Machine Vision

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March 2019

EE6222: Machine Vision

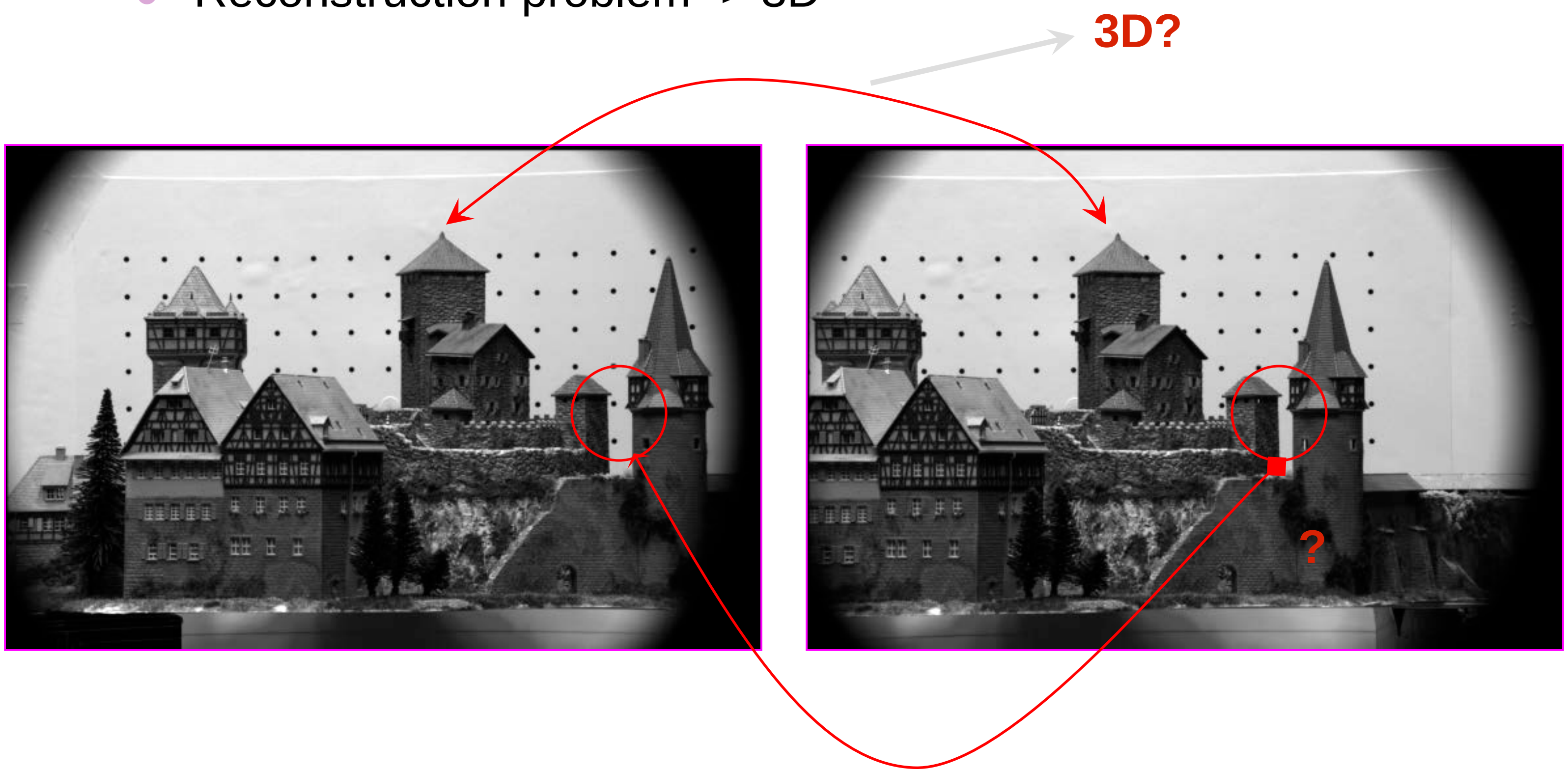
1. Stereo Vision

- Problem
  - Infer 3D structure of a scene from two or more images taken from different viewpoints

- Two primary Sub-problems
  - Correspondence problem (stereo match) -> disparity map
    - Similarity instead of identity
    - Occlusion problem: some parts of the scene are visible only in one eye
  - Reconstruction problem -> 3D
    - What we need to know about the cameras' parameters
    - Often a stereo calibration problem
- Lectures on Stereo Vision
  - Stereo Geometry – Epipolar Geometry (*)
  - Correspondence Problem (*) – Two classes of approaches
  - 3D Reconstruction Problems – Three approaches

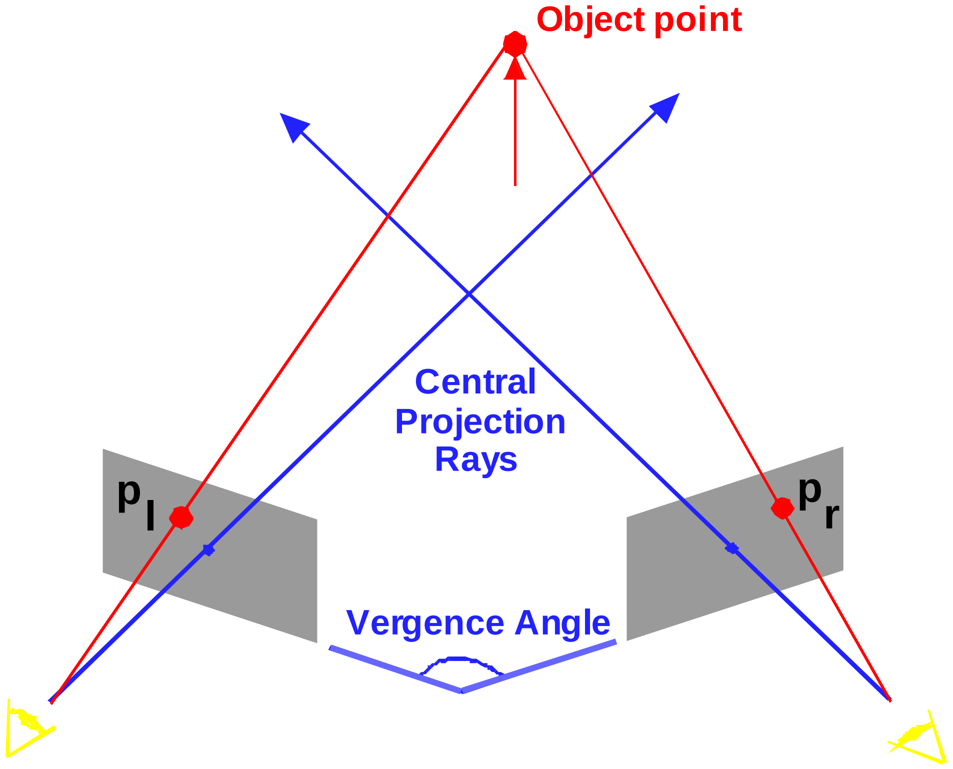
A Stereo Pair

- Problems
  - Correspondence problem (stereo match) -> disparity map
  - Reconstruction problem -> 3D



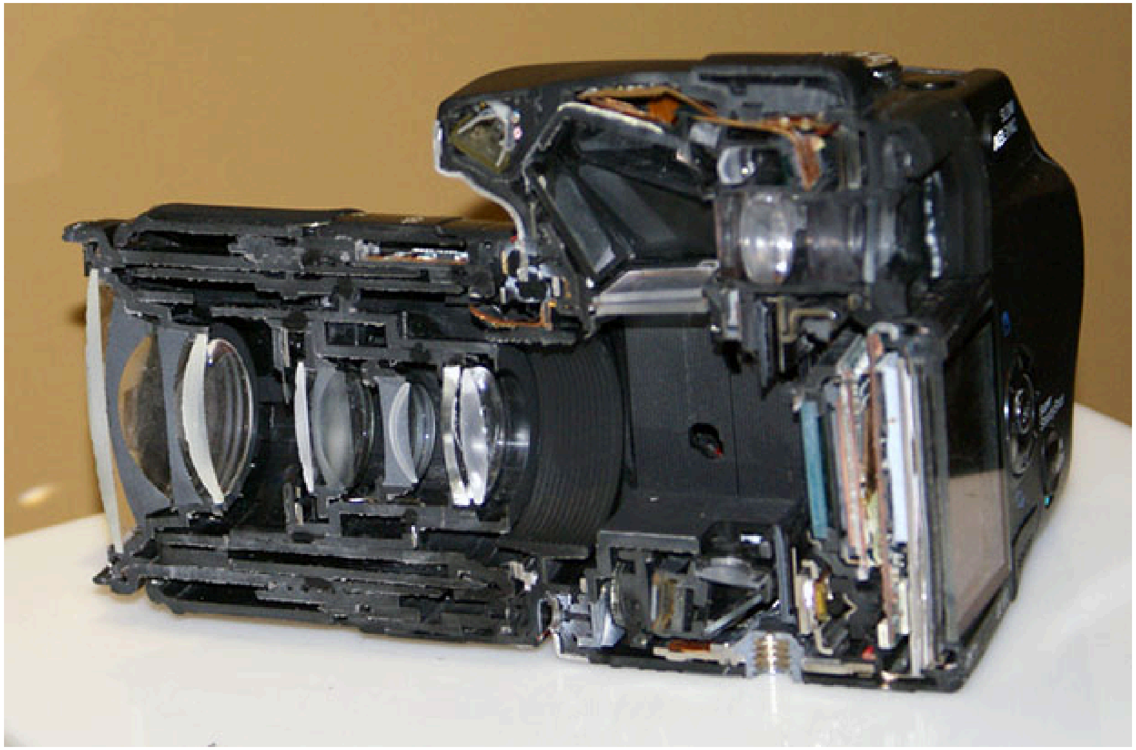
CMU CIL Stereo Dataset : Castle sequence
http://www-2.cs.cmu.edu/afs/cs/project/cil/ftp/html/cil-ster.html

Stereo Geometry

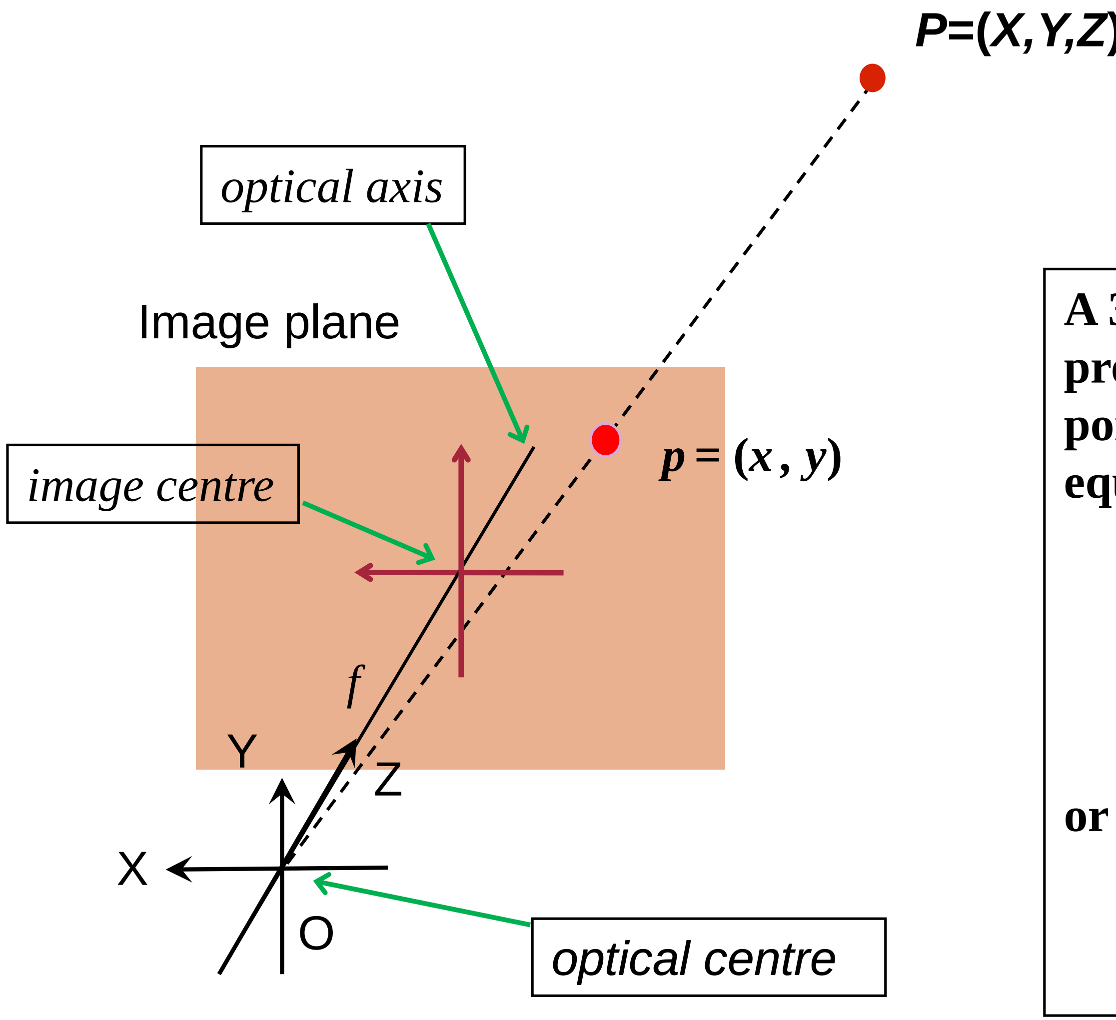


- Converging Axes – Usual setup of human eyes
- Depth obtained by triangulation
- Correspondence problem: p_l and p_r correspond to the left and right projections of P, respectively.

Modern Camera Anatomy



The Pinhole Camera



A 3D point *P* is projected on the image point *p*. The projection equation is

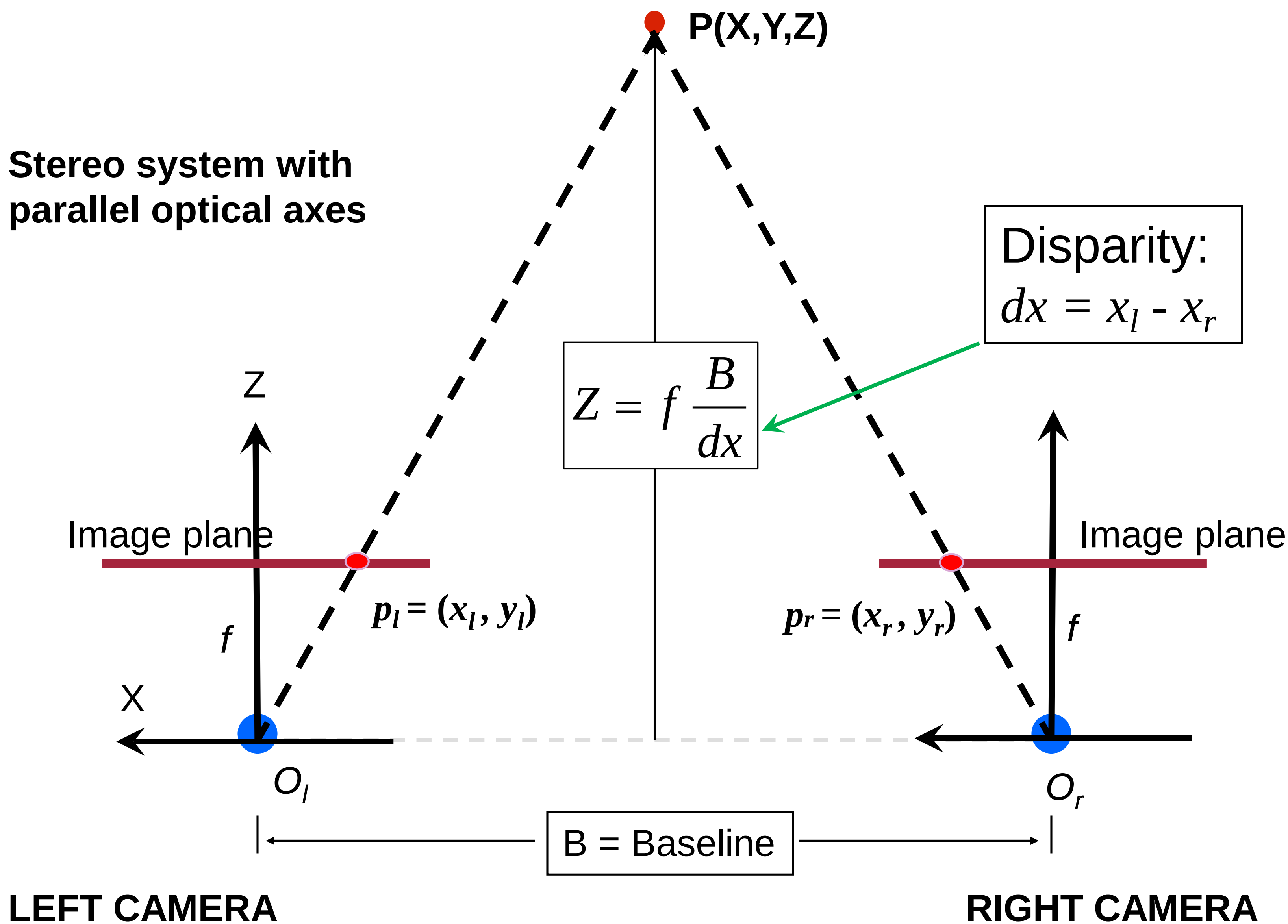
$$x = \frac{f}{Z} X$$

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

or

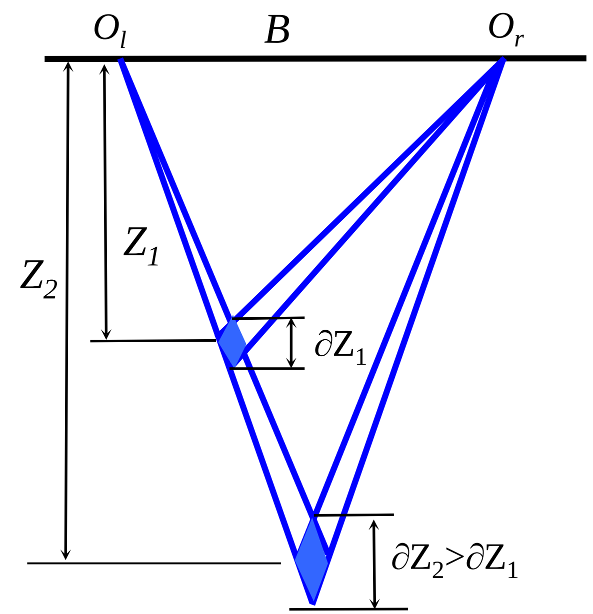
$$\begin{pmatrix} x \\ y \\ f \end{pmatrix} = \frac{f}{Z} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

Disparity Equation



Depth Accuracy

- Given the same image localization error
  - Angle of cones in the figure
- Depth Accuracy (Depth Resolution) vs. Baseline
  - Depth Error $\propto$ 1/B (Baseline length)
  - PROS of Longer baseline,
    - better depth estimation
  - CONS
    - smaller common FOV
    - Correspondence harder due to occlusion
- Depth Accuracy (Depth Resolution) vs. Depth
  - Disparity (>0) $\propto$ 1/ Depth
  - Depth Error $\propto$ Depth^2
  - Nearer the point, better the depth estimation



Absolute error

$$\partial Z = \frac{Z^2}{fB}\partial(dx)$$

Relative error

$$\frac{\partial Z}{Z} = \frac{Z}{fB}\partial(dx)$$

Depth Accuracy (USV example)

- For the ST Electronics project, we have obtained the following parameters.
- Z = 500m
- B = 3m
- f = 2700 pixel (obtained from calibration)
- We set $\partial(dx) = 1$ pixel
- The absolute error

$$\partial Z = \frac{Z^2}{fB}\partial(dx) = 30m$$

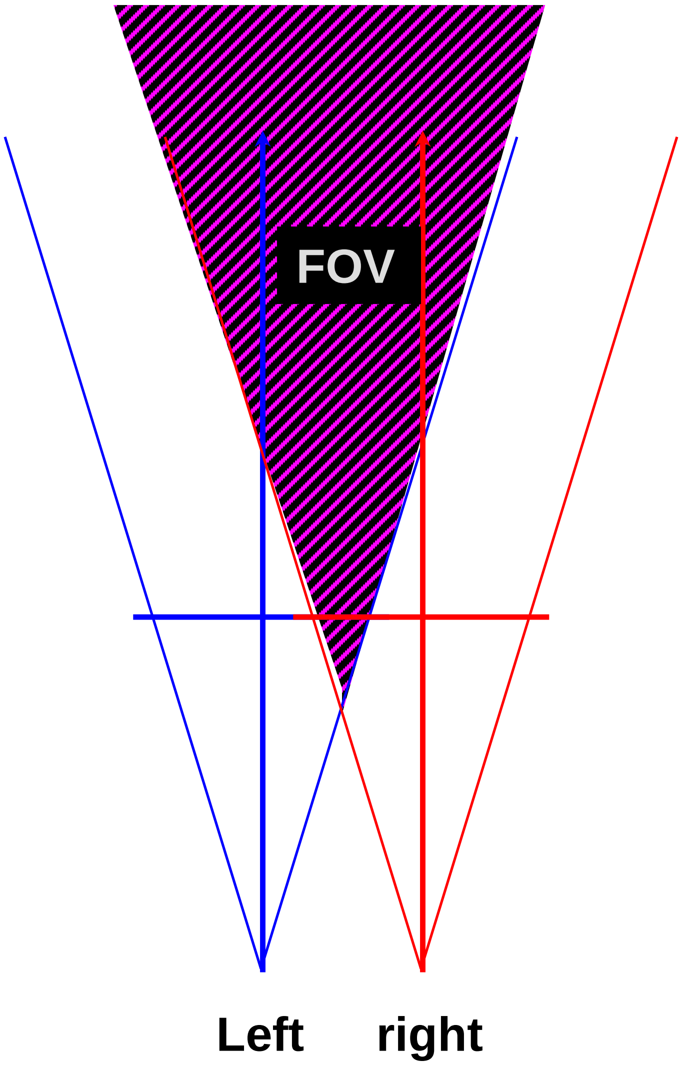
- If we can obtain sub-pixel accuracy, for example, $\partial(dx) = 0.25$ pixel, then, the error is reduced to

$$\partial Z = \frac{Z^2}{fB}\partial(dx) = 7.5m$$

Stereo with Parallel Cameras

- Stereo with Parallel Axes
  - Short baseline
    - large common FOV (Field of View)
    - large depth error
  - Long baseline
    - small depth error
    - small common FOV
    - More occlusion problems

- Two optical axes intersect at the Fixation Point
  - converging angle θ
  - The common FOV Increases



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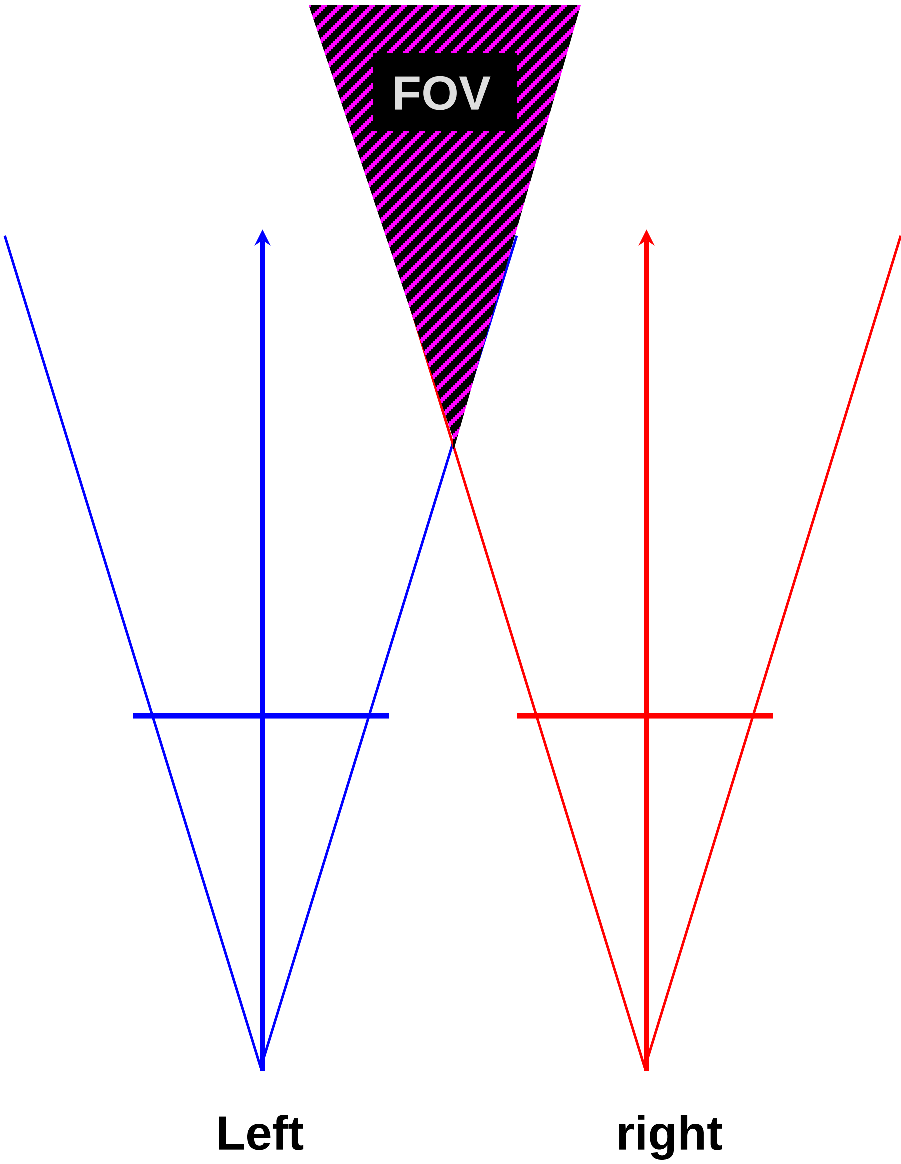
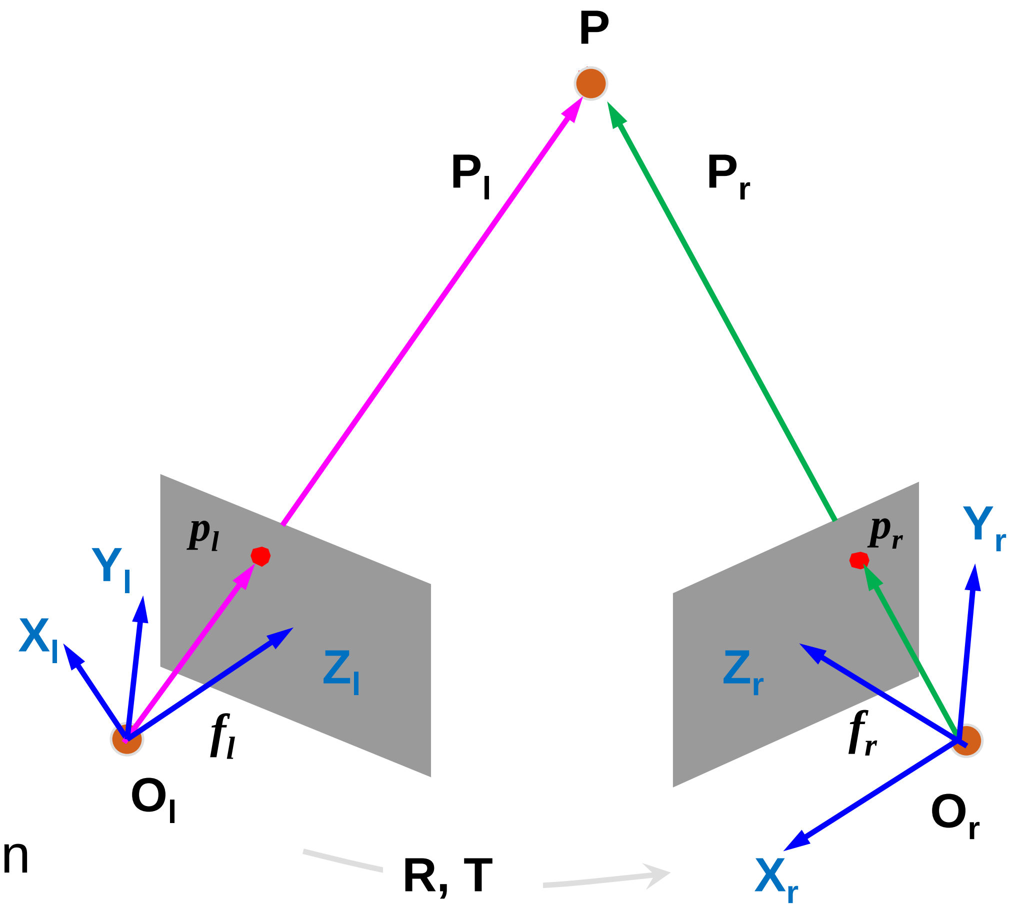


Parameters of a Stereo System

- Intrinsic Parameters
  Characterize the transformation from camera to pixel coordinate systems of each camera:
  - focal length,
  - image center,
  - aspect ratio,
  - distortion
- Extrinsic parameters
  Describe the relative position and orientation of the two cameras:
  - Rotation matrix R
  - translation vector T



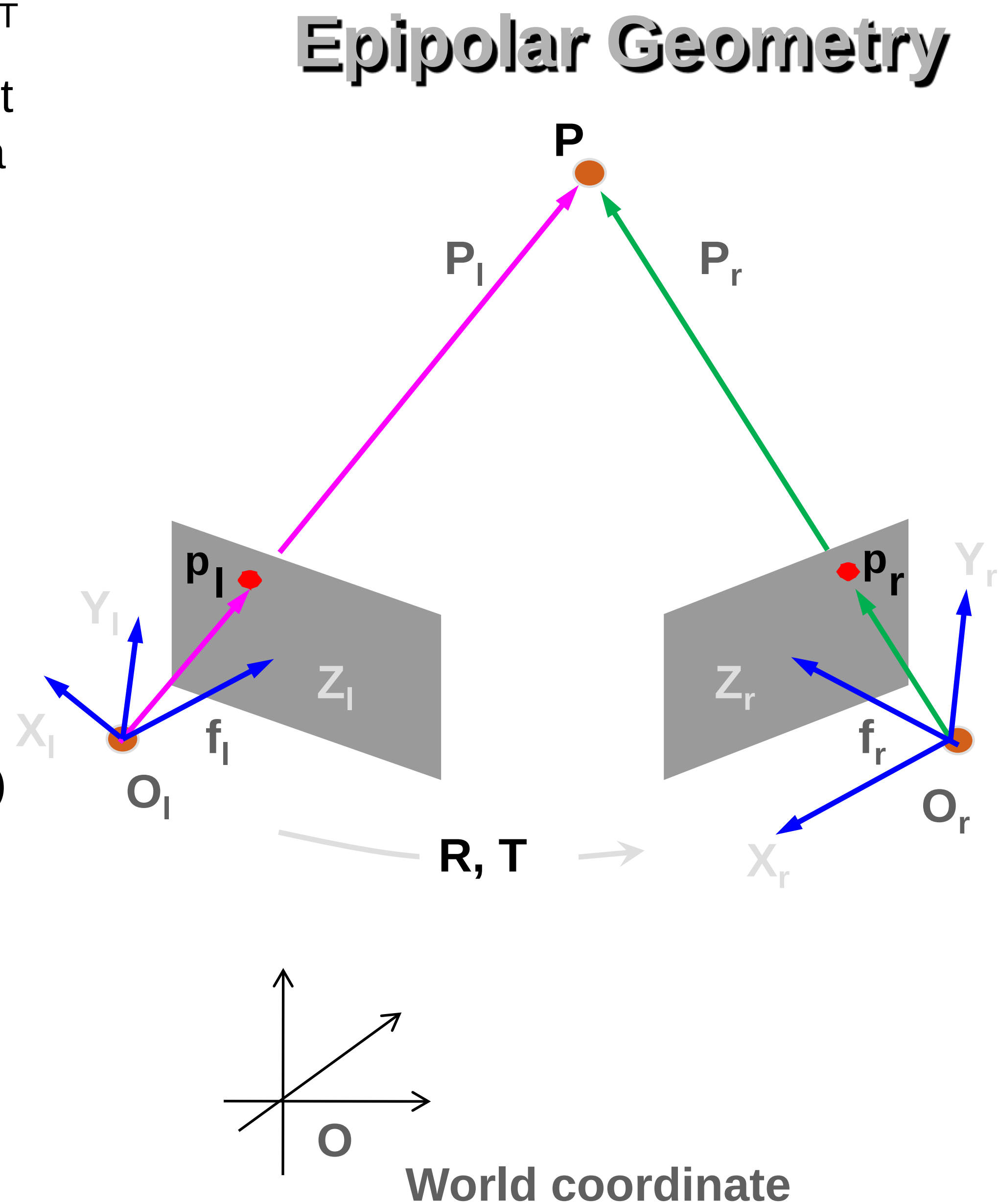
- Notations
  - $\boldsymbol{P}_l = (X_l, Y_l, Z_l)^T$, $\boldsymbol{P}_r = (X_r, Y_r, Z_r)^T$
    - Vectors of the same 3-D point P, in the left and right camera coordinate systems respectively
  - Projection Equation

$$\mathbf{p}_l = \frac{f_l}{Z_l}\mathbf{P_l} \qquad \mathbf{p}_r = \frac{f_r}{Z_r}\mathbf{P}_r$$

  - $p_l = (x_l, y_l, f_l)$, $p_r = (x_r, y_r, f_r)$
  - Extrinsic Parameters
    - Translation Vector $T = (O_r - O_l)$
    - Rotation Matrix R and

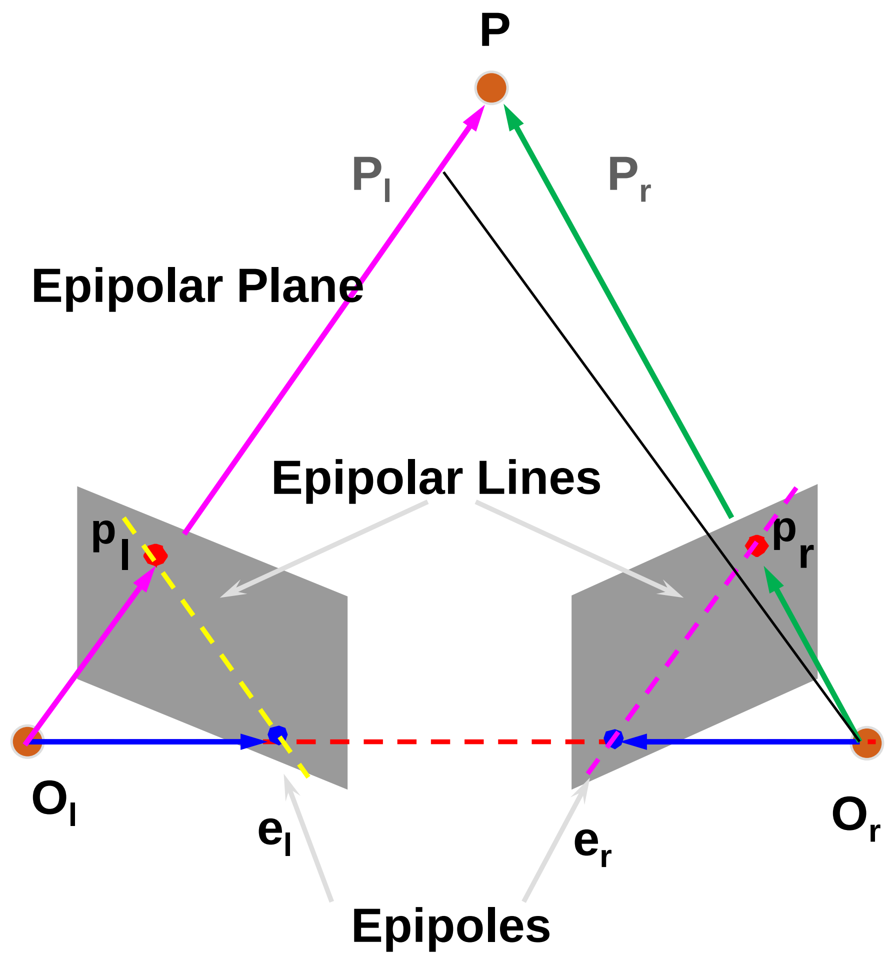
$$\mathbf{P_r} = \mathbf{R}^T(\mathbf{P_l} - \mathbf{T})$$

  - **P**, **O**$_l$ and **O**$_r$ are in the world coordinates.



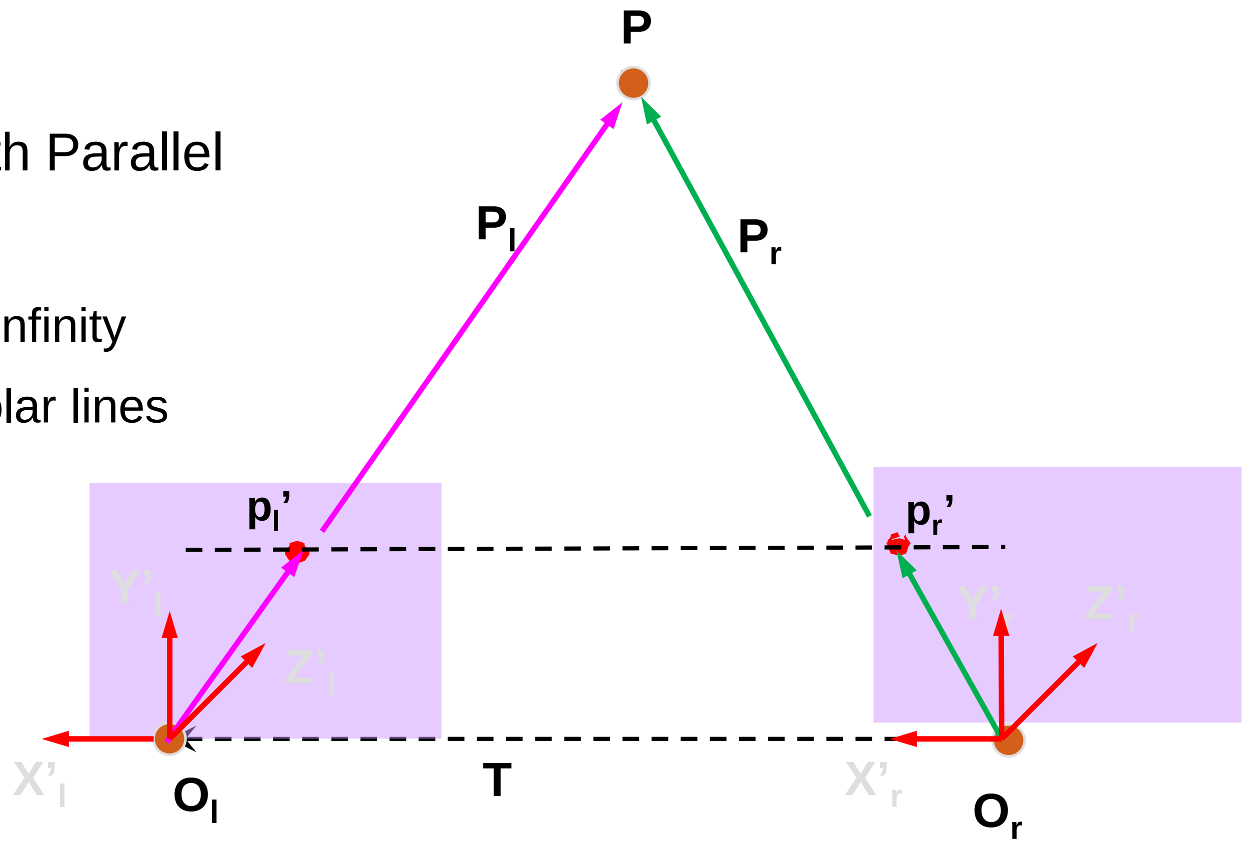
Epipolar Geometry

- Motivation: where to search correspondences?
  - Epipolar Plane
    - A plane going through point P and the centers of projection (COPs) of the two cameras
  - Conjugated Epipolar Lines
    - Lines where epipolar plane intersects the image planes
  - Epipoles
    - The image in one camera of the COP of the other
- Epipolar Constraint
  - Corresponding points must lie on conjugated epipolar lines



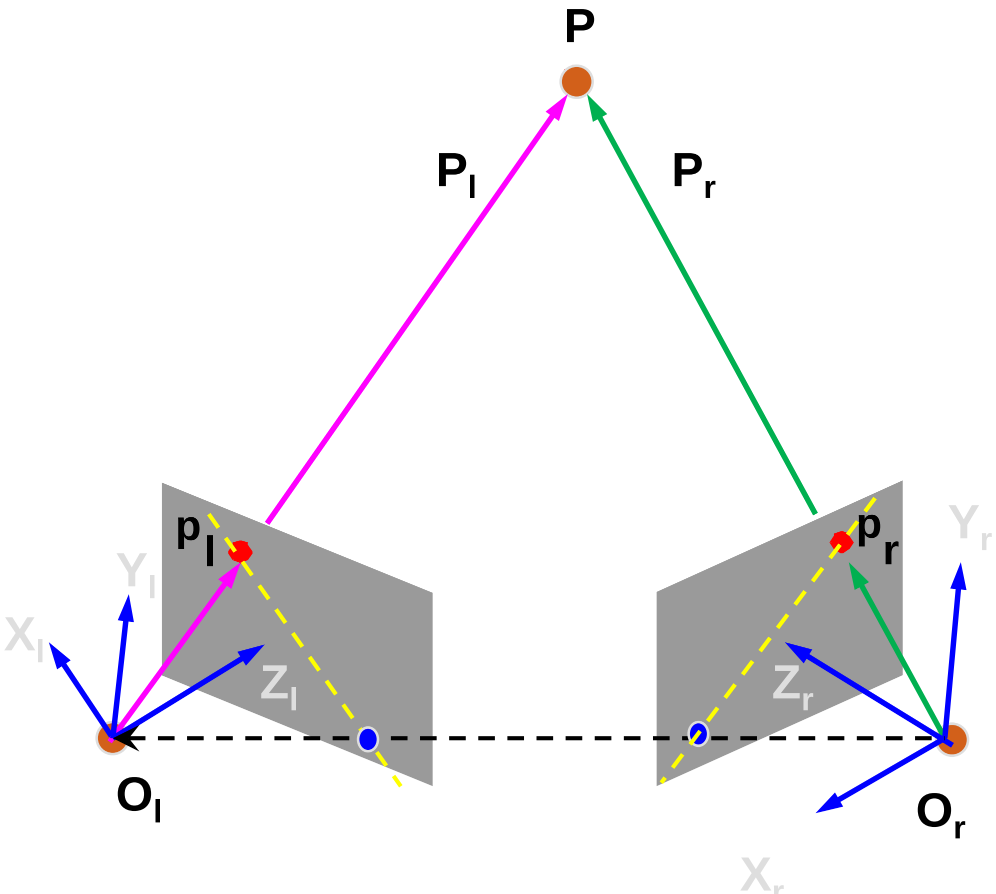
Stereo Rectification

- Stereo System with Parallel Optical Axes
  - Epipoles are at infinity
  - Horizontal epipolar lines

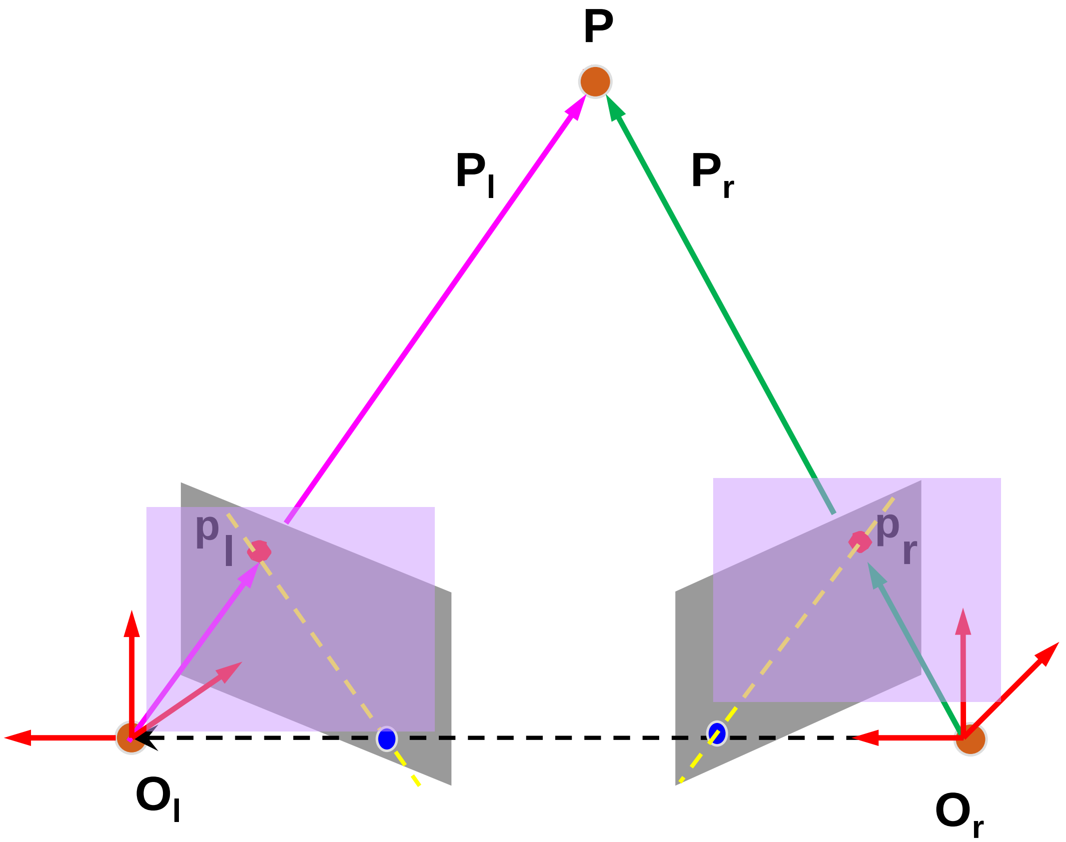


- Rectification
  - Given a stereo pair, the intrinsic and extrinsic parameters, find the image transformation to achieve a stereo system of horizontal epipolar lines
  - A simple algorithm: Assuming calibrated stereo cameras

Stereo Rectification



Stereo Rectification



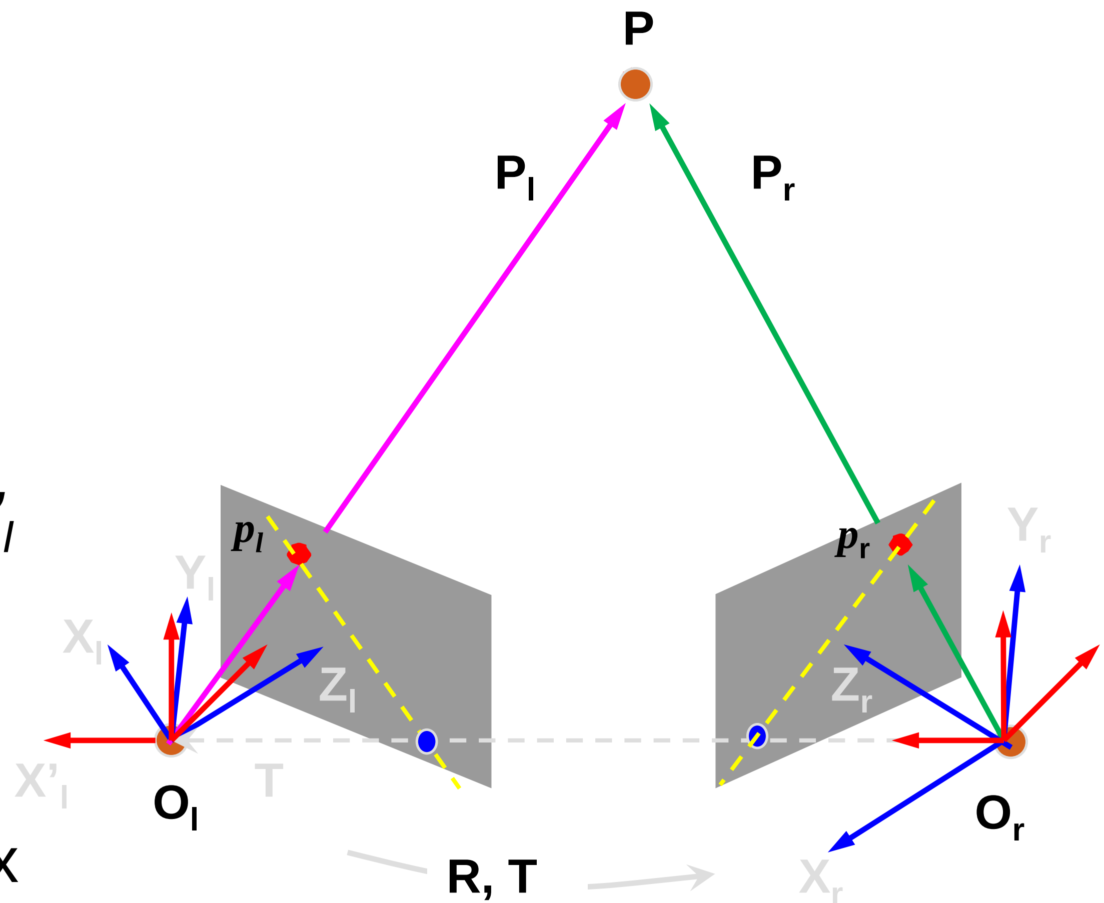
Algorithm(optional)

- Rotate both left and right camera so that they share the same X axis : O_r-O_l = T
- Find a new virtual camera pose: $O_l'X_l'Y'_lZ'_l$

$$X_l' = \frac{-T}{\|T\|} \qquad Y_l' = -X_l' \times Z_l$$

$$Z_l' = X_l' \times Y_l'$$

- Form the rotation matrix R_{rect} for the left camera from $O_lX_lY_lZ_l$ to $O_l'X_l'Y'_lZ'_l$
- Rotation Matrix for the right camera is $R_{rect}R^T$



How to find R_{rect}?

Stereo Rectification

The left image will be rotated to:

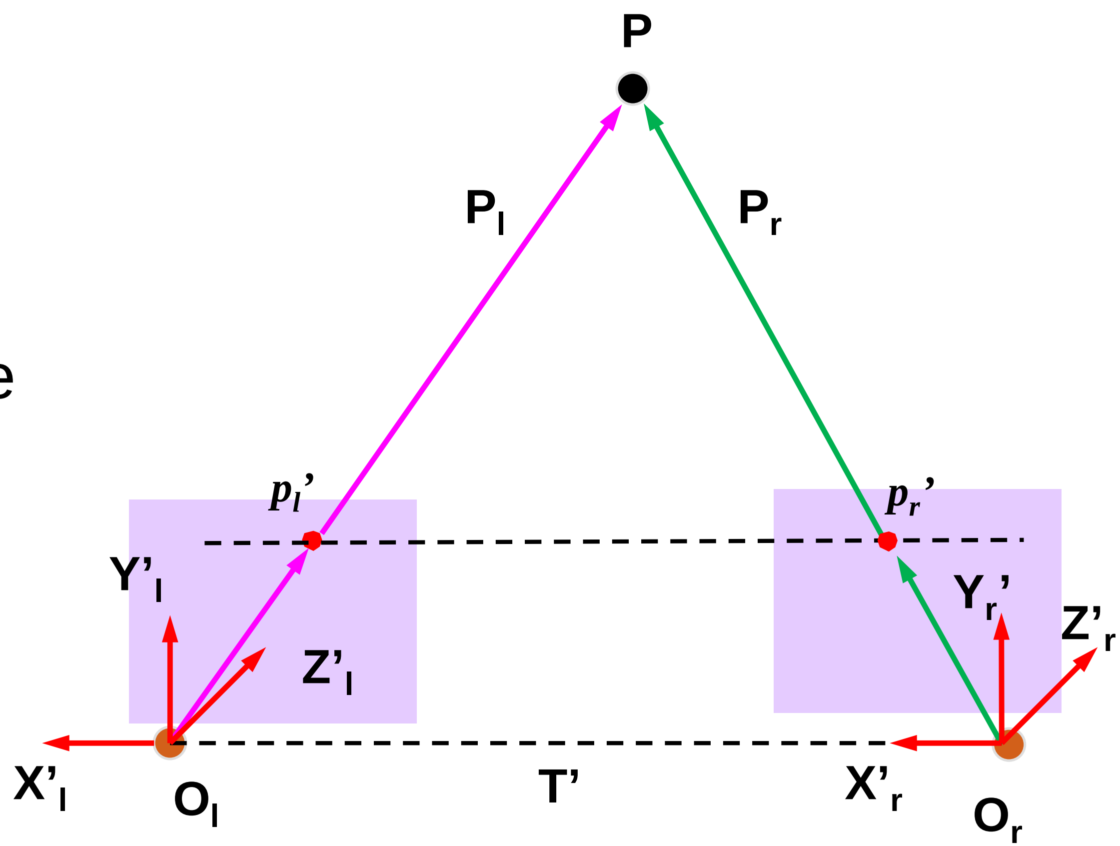
$R_{rect}\,(x_l, y_l, f_l)^T$

The right image will be rotated to:

$R_{rect} R^T (x_r, y_r, f_r)^T$

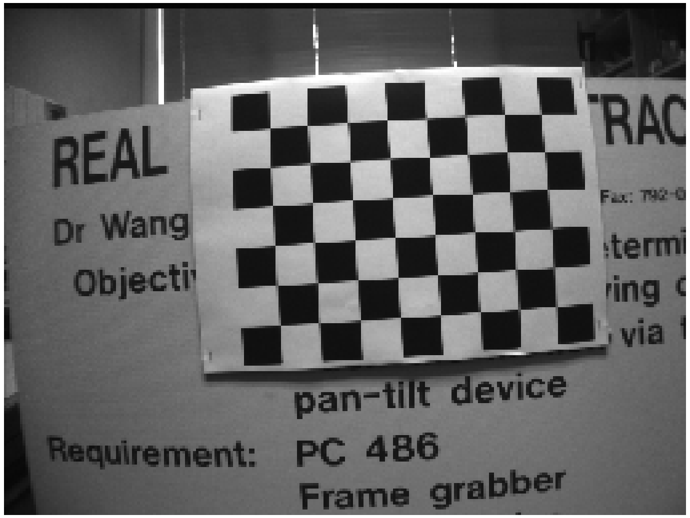
After rectification,

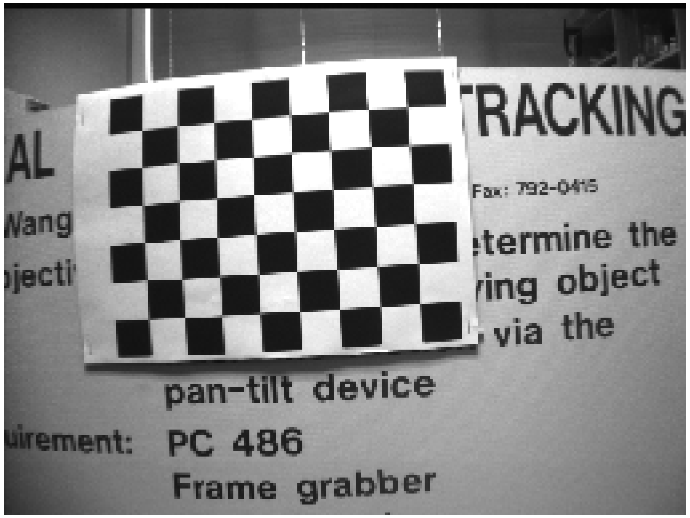
T' = (B, 0, 0),
$P'_r = P'_l - T'$



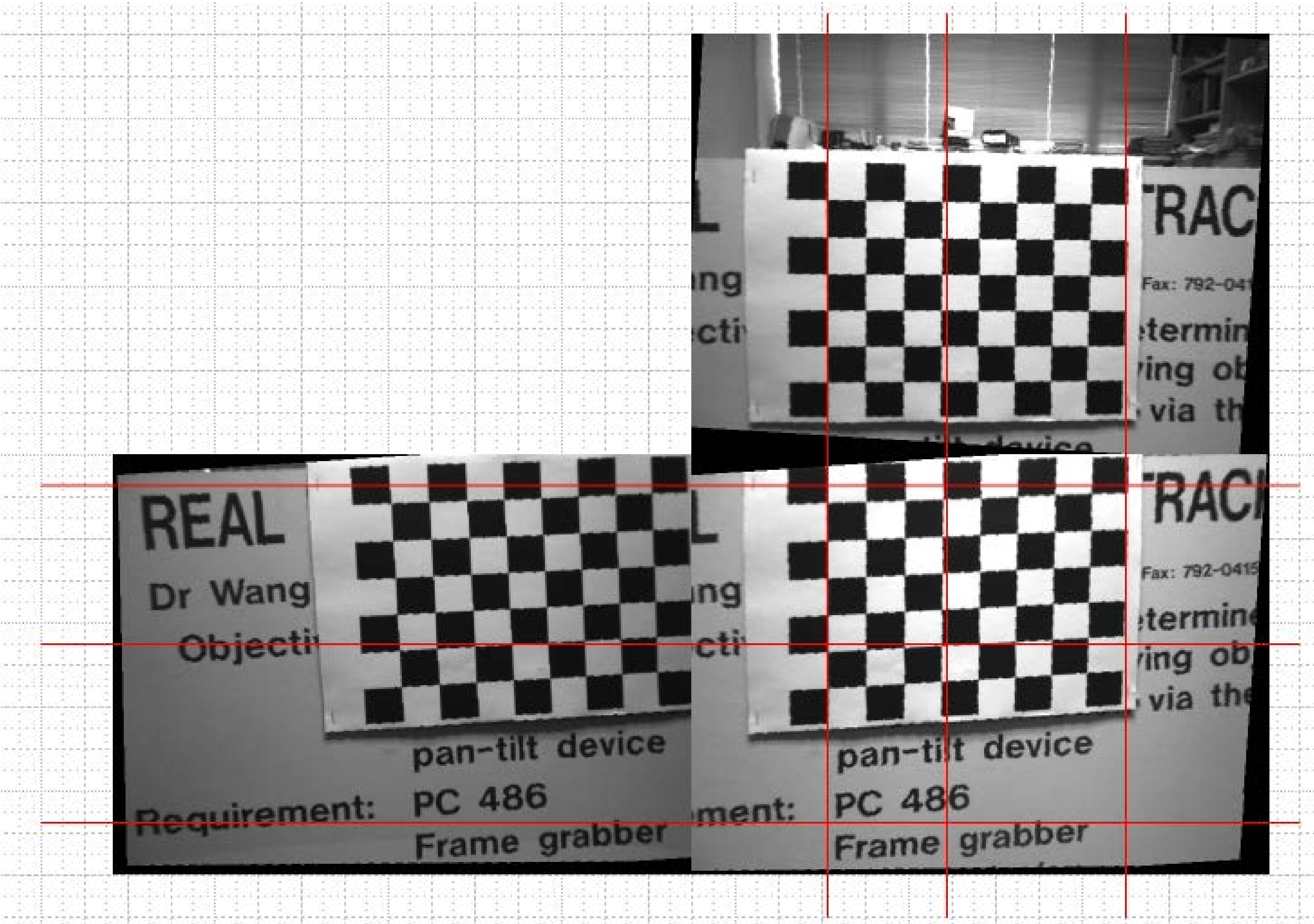
Before rectification

Another procedure is required here: to correct the radial distortion. We skip its derivation.





After



REAL
Dr Wang
Objecti
pan-tilt device
Requirement:
PC 486
Frame grabber
Fax: 792-0415

Radial Distortion

$$x_{\mathrm{u}} = x_{\mathrm{c}} + \frac{x_{\mathrm{d}} - x_{\mathrm{c}}}{1 + K_1 r^2 + K_2 r^4 + \cdots}$$

$$y_{\mathrm{u}} = y_{\mathrm{c}} + \frac{y_{\mathrm{d}} - y_{\mathrm{c}}}{1 + K_1 r^2 + K_2 r^4 + \cdots}$$

(x_d, y_d) = distorted image point as projected on image plane using specified lens,
(x_u, y_u) = undistorted image point as projected by an ideal pinhole camera,
(x_c, y_c) = distortion center (assumed to be the principal point),
K_n = n^{th} radial distortion coefficient (can be found by collecting many images at different distance, pose, …, and apply an optimisation equation.)

$$r = \sqrt{(x_d - x_c)^2 + (y_d - y_c)^2}$$

Essential Matrix

- Equation of the epipolar plane
  - Co-planarity condition of vectors P_l, T and P_l-T

$$(\mathbf{P_l} - \mathbf{T})^T \mathbf{T} \times \mathbf{P_l} = 0$$

$$\mathbf{P_r} = \mathbf{R}^T (\mathbf{P_l} - \mathbf{T})$$

- Essential Matrix E = RS
  - 3x3 matrix constructed from R and T (extrinsic only)
    - Rank (E) = 2, two equal nonzero singular values

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

$$S = \begin{bmatrix} 0 & -T_z & T_y \\ T_z & 0 & -T_x \\ -T_y & T_x & 0 \end{bmatrix}$$

Rank (R) =3

Rank (S) =2

$$\mathbf{P_r}^{\mathbf{T}} \mathbf{E} \mathbf{P_l} = 0$$

$$\mathbf{p}_l = \frac{f_l}{Z_l} \mathbf{P_l} \qquad \mathbf{p}_r = \frac{f_r}{Z_r} \mathbf{P}_r$$

$$\mathbf{p_r}^{\mathbf{T}} \mathbf{E} \mathbf{p_l} = 0$$

Essential Matrix

- Essential Matrix $E = RS$ $\quad$ $\mathbf{p_r}^{\mathbf{T}}\mathbf{E}\mathbf{p_l} = 0$
  - A natural link between the stereo point pair and the extrinsic parameters of the stereo system
    - One correspondence -> a linear equation of 9 entries
    - Given 8 pairs of (p_l, p_r) -> E
  - Mapping between points and epipolar lines we are looking for
    - Given p_l, E -> p_r on the projective line in the right plane
    - Equation represents the epipolar line of either p_r (or p_l) in the right (or left) image
- Note:
  - $\mathbf{p_l}$, $\mathbf{p_r}$ are in the camera coordinate system, not pixel coordinates that we can measure(eg. unit focal length).

Fundamental Matrix

- Mapping between points and epipolar lines in the pixel coordinate systems
  - With no prior knowledge on the stereo system
- From Camera to Pixels: Matrices of intrinsic parameters

$$\mathbf{M}_{\text{int}} = \begin{bmatrix} -f_x & 0 & o_x \\ 0 & -f_y & o_y \\ 0 & 0 & 1 \end{bmatrix}$$

Rank (M_{int}) =3

$$\mathbf{p_r}^{\mathbf{T}}\mathbf{E}\mathbf{p_l} = 0$$

$$\mathbf{p}_r = \mathbf{M}_r^{-1}\overline{\mathbf{p}}_r \qquad \mathbf{p_l} = \mathbf{M_l}^{-1}\overline{\mathbf{p}}_\mathbf{l}$$

$$\overline{\mathbf{p}}_\mathbf{r}^{\mathbf{T}}\mathbf{F}\overline{\mathbf{p}}_\mathbf{l} = 0$$

$$\mathbf{F} = \mathbf{M}_r^{-\mathbf{T}}\mathbf{E}\mathbf{M}_l^{-1}$$

- Questions:
  - What are f_x, f_y, o_x, o_y ?
  - How to measure $\overline{p}_l$ in images?

Fundamental Matrix

- Fundamental Matrix
  - Rank (F) = 2
  - Encodes info on both intrinsic and extrinsic parameters

$$\mathbf{F} = \mathbf{M}_r^{-\mathbf{T}} \mathbf{E} \mathbf{M}_l^{-1}$$

  - Enables full reconstruction of the epipolar geometry
  - In pixel coordinate systems without any knowledge of the intrinsic and extrinsic parameters
  - Linear equation of the 9 entries of F

$$\overline{\mathbf{p}}_{\mathbf{r}}^{\mathbf{T}} \mathbf{F} \overline{\mathbf{p}}_{\mathbf{l}} = 0 \quad \Rightarrow \quad \begin{pmatrix} x_{im}^{(l)} & y_{im}^{(l)} & 1 \end{pmatrix} \begin{bmatrix} f11 & f12 & f13 \\ f21 & f22 & f23 \\ f31 & f32 & f33 \end{bmatrix} \begin{pmatrix} x_{im}^{(r)} \\ y_{im}^{(r)} \\ 1 \end{pmatrix} = 0$$

Computing F: The Eight-point Algorithm

- Input: n point correspondences (n >= 8)
  - Construct homogeneous system Ax= 0 from $\overline{\mathbf{p}}_{\mathbf{r}}^{\mathbf{T}}\mathbf{F}\overline{\mathbf{p}}_{\mathbf{l}} = 0$
    - x = (f_{11},f_{12}, ,f_{13}, f_{21},f_{22},f_{23} f_{31},f_{32}, f_{33}) : entries in F
    - Each correspondence give one equation
    - A is a nx9 matrix
  - Obtain estimate F^ by SVD of A $\mathbf{A} = \mathbf{UDV}^T$
    - x (up to a scale) is column of V corresponding to the least singular value
  - Enforce singularity constraint: since Rank (F) = 2
    - Compute SVD of F^ $\hat{\mathbf{F}} = \mathbf{UDV}^T$
    - Set the smallest singular value to 0: D -> D'
    - Correct estimate of F : $\mathbf{F}' = \mathbf{UD}'\mathbf{V}^T$
- Output: the estimate of the fundamental matrix, F'
- Similarly we can compute E given intrinsic parameters

Locating the Epipoles from F

$$\overline{\mathbf{p}}_{\mathbf{r}}{}^{\mathbf{T}}\mathbf{F}\overline{\mathbf{p}}_{\mathbf{l}} = 0$$

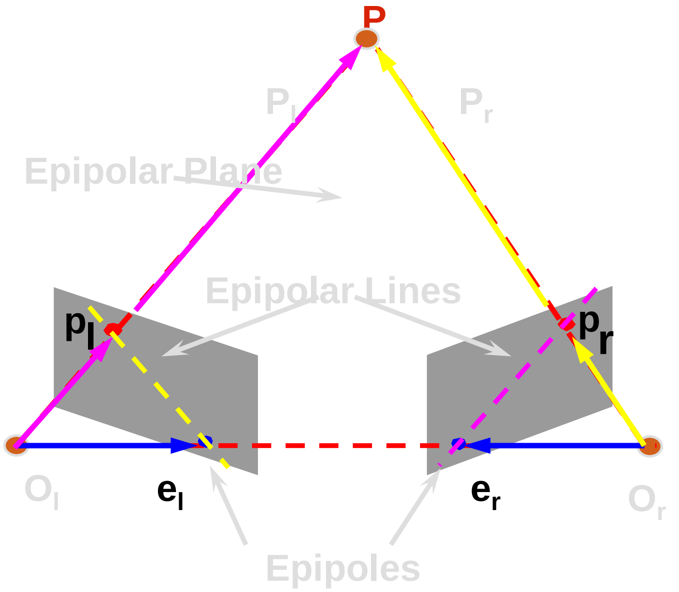
e_l lies on all the epipolar lines of the left image

$$\overline{\mathbf{p}}_{\mathbf{r}}{}^{\mathbf{T}}\mathbf{F}\overline{\mathbf{e}}_{\mathbf{l}} = 0$$

For every p_r

F is not identically zero

$$\mathbf{F}\overline{\mathbf{e}}_{\mathbf{l}} = 0$$



- Input: Fundamental Matrix F
  - Find the SVD of F
  - The epipole e_l is the column of V corresponding to the null singular value (as shown above)
  - The epipole e_r is the column of U corresponding to the null singular value
- Output: Epipole e_l and e_r

$$\mathbf{F} = \mathbf{U}\mathbf{D}\mathbf{V}^{T}$$

Epipolar Geometry

- Purpose
  - where to search correspondences

$$\mathbf{P}_r^T \mathbf{R}^T \mathbf{T} \times \mathbf{P}_l = 0$$

- Epipolar plane, epipolar lines, and epipoles
  - known intrinsic (f) and extrinsic (R, T)
    - co-planarity equation
  - known intrinsic but unknown extrinsic
    - essential matrix
  - unknown intrinsic and extrinsic
    - fundamental matrix

$$\mathbf{p_r}^{\mathbf{T}} \mathbf{E} \mathbf{p_l} = 0$$

$$\overline{\mathbf{p}}_{\mathbf{r}}^{\mathbf{T}} \mathbf{F} \overline{\mathbf{p}}_{\mathbf{l}} = 0$$

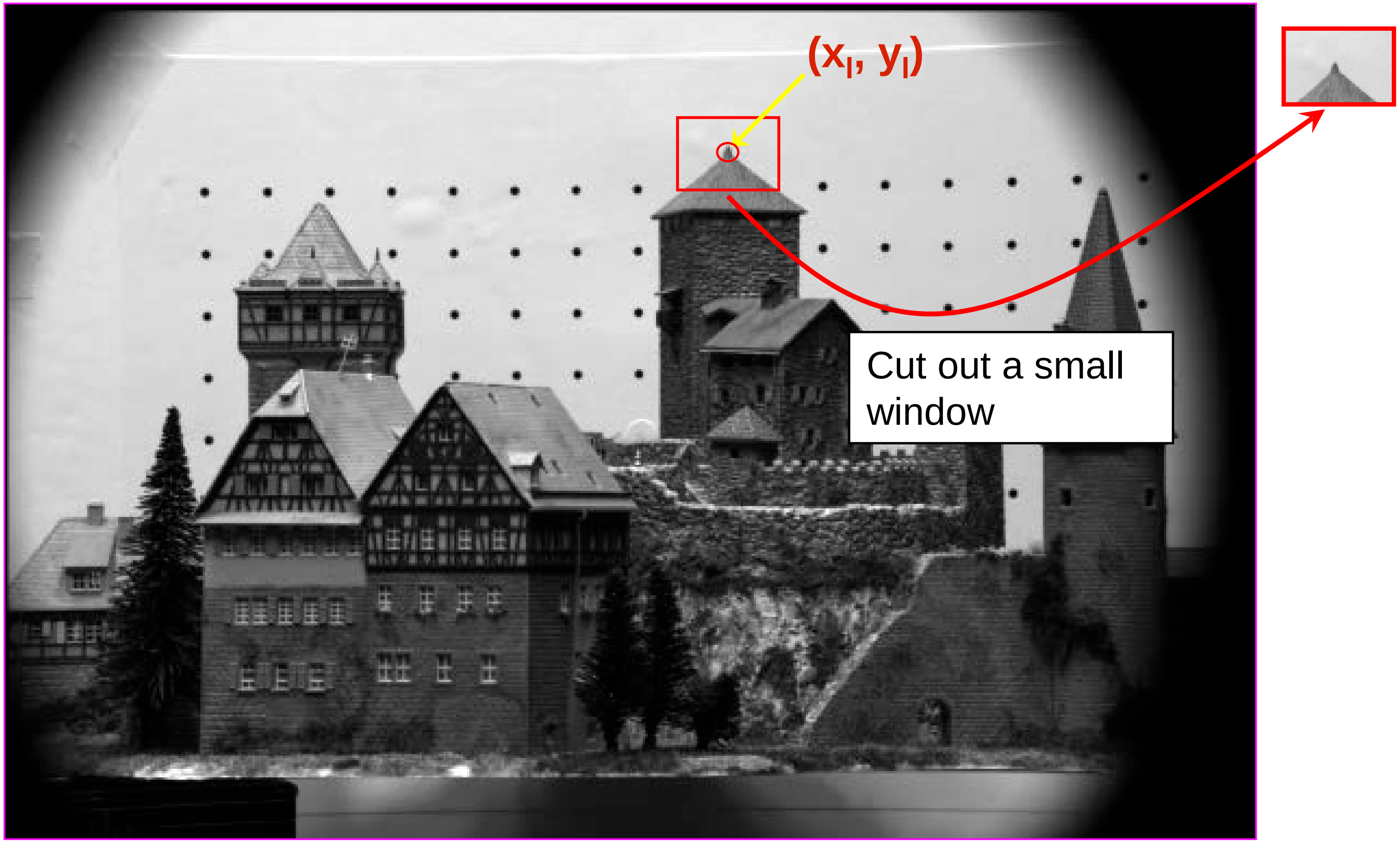
- Rectification
  - Generate stereo pair (by software) with parallel optical axis and thus horizontal epipolar lines

Correspondence problem

- Three Questions
  - What to match?
    - Features: point, line, area, structure?
  - Where to search correspondence?
    - Epipolar line?
  - How to measure similarity?
    - Depends on features
- Approaches
  - Correlation-based approach
  - Feature-based approach
- Advanced Topics
  - Image filtering to handle illumination changes
  - Adaptive windows to deal with multiple disparities
  - Local warping to account for perspective distortion
  - Sub-pixel matching to improve accuracy
  - Self-consistency to reduce false matches
  - Multi-baseline stereo

Correlation Approach

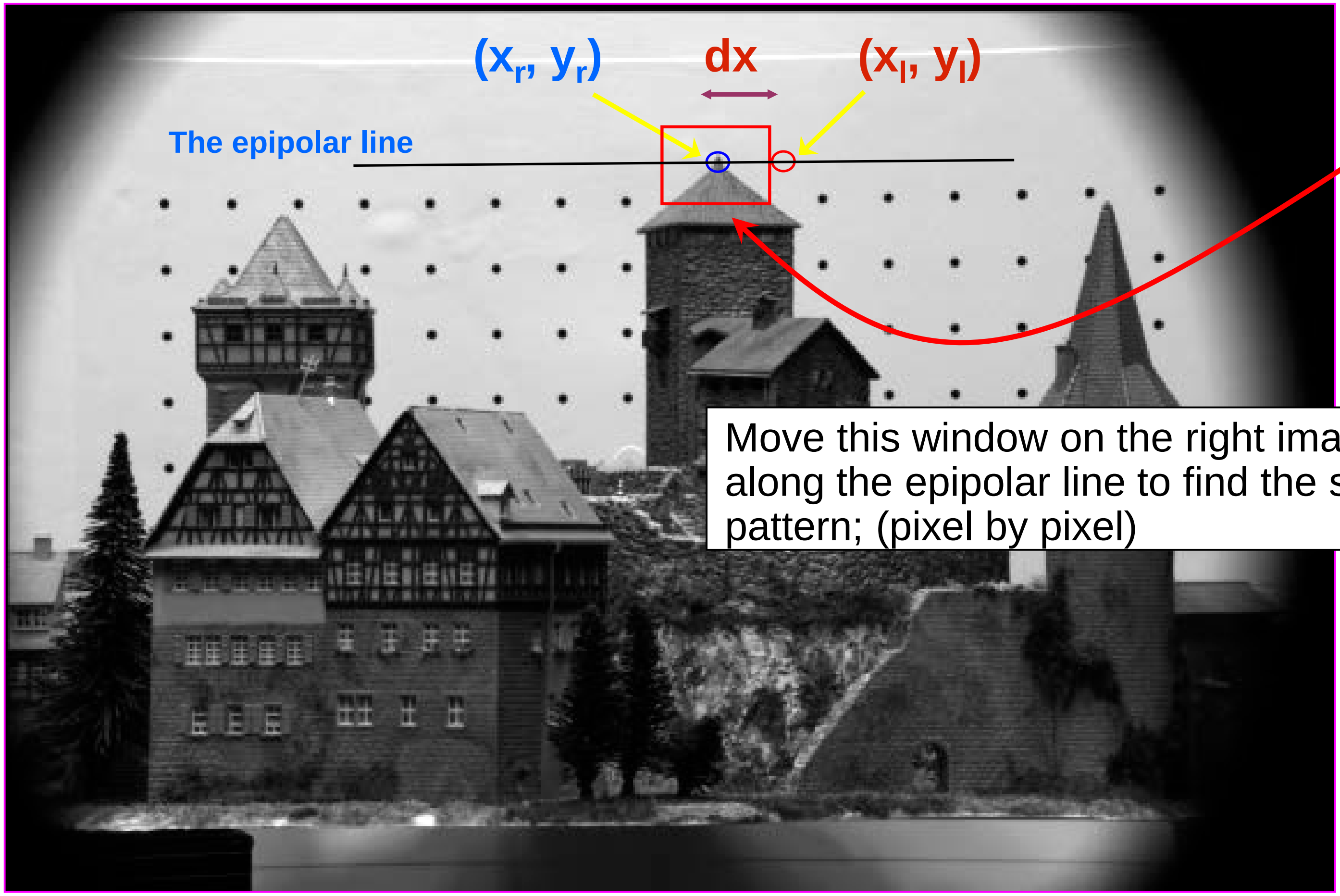
LEFT IMAGE

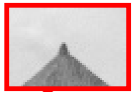


- For Each point (x_l, y_l) in the left image, define a window centered at the point

Correlation Approach

RIGHT IMAGE





- The epipolar line is perfectly horizontal, because we have parallel optical axes after rectification. It means reduced effort in searching for matched pattern, and less ambiguity.

Correlation Approach

- Elements to be matched
  - Image window of fixed size centered at each pixel in the left image
- Similarity criterion
  - A measure of similarity between windows in the two images
  - The corresponding element is given by window that maximizes the similarity criterion within a search region
- Search regions
  - Theoretically, search region can be reduced to a 1-D segment, along the epipolar line, and within the disparity range.
  - In practice, search a slightly larger region due to errors in calibration

Correlation Approach

- Equations

$$c(dx,dy)=\sum_{k=-W}^{W}\sum_{l=-W}^{W}\psi(I_l(x_l+k,y_l+l),I_r(x_l+dx+k,y_l+dy+l))$$

- disparity

$$\bar{\mathbf{d}}=(\bar{d}x,\bar{d}y)=\arg\max_{\mathbf{d}\in R}\{c(dx,dy)\}$$

- Similarity criterion
  - Cross-Correlation $\Psi(u,v)=uv$
  - Sum of Square Difference (SSD) $\Psi(u,v)=-(u-v)^2$
  - Sum of Absolute Difference(SAD) $\Psi(u,v)=-|u-v|$

Correlation Approach

- PROS
  - Easy to implement
  - Produces dense disparity map
  - Maybe slow
- CONS
  - Needs textured images to work well
  - Inadequate for matching image pairs from very different viewpoints due to illumination changes
  - Window may cover points with quite different disparities
  - Inaccurate disparities on the occluding boundaries

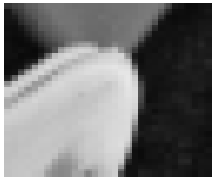
Template matching of Lena's hat

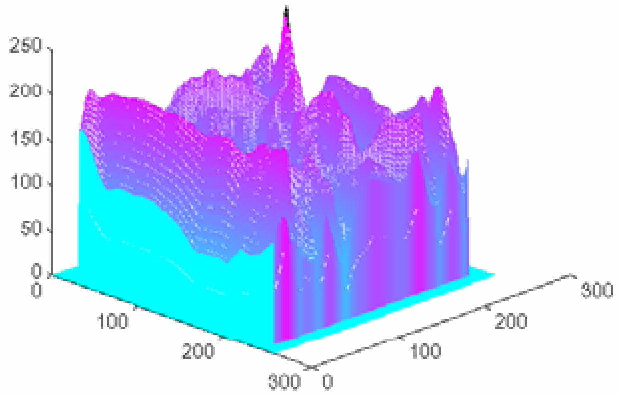
Scan the template over each pixel of the image of Lena and compute γ for each pixel.

We obtain the 2D γ-map. If we represent higher values of γ as brighter intensity, we get the γ image. The max value of γ is deemed the best match.

Original image of Lena

template





γ - map

Max γ

Result of template matching

Example

① Vectorize the template, $t = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$

$$\vec{t} = (1, 1, 1, 1, 0, 1, 0, 0, 0)$$

Copy out each pixel, form a 1x9 vector. If the template is 15x15, the vector is 1x225.

find the mean

$$t_{mean} = \frac{5}{9}$$

Adjust $\vec{t}$, so that it is zero-meaned.

$$\vec{t} = (1 - t_{mean}, \cdots)$$

$$= \left(\frac{4}{9}, \frac{4}{9}, \frac{4}{9}, \frac{4}{9}, -\frac{5}{9}, \frac{4}{9}, -\frac{5}{9}, -\frac{5}{9}, -\frac{5}{9}\right)$$

Make it into unit vector;

$$\|\vec{t}\| = \sqrt{\left(\frac{4}{9}\right)^2 + \left(\frac{4}{9}\right)^2 + \cdots} = \frac{\sqrt{180}}{9}$$

$$\vec{T} = \frac{\vec{t}}{\|\vec{t}\|} = \frac{9}{\sqrt{180}}\left(\frac{4}{9}, \frac{4}{9}, \cdots\right)$$

$$= \frac{1}{\sqrt{180}}(4, 4, 4, 4, -5, \cdots)$$

Note: $\|\vec{T}\| = 1$

This vectorised template is then used to match against data. For example, a 3x3 window extracted from the right image on the epipolar line. The left is a sample. The triangle pattern is there, but this image is brighter.

Repeat the same process to vectorise this data.

(2) vectorize the image $i =$

100	100	100
100	10	100
10	10	10

$\therefore \vec{i} = (100, 100, 100, 100, 10, \cdots)$

find the mean

$i_{mean} = 60$

adjust $\vec{i}$, it is zero-meaned

$\vec{i} = (100-60, 100-60, \cdots)$

$= (40, 40, 40, 40, -50, \cdots)$

make it into unit vector

$\|\vec{i}\| = \sqrt{40^2+40^2+\cdots} = \sqrt{18000}$

$\therefore \vec{I} = \frac{\vec{i}}{\|\vec{i}\|} = \frac{1}{\sqrt{18000}}(40, 40, \cdots)$

$= \frac{1}{\sqrt{180}}(4, 4, 4, 4, -5, \cdots)$

③ Inner product $\vec{T} \cdot \vec{I}$

note: $\vec{T} = \vec{I}$

$\therefore \quad \vec{T} \cdot \vec{I} = 1$

1 means the 2 patterns are identical. The worst case is -1 (when 2 vectors are in opposite direction).

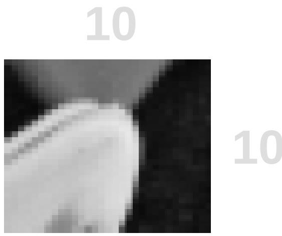
④ You may try other pattern of

$i =$

1	2	3
3	2	1
2	3	4

and observe the new

$\vec{T} \cdot \vec{I} < 1$



Suppose the template has 10x10 pixels, we slice the template in raster order. Then form a list of 100 pixels. We treat this list as an 100 dimension vector, namely *w*. We search through the image. At each pixel location, we cut out a sample of 10x10, then form another 100-vector, call it *f*. The following method is better than SAD.

The objective is to measure the similarity between *f* and *w*.

Let

$f=(f_1,f_2,\ldots f_{100})$ and $w=(w_1,w_2, \ldots w_{100})$

We first find the mean of *f* and *w*, and adjust each vector by subtracting the mean f_{av} & w_{av} and then normalise the two vectors into unit vectors.

Mean adjustment is necessary, as this reduces side effect of lighting changes between template and image.

As we understand that if two unit vectors are identical, the inner product of the two will produce 1. Any “dissimilarity” will make the product less than 1. The worst case is -1.

For example

<u>*Calculating ZNCC in vector form*</u>

In the previous example, $\boldsymbol{f}$ and $\boldsymbol{w}$ were put into vector form thus :

$$\boldsymbol{f} = [6 \quad 7 \quad 2 \quad 5 \quad 6 \quad 9 \quad 7 \quad 8 \quad 9\,]^{\mathrm{T}} \text{ and } \boldsymbol{w} = [5 \quad 6 \quad 7 \quad 44 \quad 5 \quad 6 \quad 6 \quad 7 \quad 8\,]^{\mathrm{T}}$$

In general, let $\boldsymbol{h} = \boldsymbol{f} - \boldsymbol{f}_{\text{ave}}$ and $\boldsymbol{g} = \boldsymbol{w} - \boldsymbol{w}_{\text{ave}}$, then

$$\gamma = \frac{\boldsymbol{h}^T \boldsymbol{g}}{\|\boldsymbol{h}\| \, \|\boldsymbol{g}\|}. \quad \textit{Since} \quad \frac{\boldsymbol{h}}{\|\boldsymbol{h}\|} \textit{ is a unit vector and so is } \frac{\boldsymbol{g}}{\|\boldsymbol{g}\|},$$

therefore $\boxed{\gamma = \cos\theta}$ where θ is the angle between $\boldsymbol{h}$ and $\boldsymbol{g}$.

Recall : $\boldsymbol{a}^{\mathrm{T}}\boldsymbol{b} = \|\,\boldsymbol{a}\,\| \; \|\,\boldsymbol{b}\,\| \; \cos\theta$

So ZNCC is simply the inner product between two unit vectors !!!

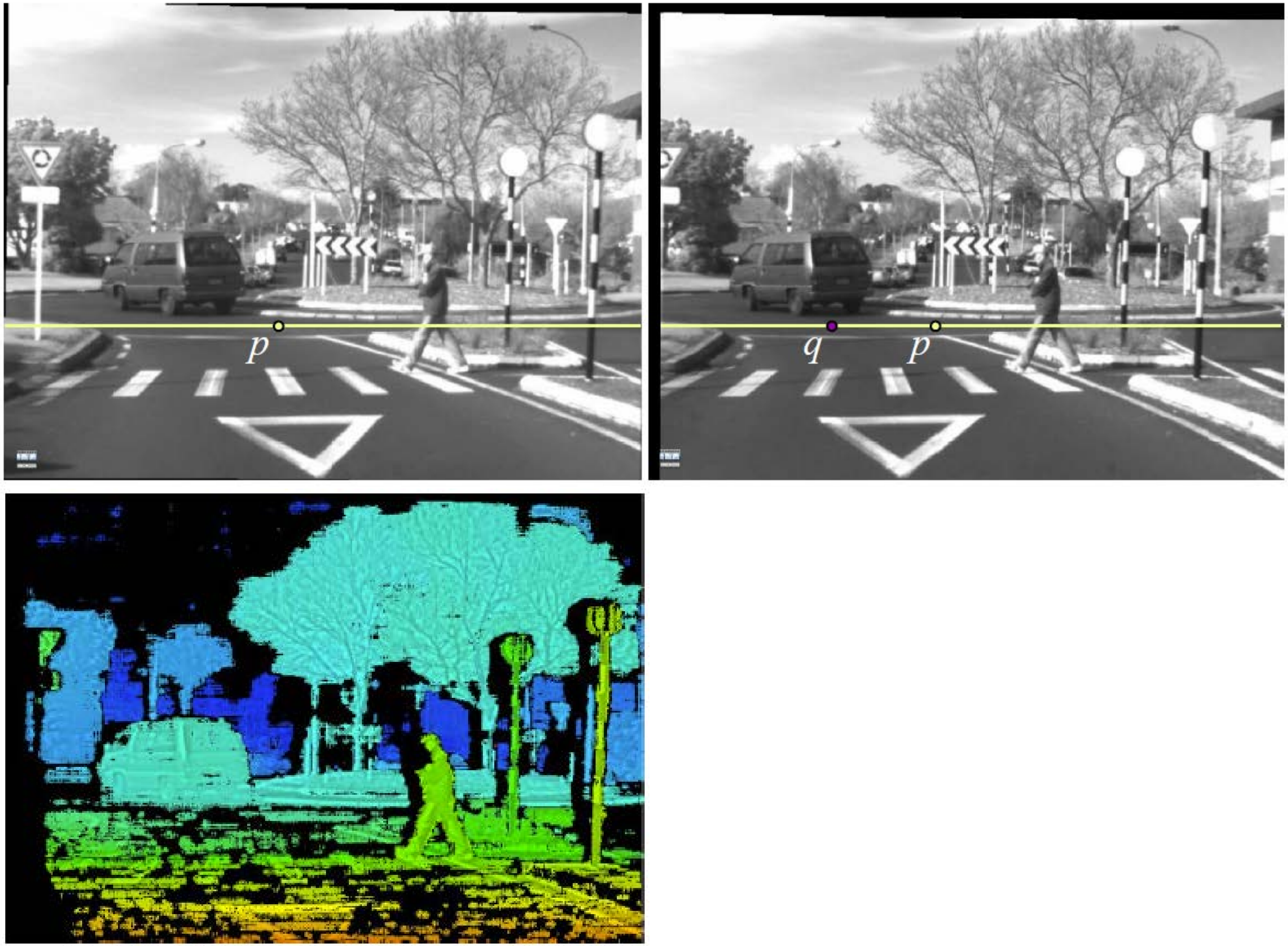
Now you know why γ is between -1 and 1.

This method is called ZNCC—zero centred normalised correlation coefficient

Properties of γ = ZNCC :

- $-1 \le \gamma(s,t) \le 1$ (why ?)
- summation is taken over the image region where ***w*** and ***f*** overlap.
- The ***maximum*** value of $\gamma(s,t)$ appears at the position where $\boldsymbol{w}(x, y)$ best matches $\boldsymbol{f}(x, y)$.
- Advantage : easy to implement.
- Disadvantages : sensitive to image rotation and image scale changes, etc.

Correlation Approach (dense stereo example)



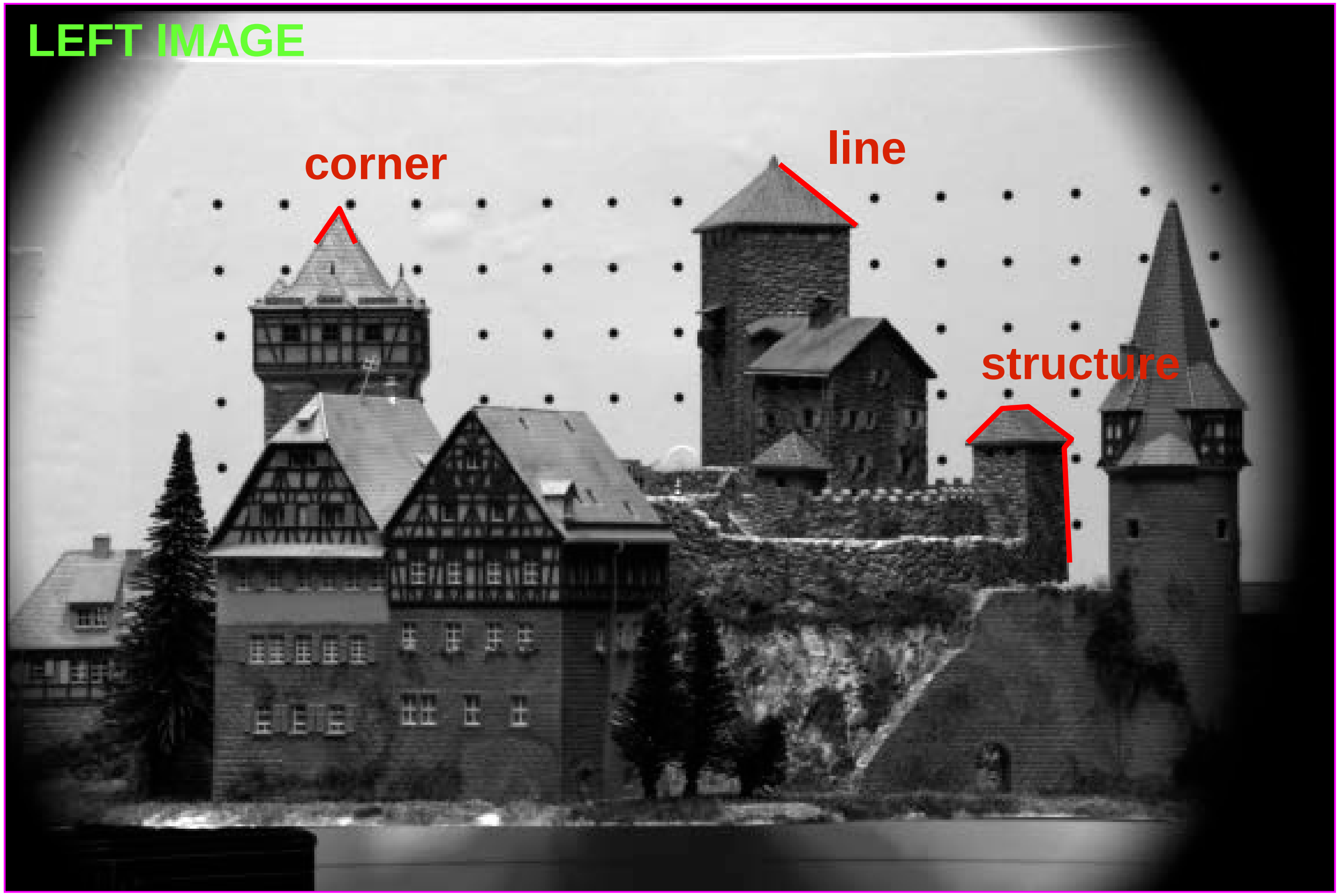
- A Stereo Pair of NTU Campus with corners superimposed

Feature-based Approach

- Features
  - Edge points
  - Lines (length, orientation, average contrast)
  - Corners
  - SIFT

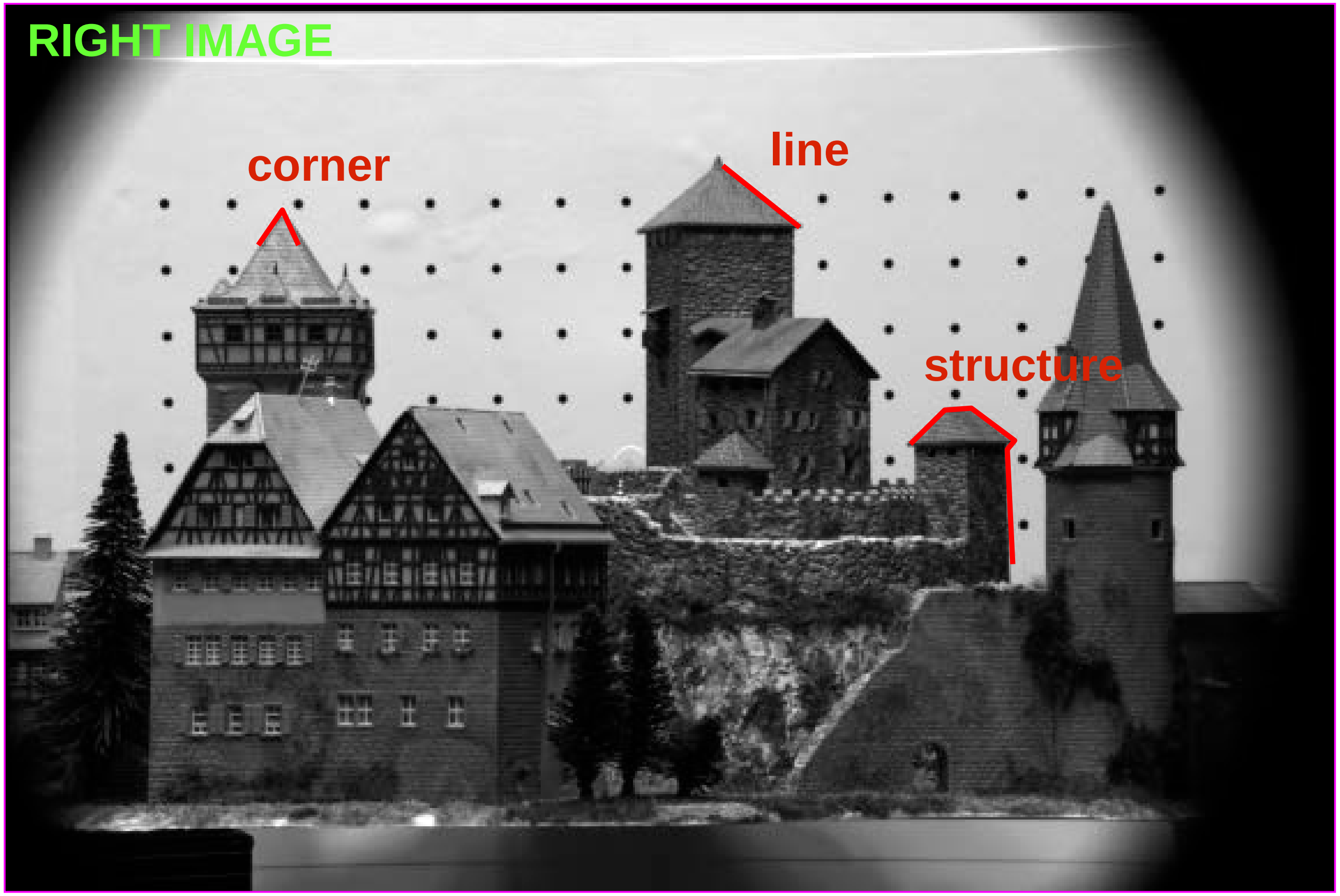
- Matching algorithm
  - Extract features in the stereo pair
  - Define similarity measure
  - Search correspondences using similarity measure and the epipolar geometry

Feature-based Approach



- For each feature in the left image…

Feature-based Approach



- Search in the right image… the disparity (dx, dy) is the displacement when the similarity measure is maximum

Feature-based Approach

- PROS
  - Relatively insensitive to illumination changes
  - Good for man-made scenes with strong lines but weak texture or textureless surfaces
  - Work well on the occluding boundaries (edges)
  - Could be faster than the correlation approach
- CONS
  - Only sparse depth map
  - Feature extraction may be tricky
    - Lines (Edges) might be partially extracted in one image
    - How to measure the similarity between two lines?

Summary

- Fundamental concepts and problems of stereo
- Epipolar geometry and stereo rectification
- Correspondence problem and two techniques: correlation and feature based matching
- Reconstruct 3-D structure from image correspondences given
  - Fully calibrated
  - Partially calibration
  - Uncalibrated stereo cameras (*)