zx - a_{44}x = 0$$

$$a_{21}X + a_{22}Y + a_{23}Z + a_{24} - a_{41}Xy - a_{42}Yy - a_{43}Zy - a_{44}y = 0$$

# Camera Model

$$a_{11}X + a_{12}Y + a_{13}Z + a_{14} - a_{41}Xx - a_{42}Yx - a_{43}Zx - a_{44}x = 0$$

$$a_{21}X + a_{22}Y + a_{23}Z + a_{24} - a_{41}Xy - a_{42}Yy - a_{43}Zy - a_{44}y = 0 \quad \text{One point}$$

$$a_{11}X_1 + a_{12}Y_1 + a_{13}Z_1 + a_{14} - a_{41}X_1x_1 - a_{42}Y_1x_1 - a_{43}Z_1x_1 - a_{44}x_1 = 0$$

$$a_{11}X_2 + a_{12}Y_2 + a_{13}Z_2 + a_{14} - a_{41}X_2x_2 - a_{42}Y_2x_2 - a_{43}Z_2x_2 - a_{44}x_2 = 0$$

⋮

$$a_{11}X_n + a_{12}Y_n + a_{13}Z_n + a_{14} - a_{41}X_nx_n - a_{42}Y_nx_n - a_{43}Z_nx_n - a_{44}x_n = 0$$

n points

$$a_{21}X_1 + a_{22}Y_1 + a_{23}Z_1 + a_{24} - a_{41}X_1y_1 - a_{42}Y_1y_1 - a_{43}Z_1y_1 - a_{44}y_1 = 0$$

2n equations,  
12 unknowns

$$a_{21}X_2 + a_{22}Y_2 + a_{23}Z_2 + a_{24} - a_{41}X_2y_2 - a_{42}Y_2y_2 - a_{43}Z_2y_2 - a_{44}y_2 = 0$$

⋮

$$a_{21}X_n + a_{22}Y_n + a_{23}Z_n + a_{24} - a_{41}X_ny_n - a_{42}Y_ny_n - a_{43}Z_ny_n - a_{44}y_n = 0$$

# Camera Model

$$\begin{bmatrix}
 X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -x_1X_1 & -x_1Y_1 & -x_1Z_1 & -x_1 \\
 X_2 & Y_2 & Z_2 & 1 & 0 & 0 & 0 & 0 & -x_2X_2 & -x_2Y_2 & -x_2Z_2 & -x_2 \\
 & & & & & & \vdots & & & & & \\
 X_n & Y_n & Z_n & 1 & 0 & 0 & 0 & 0 & -x_nX_n & -x_nY_n & -x_nZ_n & -x_n \\
 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -y_1X_1 & -y_1Y_1 & -y_1Z_1 & -y_1 \\
 0 & 0 & 0 & 0 & X_2 & Y_2 & Z_2 & 1 & -y_2X_2 & -y_2Y_2 & -y_2Z_2 & -y_2 \\
 & & & & & & \vdots & & & & & \\
 0 & 0 & 0 & 0 & X_n & Y_n & Z_n & 1 & -y_nX_n & -y_nY_n & -y_nZ_n & -y_n
 \end{bmatrix}
 \begin{bmatrix}
 a_{11} \\
 a_{12} \\
 a_{13} \\
 a_{14} \\
 a_{21} \\
 a_{22} \\
 a_{23} \\
 a_{24} \\
 a_{41} \\
 a_{42} \\
 a_{43} \\
 a_{44}
 \end{bmatrix}
 =
 \begin{bmatrix}
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0 \\
 0
 \end{bmatrix}$$

This is a homogenous system, no unique solution

$$CP = 0$$

Select  $a_{44} = 1$

# Camera Model

$$\begin{bmatrix}
 X_1 & Y_1 & Z_1 & 1 & 0 & 0 & 0 & 0 & -x_1 X_1 & -x_1 Y_1 & -x_1 Z_1 \\
 X_2 & Y_2 & Z_2 & 1 & 0 & 0 & 0 & 0 & -x_2 X_2 & -x_2 Y_2 & -x_2 Z_2 \\
 & & & & & & \vdots & & & & \\
 X_n & Y_n & Z_n & 1 & 0 & 0 & 0 & 0 & -x_n X_n & -x_n Y_n & -x_n Z_n \\
 0 & 0 & 0 & 0 & X_1 & Y_1 & Z_1 & 1 & -y_1 X_1 & -y_1 Y_1 & -y_1 Z_1 \\
 0 & 0 & 0 & 0 & X_2 & Y_2 & Z_2 & 1 & -y_2 X_2 & -y_2 Y_2 & -y_2 Z_2 \\
 & & & & & & \vdots & & & & \\
 0 & 0 & 0 & 0 & X_n & Y_n & Z_n & 1 & -y_n X_n & -y_n Y_n & -y_n Z_n
 \end{bmatrix}
 \begin{bmatrix}
 a_{11} \\
 a_{12} \\
 a_{13} \\
 a_{14} \\
 a_{21} \\
 a_{22} \\
 a_{23} \\
 a_{24} \\
 a_{41} \\
 a_{42} \\
 a_{43}
 \end{bmatrix}
 =
 \begin{bmatrix}
 x_1 \\
 x_2 \\
 \\
 \\
 x_n \\
 y_1 \\
 y_2 \\
 \\
 \\
 y_n
 \end{bmatrix}$$

Pseudo inverse  
Least squares fit

$$DQ = R$$

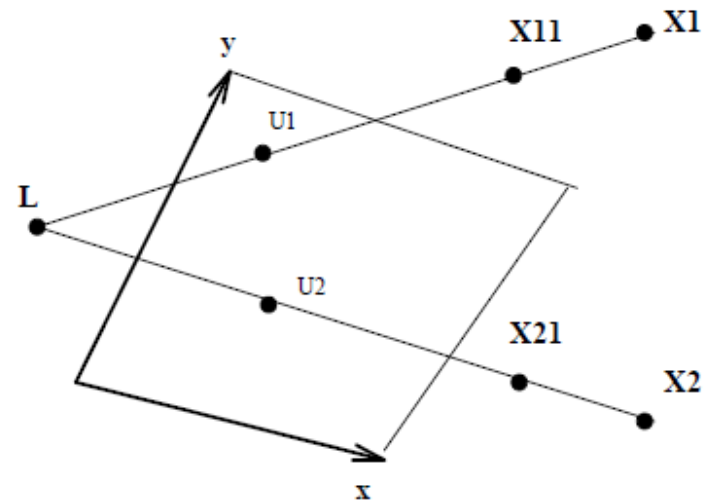
$$D^T DQ = D^T R$$

$$Q = (D^T D)^{-1} D^T R$$



# Finding Camera Location

- Take one 3D point  $X_1$  and find its image homogenous coordinates.
- Set the third component of homogenous coordinates to zero, find corresponding World coordinates of that point,  $X_{11}$
- Connect  $X_1$  and  $X_{11}$  to get a line in 3D.
- Repeat this for another 3D point  $X_2$  and find another line
- Two lines will intersect at the location of camera.



# Camera Location

$$C_h = AW_h$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_3 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$U_1 = AX_1$$

$$U_1' = (Ch_1 \quad Ch_2 \quad 0 \quad Ch_4)$$

$$X_{11} = A^{-1}U_1'$$

$$U_2 = AX_2$$

$$U_2' = (Ch_1 \quad Ch_2 \quad 0 \quad Ch_4)$$

$$X_{22} = A^{-1}U_2'$$

# Camera Orientation

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_3 \\ Ch_4 \end{bmatrix} = A \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

• Only time the image will be formed at infinity if  $Ch_4=0$ .

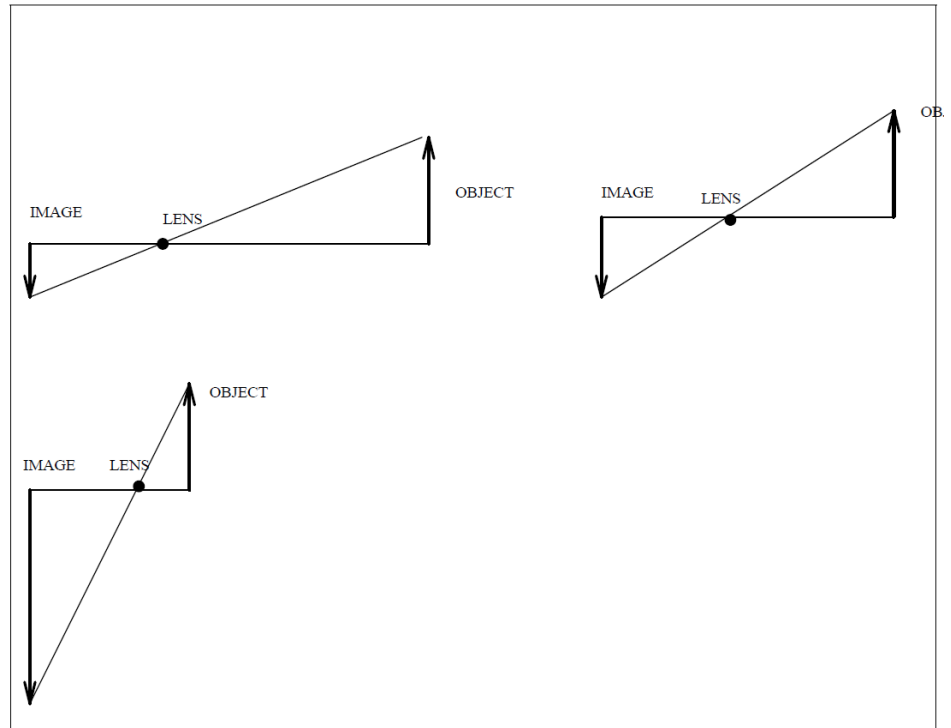
$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_3 \\ 0 \end{bmatrix} = A \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$a_{41}X + a_{42}Y + a_{43}Z + a_{44} = 0$$

This is equation of a plane, going through the lens, which is parallel to image plane.

$$x = \frac{C_{h1}}{C_{h4}}$$

$$y = \frac{C_{h2}}{C_{h4}}$$



# Application

$$M = \begin{bmatrix} .17237 & -.15879 & .01879 & 274.943 \\ .131132 & .112747 & .2914 & 258.686 \\ .000346 & .0003 & .00006 & 1 \end{bmatrix}$$

Camera location: intersection of California and Mason streets, at an elevation of 435 feet above sea level. The camera was oriented at an angle of  $8^\circ$  above the horizon.  $fs_x=495$ ,  $fs_y=560$ .

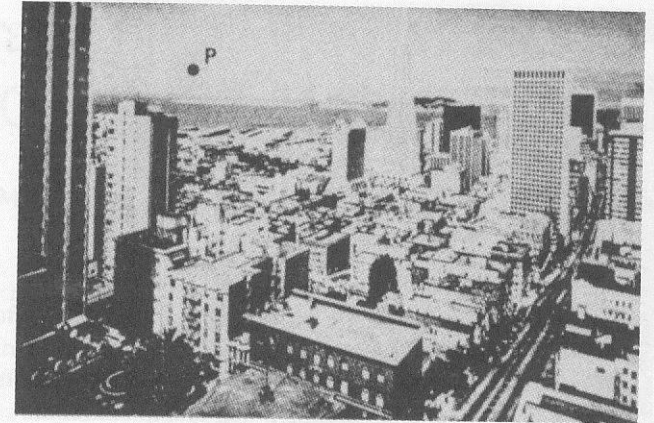


FIGURE 8 PHOTOGRAPH OF SAN FRANCISCO

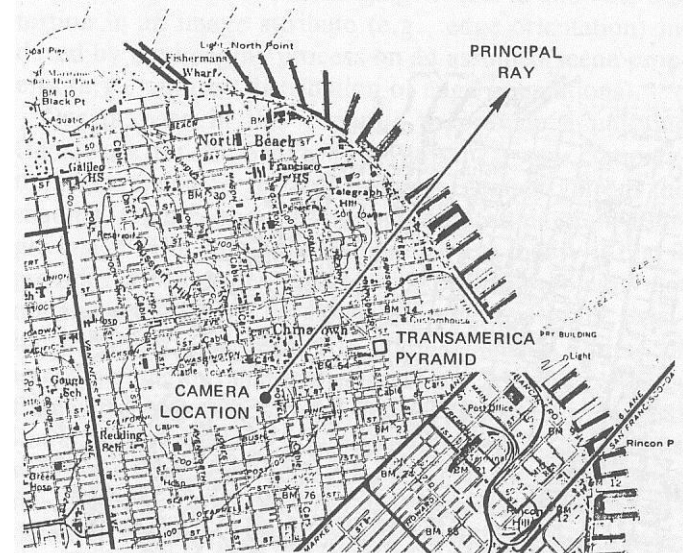


FIGURE 9 MAP OF SAN FRANCISCO

# Application

$$M = \begin{bmatrix} -.175451 & -.10520 & .00435 & 297.83 \\ .02698 & -.09635 & .2303 & 249.574 \\ .00015 & -.00016 & .00001 & 1.0 \end{bmatrix}$$

Camera location: at an elevation of 1200 feet above sea level. The camera was oriented at an angle of  $4^\circ$  above the horizon.  $fs_x=876$ ,  $fs_y=999$ .

**Recovering the camera parameters from a transformation matrix**

TM Strat - Readings in Computer Vision, 1987

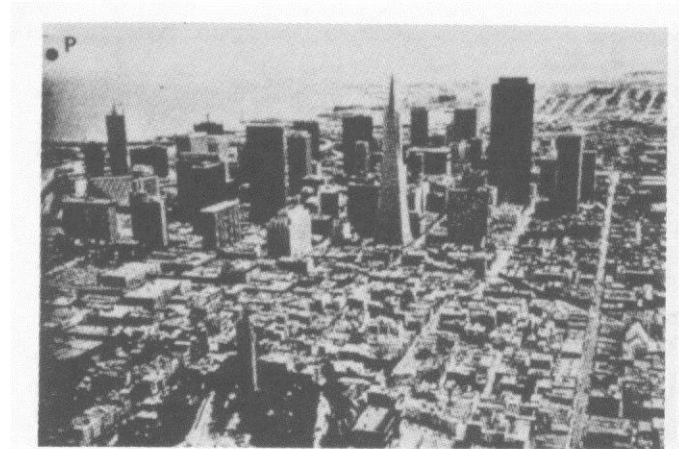


FIGURE 10 ANOTHER PHOTOGRAPH OF SAN FRANCISCO

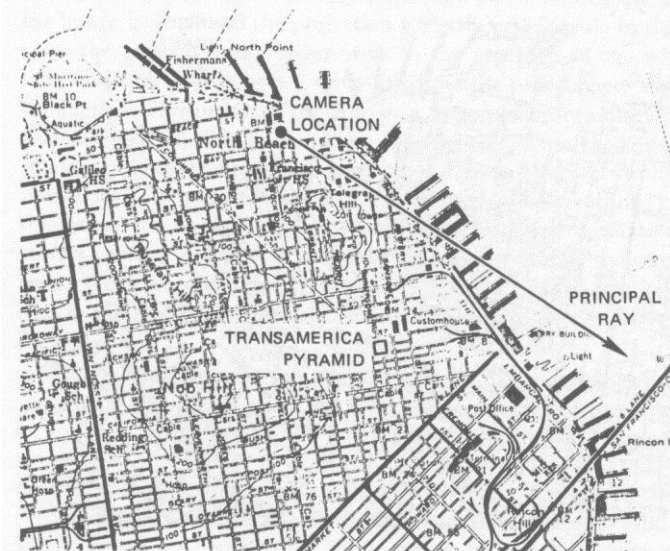


FIGURE 11 MAP OF SAN FRANCISCO

# Camera Parameters

- Extrinsic parameters
  - Parameters that define the location and orientation of the camera reference frame with respect to a known world reference frame
    - 3-D translation vector
    - A 3 by 3 rotation matrix
- Intrinsic parameters
  - Parameters necessary to link the pixel coordinates of an image point with the corresponding coordinates in the camera reference frame
    - Perspective projection (focal length)
    - Transformation between camera frame coordinates and pixel coordinates

# Camera Model Revisited: Rotation & Translation

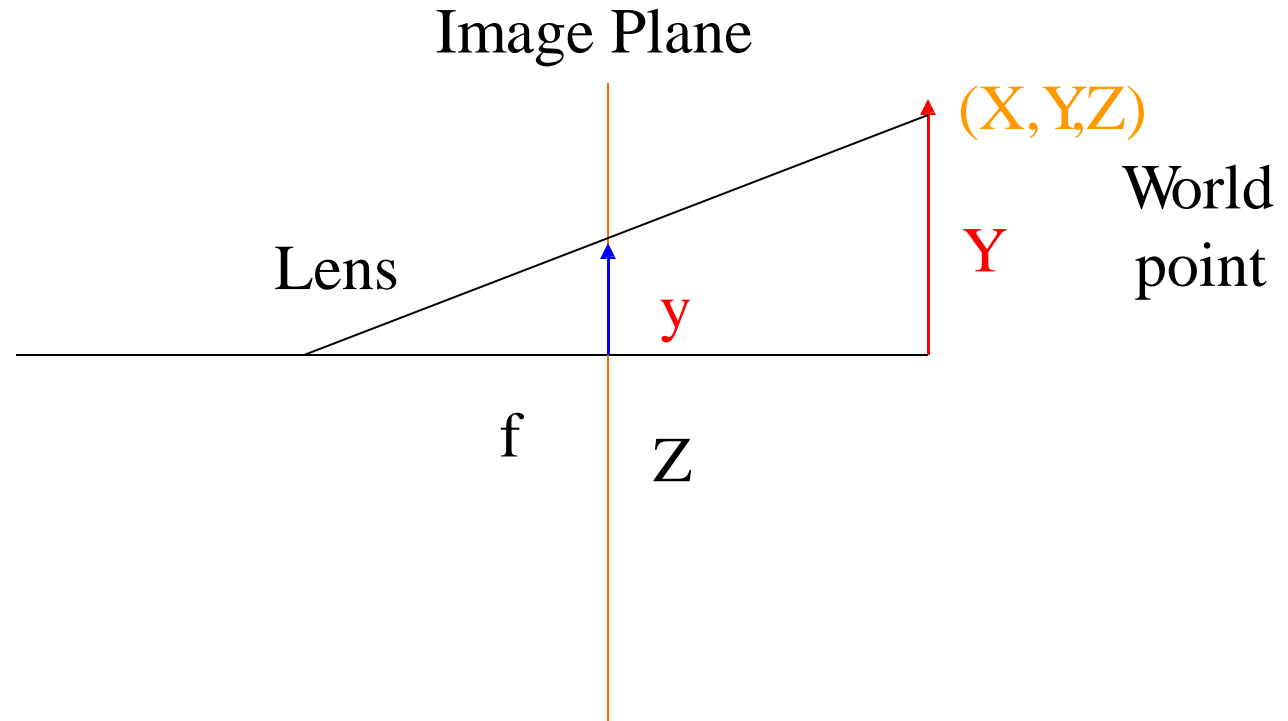
$$P_c = TRP_w = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & 0 \\ r_{21} & r_{22} & r_{23} & 0 \\ r_{31} & r_{32} & r_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$P_c = \begin{bmatrix} r_{11} & r_{12} & r_{13} & T_x \\ r_{21} & r_{22} & r_{23} & T_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$P_c = M_{ext} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$



# Perspective Projection: Revisited



$$\frac{y}{Y} = \frac{f}{Z}$$

$$y = \frac{fY}{Z} \quad x = \frac{fX}{Z}$$

Origin at the lens

Image plane in front of the lens



# Camera Model Revisited: Perspective

$$C_h = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$x = \frac{fX}{Z}$$

$$y = \frac{fY}{Z}$$

Origin at the lens

Image plane in front of the lens

# Camera Model Revisited: Image and Camera coordinates

$$x = -(x_{im} - o_x)s_x$$

$$y = -(y_{im} - o_y)s_y$$

$$x_{im} = -\frac{x}{s_x} + o_x$$

$$y_{im} = -\frac{y}{s_y} + o_y$$

$(x_{im}, y_{im})$  image coordinates

$(x, y)$  camera coordinates

$(o_x, o_y)$  image center (in pixels)

$(s_x, s_y)$  effective size of pixels (in millimeters) in the horizontal and vertical directions.

$$\begin{bmatrix} x_{im} \\ y_{im} \\ 1 \end{bmatrix} = \begin{bmatrix} -\frac{1}{s_x} & 0 & o_x \\ 0 & -\frac{1}{s_y} & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

# Camera Model Revisited

$$C_h = C'P'T'R'W_h$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} -\frac{1}{s_x} & 0 & o_x \\ 0 & -\frac{1}{s_y} & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & T_x \\ r_{21} & r_{22} & r_{23} & T_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} -\frac{f}{s_x} & 0 & o_x \\ 0 & -\frac{f}{s_y} & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & T_x \\ r_{21} & r_{22} & r_{23} & T_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = M_{\text{int}} M_{\text{ext}} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = M \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

# Camera Model Revisited

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} -\frac{f}{s_x} & 0 & o_x \\ 0 & -\frac{f}{s_y} & o_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & T_x \\ r_{21} & r_{22} & r_{23} & T_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} -\frac{f}{s_x}r_{11} + r_{31}o_x & -\frac{f}{s_x}r_{12} + r_{32}o_x & -\frac{f}{s_x}r_{13} + r_{33}o_x & -\frac{f}{s_x}T_x + T_zo_x \\ -\frac{f}{s_y}r_{21} + r_{31}o_y & -\frac{f}{s_y}r_{22} + r_{32}o_y & -\frac{f}{s_y}r_{23} + r_{33}o_y & -\frac{f}{s_y}T_y + T_zo_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

# Camera Model Revisited

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} -\frac{f}{s_x}r_{11} + r_{31}o_x & -\frac{f}{s_x}r_{12} + r_{32}o_x & -\frac{f}{s_x}r_{13} + r_{33}o_x & -\frac{f}{s_x}T_x + T_z o_x \\ -\frac{f}{s_y}r_{21} + r_{31}o_y & -\frac{f}{s_y}r_{22} + r_{32}o_y & -\frac{f}{s_y}r_{23} + r_{33}o_y & -\frac{f}{s_y}T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$f_x$  effective focal length expressed in  
effective horizontal pixel size

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = \begin{bmatrix} -f_x r_{11} + r_{31}o_x & -f_x r_{12} + r_{32}o_x & -f_x r_{13} + r_{33}o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31}o_y & -f_y r_{22} + r_{32}o_y & -f_y r_{23} + r_{33}o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} Ch_1 \\ Ch_2 \\ Ch_4 \end{bmatrix} = M \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

# Computing Camera Parameters

- Using known 3-D points and corresponding image points, estimate camera matrix employing pseudo inverse method of section 1.6 (Fundamental of Computer Vision).
- Compute camera parameters by relating camera matrix with estimated camera matrix.
  - Extrinsic
    - Translation
    - Rotation
  - Intrinsic
    - Horizontal  $f_x$  and  $f_y$  vertical focal lengths
    - Translation  $o_x$  and  $o_y$

# Comparison

$$\hat{M} = \begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix}$$

$$M = \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

# Computing Camera Parameters

estimated

$$\hat{M} = \gamma M$$

Since  $M$  is defined up to a scale factor

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

Because rotation matrix  
is orthonormal

$$\sqrt{\hat{m}_{31}^2 + \hat{m}_{32}^2 + \hat{m}_{33}^2} = |\gamma| \sqrt{r_{31}^2 + r_{32}^2 + r_{33}^2} = |\gamma|$$

Divide each entry of  $\hat{M}$  by  $|\gamma|$ .



# Computing Camera Parameters

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

- Compute  $T_z$  and third row  $r_{3i}$  ( $i=1,2,3$ )
- Compute  $o_x$  and  $o_y$
- Compute  $f_x$  and  $f_y$
- Compute  $r_{1i}$  and  $r_{2i}$   $i=1,2,3$
- Computer  $T_x$  and  $T_y$

# Computing Camera Parameters: estimating third row of rotation matrix and translation in depth

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

$$T_z = \sigma \hat{m}_{34}, \quad \sigma = \pm 1$$

$$r_{3i} = \sigma \hat{m}_{3i}, \quad i = 1, 2, 3$$

Since we can determine  $T_z > 0$  (*origin of world reference is in front*)

Or  $T_z < 0$  (*origin of world reference is in back*)  
we can determine sign.

# Computing Camera Parameters

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

Let

$$q_1 = [\hat{m}_{11} \quad \hat{m}_{12} \quad \hat{m}_{13}]$$

$$q_2 = [\hat{m}_{21} \quad \hat{m}_{22} \quad \hat{m}_{23}]$$

$$q_3 = [\hat{m}_{31} \quad \hat{m}_{32} \quad \hat{m}_{33}]$$

# Computing Camera Parameters: origin of image

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

$$q_1^T q_3 = \hat{m}_{11} \hat{m}_{31} + \hat{m}_{12} \hat{m}_{32} + \hat{m}_{13} \hat{m}_{33}$$

$$\begin{aligned} \hat{m}_{11} \hat{m}_{31} + \hat{m}_{12} \hat{m}_{32} + \hat{m}_{13} \hat{m}_{33} &= \begin{pmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x \end{pmatrix} \begin{pmatrix} r_{31} & r_{32} & r_{33} \end{pmatrix} \\ &= \begin{pmatrix} -f_x r_{11} & -f_x r_{12} & -f_x r_{13} \end{pmatrix} \begin{pmatrix} r_{31} & r_{32} & r_{33} \end{pmatrix} + \\ &\quad \begin{pmatrix} r_{31} o_x & r_{32} o_x & r_{33} o_x \end{pmatrix} \begin{pmatrix} r_{31} & r_{32} & r_{33} \end{pmatrix} \\ &= \begin{pmatrix} r_{31} o_x & r_{32} o_x & r_{33} o_x \end{pmatrix} \begin{pmatrix} r_{31} & r_{32} & r_{33} \end{pmatrix} \\ &= (r_{31}^2 o_x + r_{32}^2 o_x + r_{33}^2 o_x) \\ &= o_x (r_{31}^2 + r_{32}^2 + r_{33}^2) \\ &= o_x \end{aligned}$$

$$q_1^T q_3$$

Therefore:  $o_x = q_1^T q_3$

$$o_y = q_2^T q_3$$

# Computing Camera Parameters: vertical and horizontal focal lengths

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

$$q_1^T q_1 = \hat{m}_{11} \hat{m}_{11} + \hat{m}_{12} \hat{m}_{12} + \hat{m}_{13} \hat{m}_{13}$$

$$\hat{m}_{11} \hat{m}_{11} + \hat{m}_{12} \hat{m}_{12} + \hat{m}_{13} \hat{m}_{13} =$$

$$(-f_x r_{11} + r_{31} o_x \quad -f_x r_{12} + r_{32} o_x \quad -f_x r_{13} + r_{33} o_x)(-f_x r_{11} + r_{31} o_x \quad -f_x r_{12} + r_{32} o_x \quad -f_x r_{13} + r_{33} o_x)$$

$$= (-f_x r_{11} + r_{31} o_x)^2 + (-f_x r_{12} + r_{32} o_x)^2 + (-f_x r_{13} + r_{33} o_x)^2$$

$$= (f_x^2 r_{11}^2 + r_{31}^2 o_x^2) + (f_x^2 r_{12}^2 + r_{32}^2 o_x^2) + (f_x^2 r_{13}^2 + r_{33}^2 o_x^2)$$

$$= f_x^2 + o_x^2$$

$$q_1^T q_1$$

$$\sqrt{q_1^T q_1 - o_x^2}$$

$$= f_x$$

$$f_x = \sqrt{q_1^T q_1 - o_x^2}$$

Therefore:

$$f_y = \sqrt{q_2^T q_2 - o_y^2}$$

# Computing Camera Parameters: remaining rotation and translation parameters

$$\begin{bmatrix} \hat{m}_{11} & \hat{m}_{12} & \hat{m}_{13} & \hat{m}_{14} \\ \hat{m}_{21} & \hat{m}_{22} & \hat{m}_{23} & \hat{m}_{24} \\ \hat{m}_{31} & \hat{m}_{32} & \hat{m}_{33} & \hat{m}_{34} \end{bmatrix} = \gamma \begin{bmatrix} -f_x r_{11} + r_{31} o_x & -f_x r_{12} + r_{32} o_x & -f_x r_{13} + r_{33} o_x & -f_x T_x + T_z o_x \\ -f_y r_{21} + r_{31} o_y & -f_y r_{22} + r_{32} o_y & -f_y r_{23} + r_{33} o_y & -f_y T_y + T_z o_y \\ r_{31} & r_{32} & r_{33} & T_z \end{bmatrix}$$

$$0_x r_{31} + f_x r_{11} - r_{31} 0_x = \sigma(0_x \hat{m}_{31} - \hat{m}_{11}),$$

$$r_{11} = \sigma(0_x \hat{m}_{31} - \hat{m}_{11}) / f_x,$$

$$r_{1i} = \sigma(0_x \hat{m}_{3i} - \hat{m}_{1i}) / f_x, \quad i = 1, 2, 3$$

$$r_{2i} = \sigma(0_y \hat{m}_{3i} - \hat{m}_{2i}) / f_y, \quad i = 1, 2, 3$$

$$T_x = \sigma(0_x \hat{m}_{34} - \hat{m}_{14}) / f_x$$

$$T_y = \sigma(0_y \hat{m}_{34} - \hat{m}_{24}) / f_y$$