StereoVision

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Sumary

- Introduction - Stereopsis
- Camera models and Camera calibration
- Stereo Vision
  - Frontal parallel arrangement
  - Epipolar geometry
  - Essential and Fundamental Matrix
  - Image rectification
  - Template Matching
  - Stereo Matching

Introduction

What is stereo?

Where is it coming from?

Where can you see it or use it?

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Human Visual System

- Many of the perceptual cues we use to visualize 3D structure are available in 2D projections

- Such cues include:
  - occlusion (one object partially covering another)
  - perspective (point of view)
  - familiar size (we know the real-world sizes of many objects)
  - atmospheric haze (objects further away look more washed out)

- Four cues are missing from single 2D views:
  - stereo parallax - seeing a different image with each eye
  - movement parallax -seeing different images when we move the head
  - Accommodation - the eyes’ lenses focus on the object of interest
  - Convergence - both eyes converge on the object of interest

Stereopsis

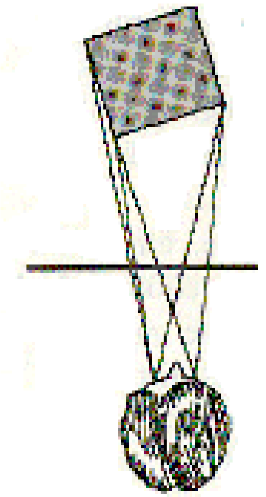
Stereo ="solid" or "three-dimensional“

opsis = appearance or sight

Also: “binocular vision” ,

“binocular depth perception”

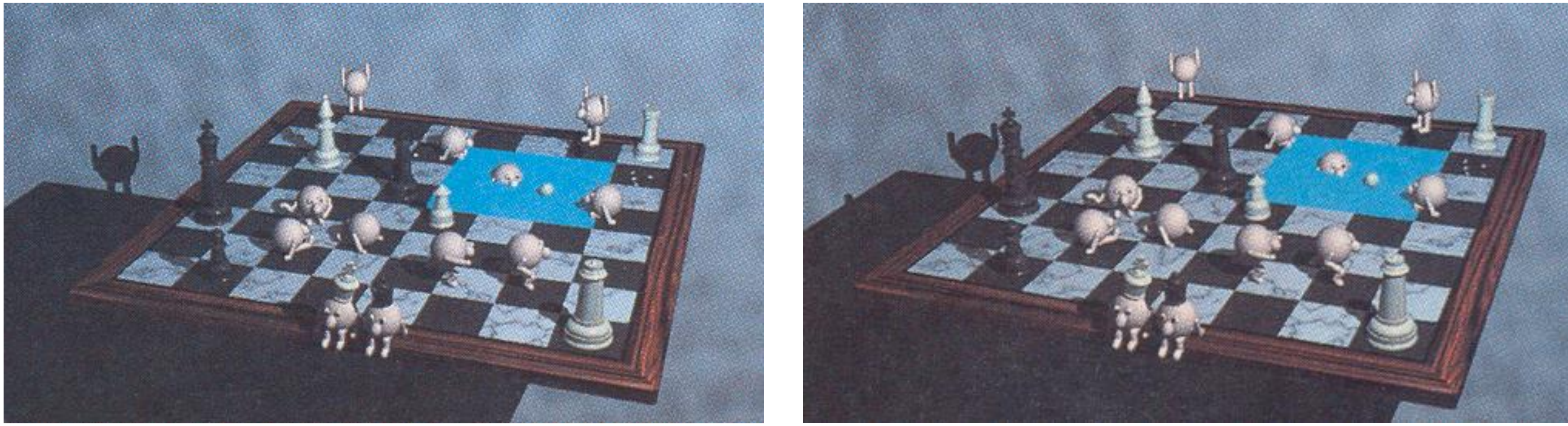
“stereoscopic depth perception”



- Stereopsis is the impression of depth that is perceived when a scene is viewed with both eyes by someone with normal binocular vision
- Binocular disparity is due to the different position of our two eyes

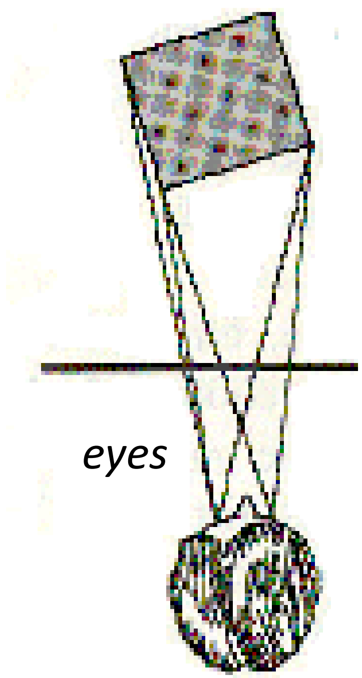
- Depth perception in stereo is based on stereopsis:
  - when the brain registers and fuses two images
  - Image parallax means that the two eyes register different images (horizontal shift)
  - The amount of shift depends on the “inter-pupillary distance” (IPD) (varies for each person in the range of 53-73 mm)
  - Works in the near field (to a few meters from the eye)

Stereopsis



(Hearn and Baker, 2002)

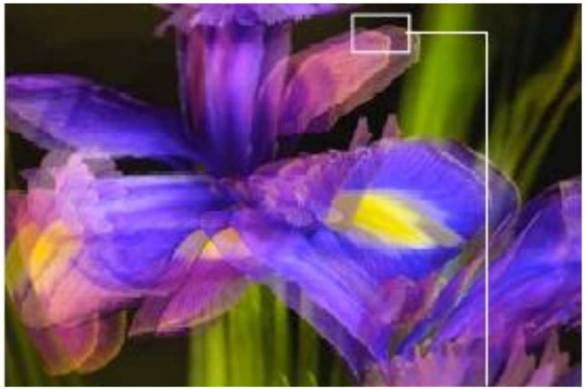
Right eye image *Left eye image*



Stereopsis: implications for Graphic devices

- Need to present two images of the same scene

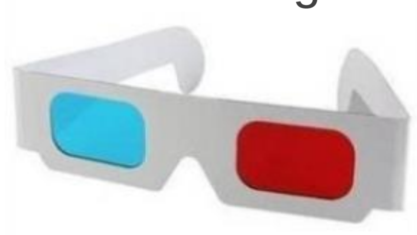
- The two images can be presented:
  - at the same time on two displays (HMD)
  - time-sequenced on one display (active glasses)
  - spatially-sequenced on one display (auto-stereoscopic displays)



Left eye, right eye images
(Burdea and Coiffet., 2003)

Common ways to produce 3D sensation

- Anaglyphs: two colored images and color coded glasses (red/cyan(green))



- Two images with different light polarization and polarizing glasses
  - Linear and circular

- Double frame-rate displays combined with LCD shutter glasses
- Autostereoscopic displays
  - Parallax barrier and lenticular lens
- Head Mounted Displays (HMDs)
- and “exotic displays”

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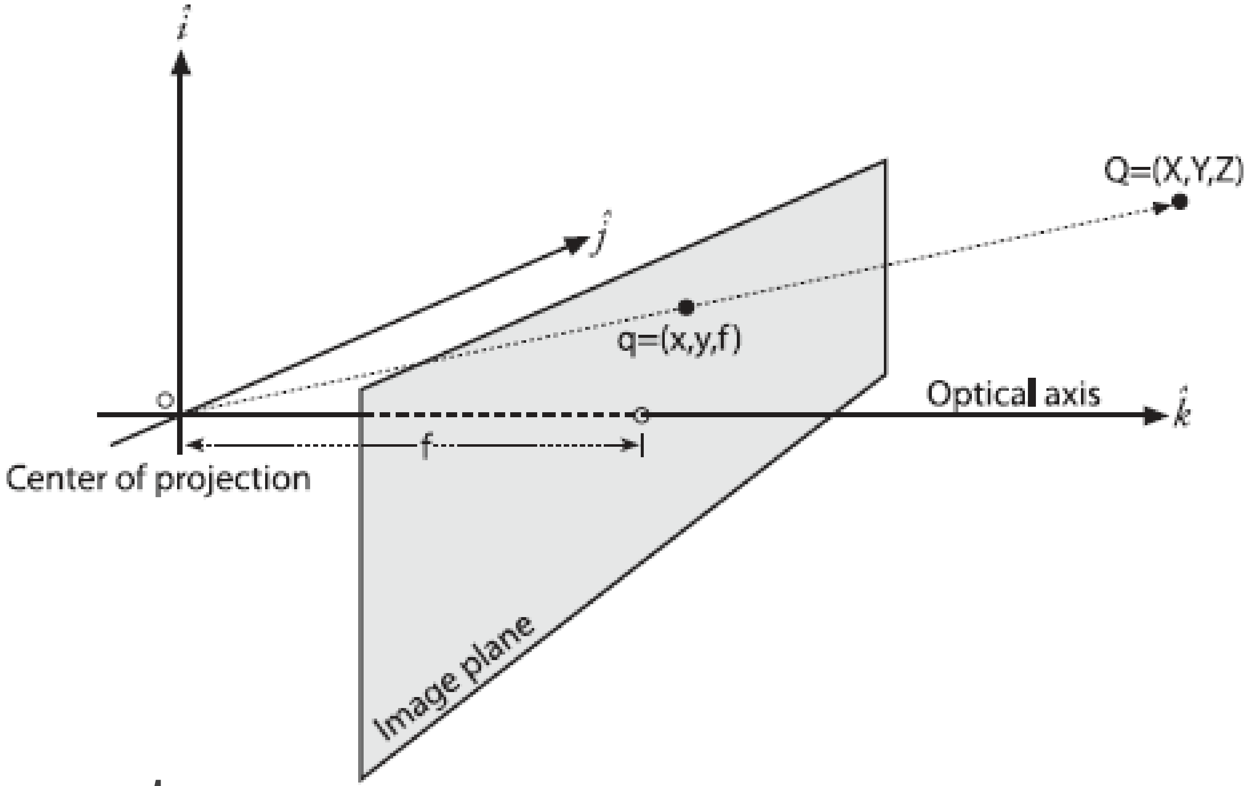
- pinhole camera model



- We get

$$x = f\frac{X}{Z} \qquad y = f\frac{Y}{Z}$$

OpenCV Camera model

- OpenCV Camera model:
  - 4 intrinsic parameters:
    - Focal distance: f_x, f_y
    - Optical centre: c_x, c_y
  - 5 distortion parameters
    - Lens distortion: k_1, k_2, k_3, p_1, p_2
  - 6 extrinsic parameters:
    - Rotation: r_x, r_y, r_z
    - Translation: t_x, t_y, t_z

Total: **15 parameters**

- Other models: Tsai, Heikkila, Zhang

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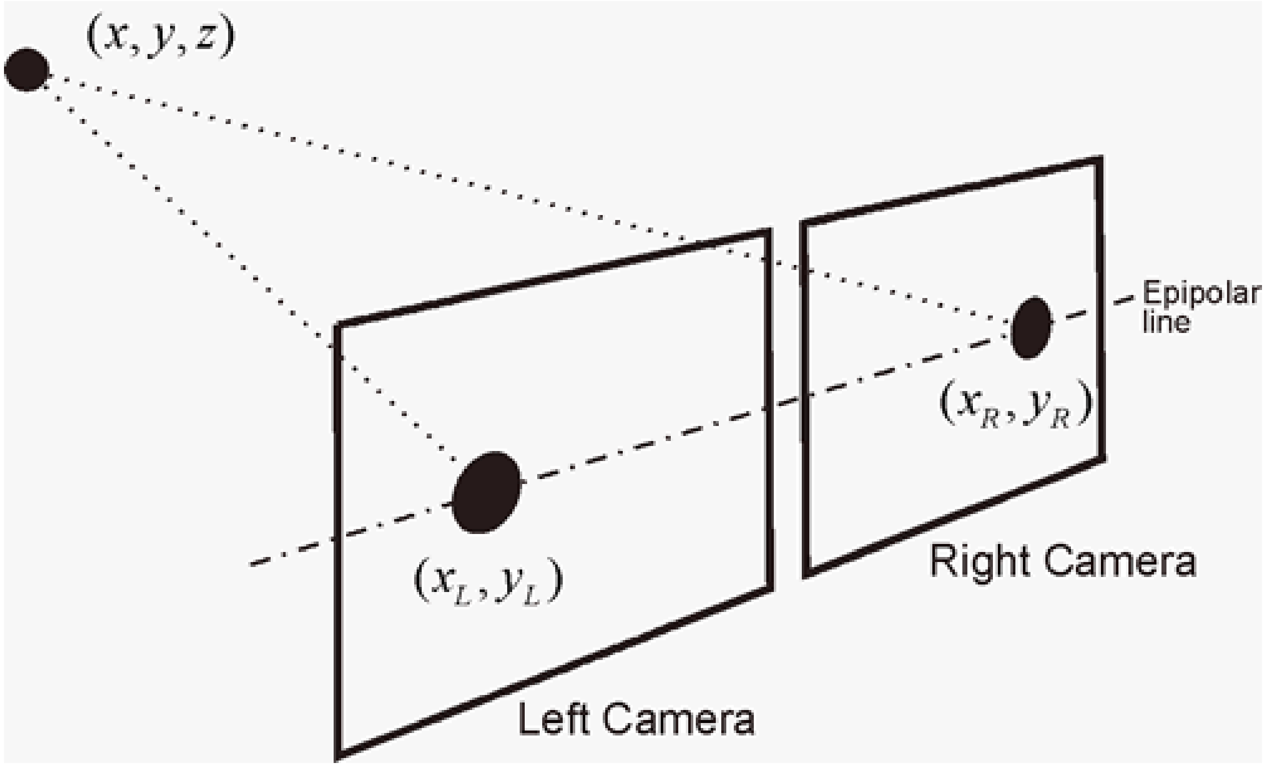
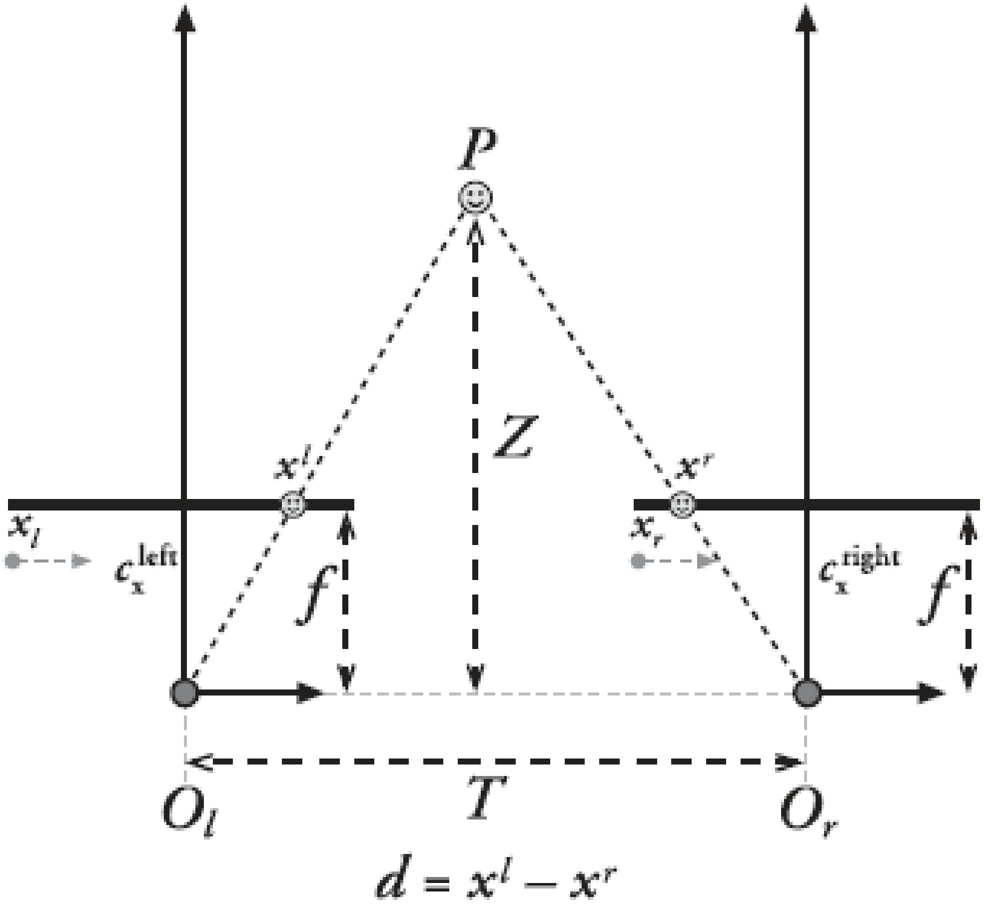
StereoVision

- Capability to define depth from 2 images
- Possible by computing correspondences between two images

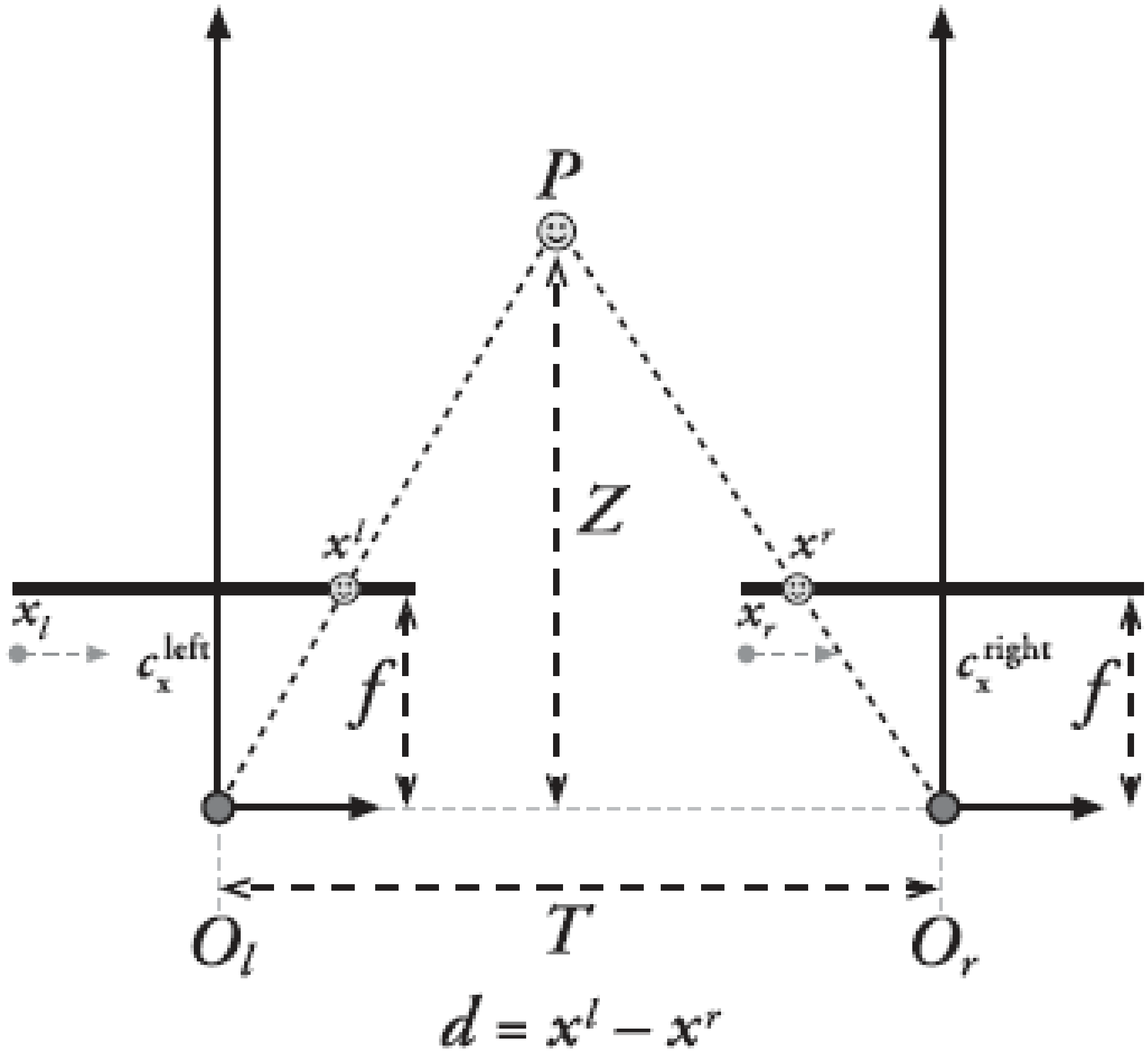


Frontal parallel arrangement

- Two perfectly aligned, coplanar cameras with same focal distance:



Frontal parallel arrangement



- Z=?

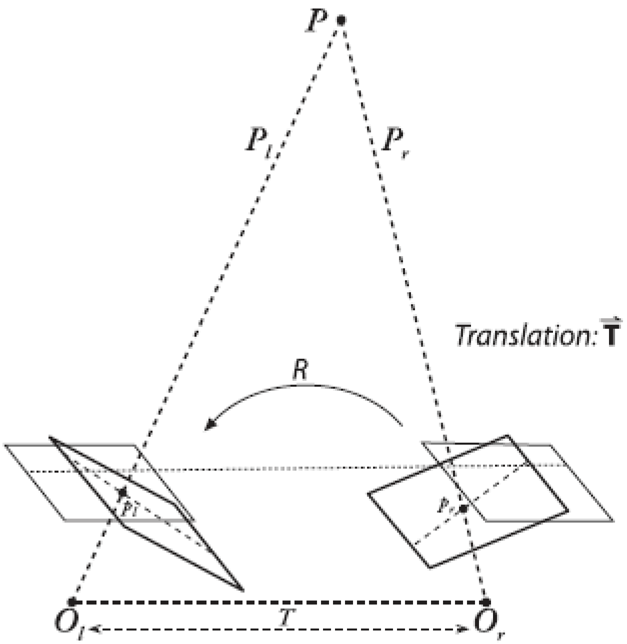
Frontal parallel arrangement

- $\frac{T}{Z} = \frac{T-(x^l-x^r)}{(Z-f)}$ then $Z = \frac{T(Z-f)}{T-(x^l-x^r)}$,
- T$Z - Z\left(x^l - x^r\right) = TZ - fT$
- So : $Z = \frac{fT}{d}$

=>Stereo system have good depth resolution for close objects since depth is inversely proportional to disparity.

Frontal parallel arrangement

- Easy to relate correspondence to depth in frontal parallel arrangement
- Problem: how to map real configuration to frontal parallel arrangement.



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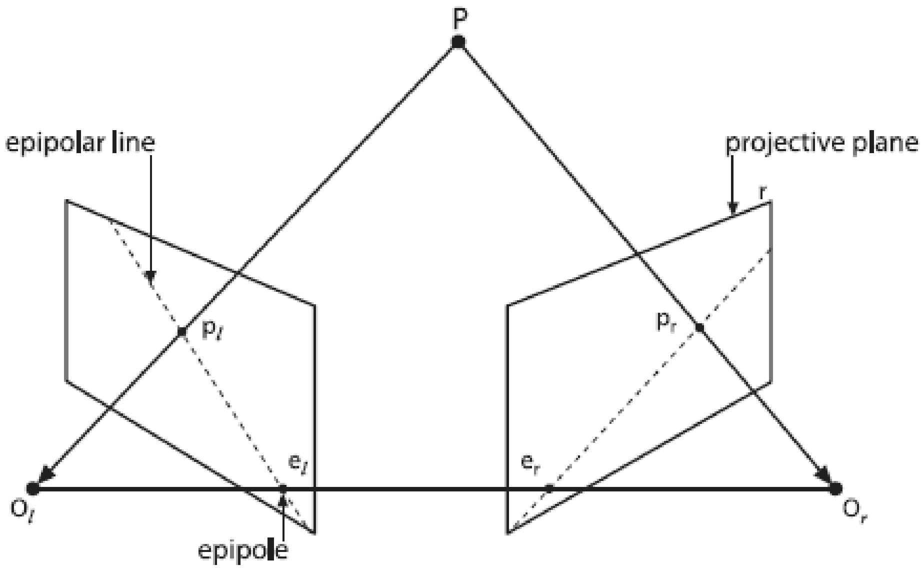
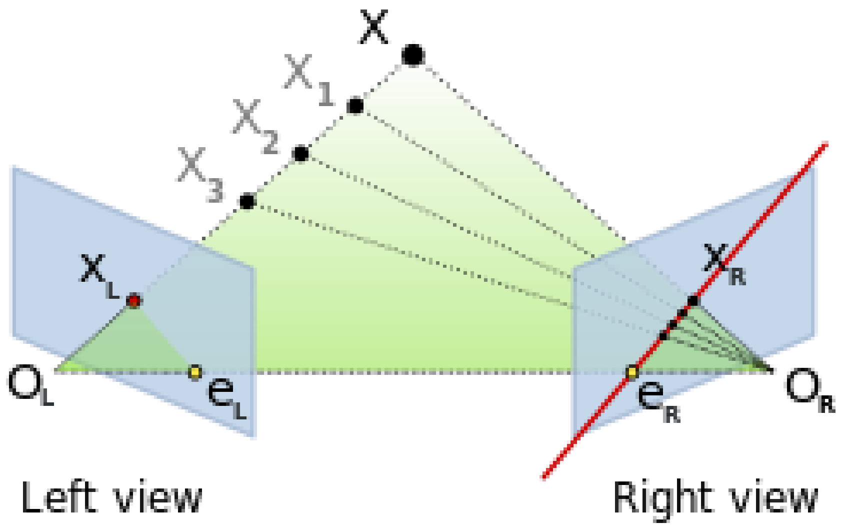
Epipolar geometry

- An epipole is a projection of the optical centre of a camera on the other image plane





- http://www.ai.sri.com/~luong/research/Meta3DViewer/EpipolarGeo.html

Epipolar geometry

- What is it useful for?:
  - Given a point in an image, its corresponding point in the other image lies on the corresponding epipolar line
  - Order is preserved (given 2 points A e B in a given order in one images, order will be the same in the other image)

=>Epipolar geometry transform a 2D search (in image) into a 1D search (along epipolar lines) saving resources and avoiding errors.

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Essential and Fundamental Matrices

- Epipolar Geometry is defined by:
  - Information about relative position between the cameras (rotation and translation) [extrinsic] – Essential Matrix(E)
  - Intrinsic parameters of the cameras (focal length, lens distortion, optical centre, etc…) – Fundamental Matrix(F)

Essential matrix

- Matrix that maps a 3D point in one image with its corresponding 3D point on the other image considering translation and rotation between cameras:
- $p_l^T E p_r = 0$
- p_l and p_r are in camera 3D coordinate system

Fundamental matrices

- Matrix that maps a pixel in one image with its corresponding pixel on the other image considering rotation, translation and intrinsic parameters of the cameras:
- $u_l^T F u_r = 0$
- u_l e u_r are in image 2D coordinate system

Fundamental and essential matrices

- Fundamental and Essential matrices represent the transformation between the stereo pair images. Fundamental matrix operates in image coordinates (pixels) and Essential matrix operates in physical coordinates.
- Possible to evaluate with 8 point correspondences (eight point algorithm: http://www.cs.unc.edu/~marc/tutorial/node54.html)

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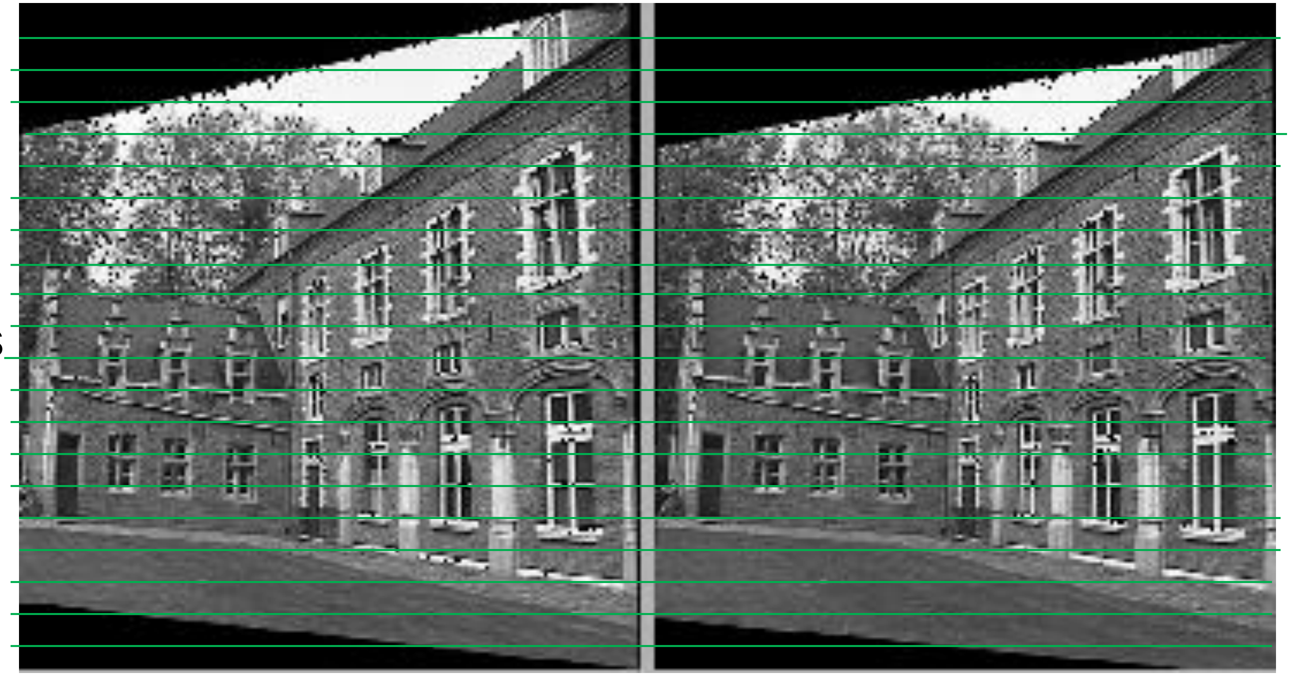
Image rectification

- Given the fundamental matrix, it is possible to rectify an image by aligning epipolar lines in rows on the two rectified images getting a frontal parallel arrangement.

Image rectification

Original images

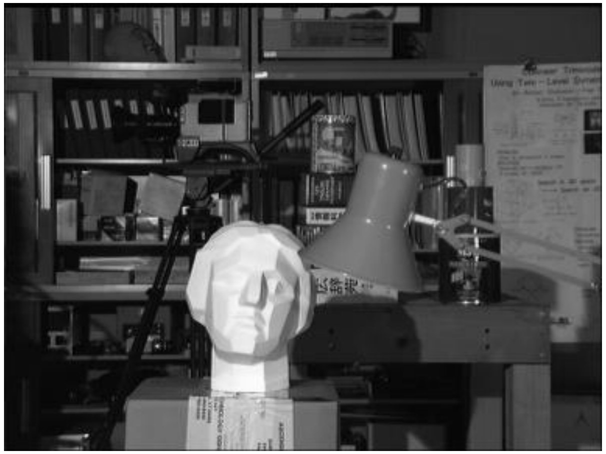
Rectified images

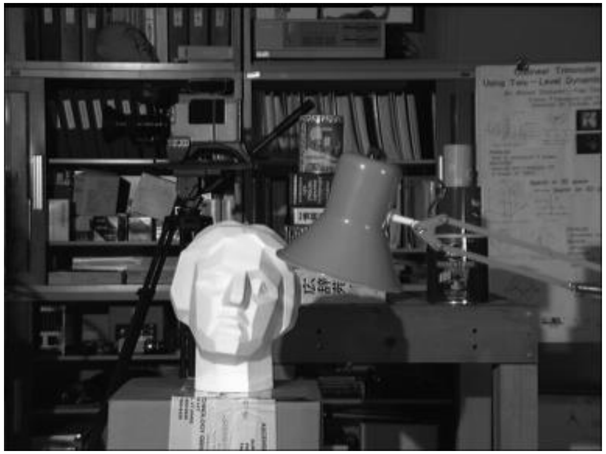


From Visual 3D Modeling from Images (http://www.cs.unc.edu/~marc/tutorial/)

Disparity map

- In rectified images, disparity is simply difference between pixel coordinates xl and xr.





Tsukuba head and lamp stereo dataset

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Template Matching

- Template matching is moved to all positions (u, v) in image and computes $p(a, b)$ to evaluate how well template matches image in that position

Original Image

Template

Template Matching

$p(a, b)$

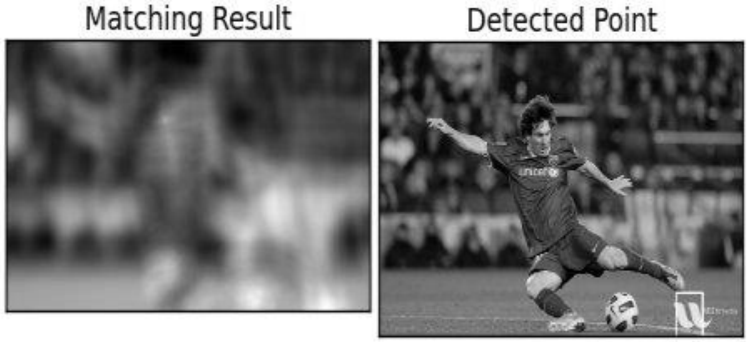
Matching function

Detected Point

- Object is on image at position where occurs $\max(p(a, b))$ if $\max(p(a, b)) > \text{threshold}$

- Several possible functions to compare template and image $p(a, b)$:
  - Square difference matching

  - Correlation matching



  - Correlation coefficient matching

  - …

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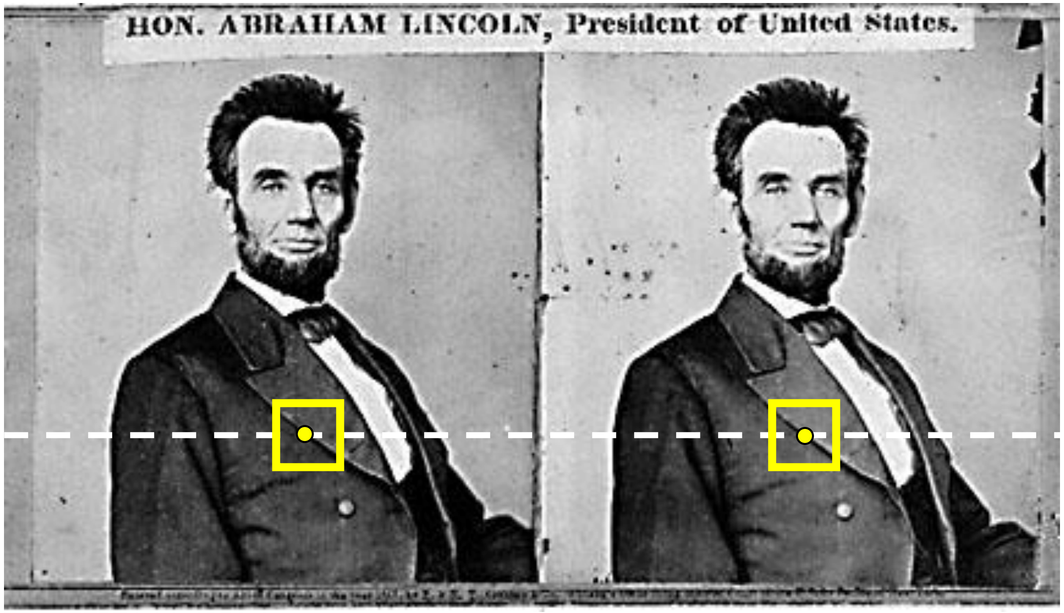
Stereo Matching algorithm

- Match Pixels in Conjugate Epipolar Lines
  - This is a tough problem
  - Numerous approaches
    - A good survey and evaluation: http://vision.middlebury.edu/stereo/

Basic stereo algorithm



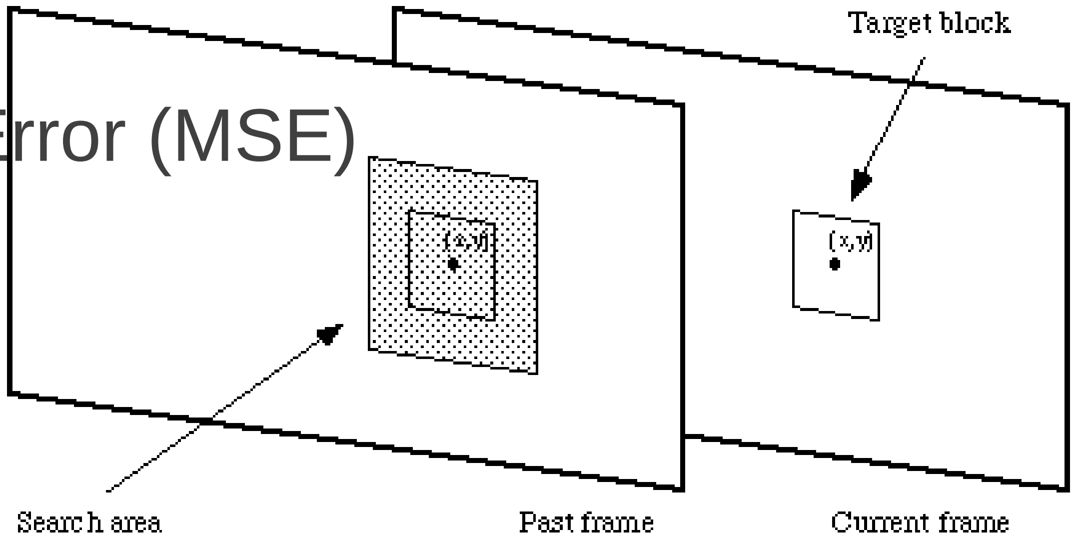
For each epipolar line

For each pixel in the left image

- compare with every pixel on same epipolar line in right image
- pick pixel with minimum match cost

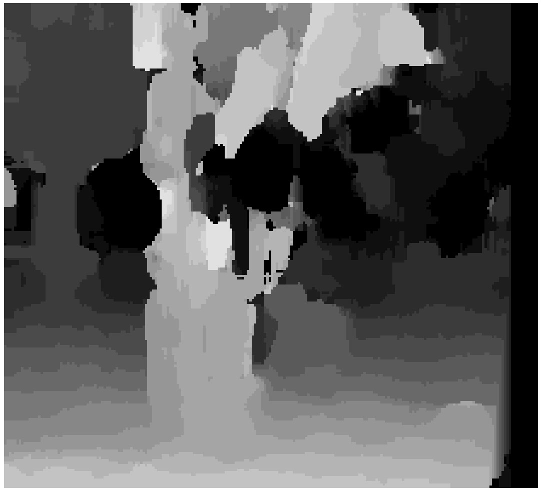
Block Matching algorithm

- Block Matching:
  - Divides an image into macroblocks and compare each with a corresponding block and its neighbours in a another image
- Several Metrics
  - Mean difference or Mean Absolute Difference (MAD)
  - Mean Squared Error (MSE)
  - …



Window size

W = 3



W = 20

Effect of window size

- Smaller window
- Larger window

Better results with *adaptive window*

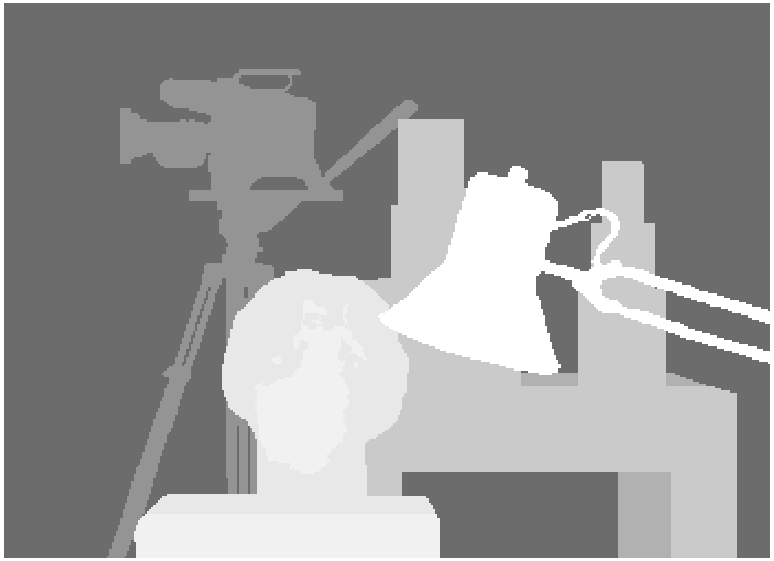
- T. Kanade and M. Okutomi, *A Stereo Matching Algorithm with an Adaptive Window: Theory and Experiment*,, Proc. International Conference on Robotics and Automation, 1991.
- D. Scharstein and R. Szeliski. Stereo matching with nonlinear diffusion. International Journal of Computer Vision, 28(2):155-174, July 1998

Stereo results

– Data from University of Tsukuba

– Similar results on other images with ground truth

Scene



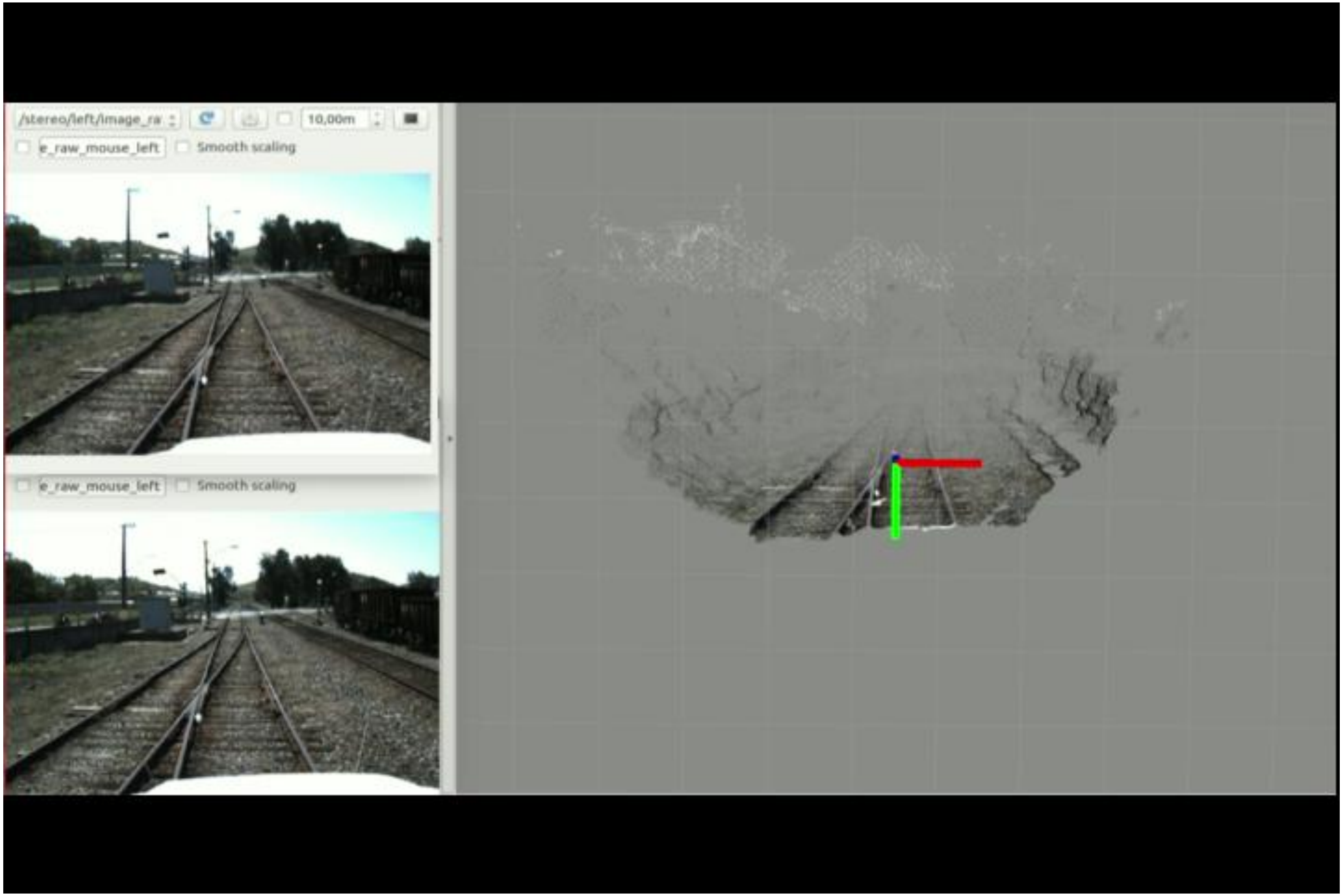
Ground truth

Stereo: Real application

- Sistemas Embarcados de Vistoria (SEV)
  - Stereo vision system with two AVT Mako cameras
  - baseline is around 0.1 meters
  - horizontally aligned.

Stereo: Real application

- Stereo Vision and SLAM



Stereo Vision – Errors

- Camera calibration errors
- Poor image resolution
- Occlusions
- Violations of brightness constancy (specular reflections)
- Large motions
- Low-contrast image regions

Stereo Vision - Steps

- Calibrate cameras
- Rectify images
- Compute disparity
- Estimate depth

Stereo Vision in OpenCV

- cvFindChessboardCorners: detect chessboard corner in stereo images
- cvStereoCalibrate: calibrates stereo rig
- cvStereoRectify: computes rotations that make both camera planes the same.
- cvInitUndistortRectifyMap and cvRemap: use to compute undistortion map and rectified images
- Stereo correspondence (ex: cvFindStereoCorrespondenceBM): computes the disparity map.
- cvReprojectImageTo3D: disparity map to 3D with calibrated cameras

OPENCV STEREO VISION DEMO

Some references

- Gary Bradski and Adrian Kaehler. *Learning OpenCV: Computer Vision with the OpenCV Library*. O'Reilly, Cambridge, MA, 2008.
- Olivier Faugeras Three-dimensional computer vision: a geometric viewpoint. MIT Press Cambridge, MA, USA ©1993
- Szeliski, R. (2010).. Computer Vision: Algorithms and Applications, Springer
- Quang-Tuan Luong. "Learning Epipolar Geometry". Retrieved 2007-03-04.