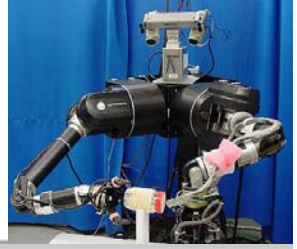
Einführung in Visual Computing

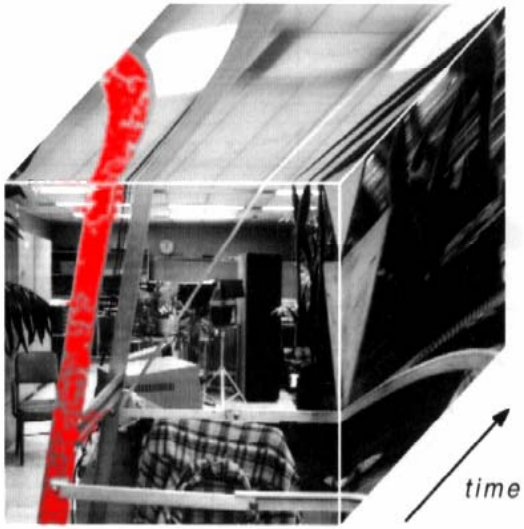
Unit 18: Stereo and Motion

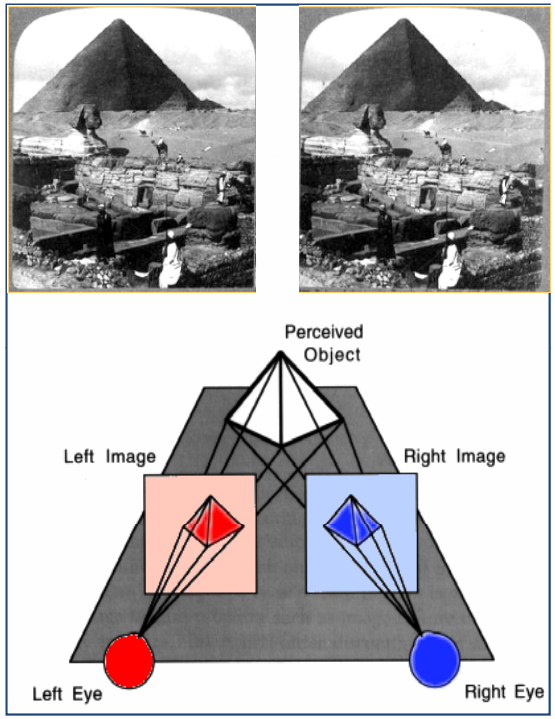


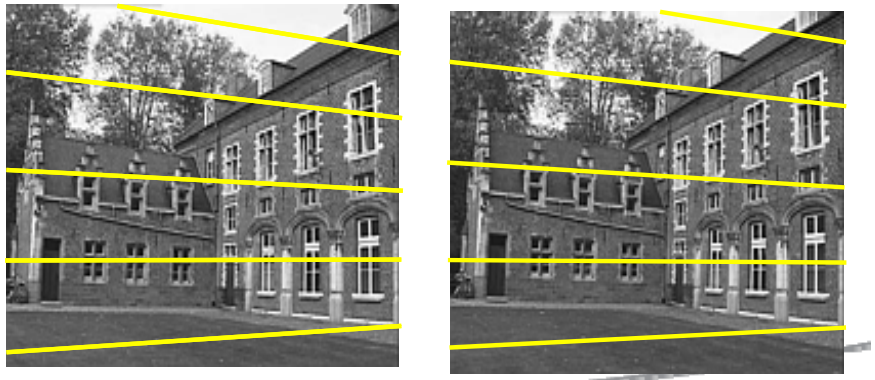
http://www.caa.tuwien.ac.at/cvl/teaching/sommersemester/evc

Content:

- Introduction to Stereo Vision
- Stereo Geometry
- Epipolar Lines
- Correspondence Problem
- Area-Based Stereo Matching
- Feature Based Stereo Matching
- Structure from Motion
  - Motion Field
  - Motion Vector
  - Optical Flow

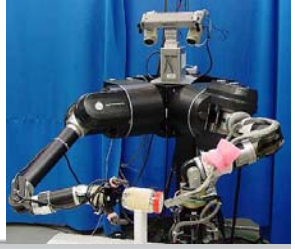






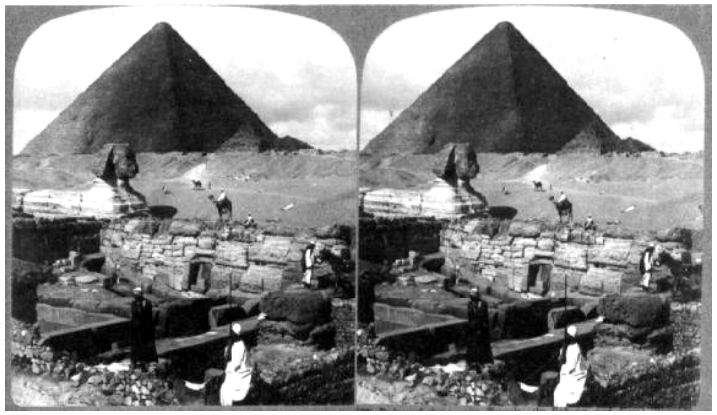
Stereo Vision

Stereo Vision

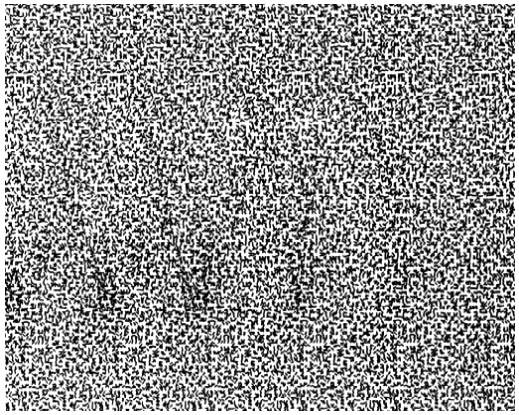


2 dim + 2 dim + geometry => 3 dim

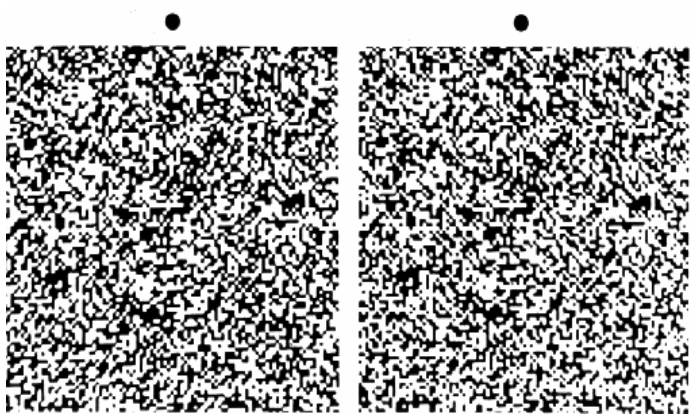
- Correct 3d information using 2d images:
  - 2 or more images taken from different geometric positions plus geometric calibration of camera
  - Tries to imitate human visual system
  - Is also used in the entertainment industry



Stereo photographs

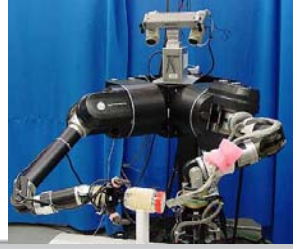


Auto stereogram

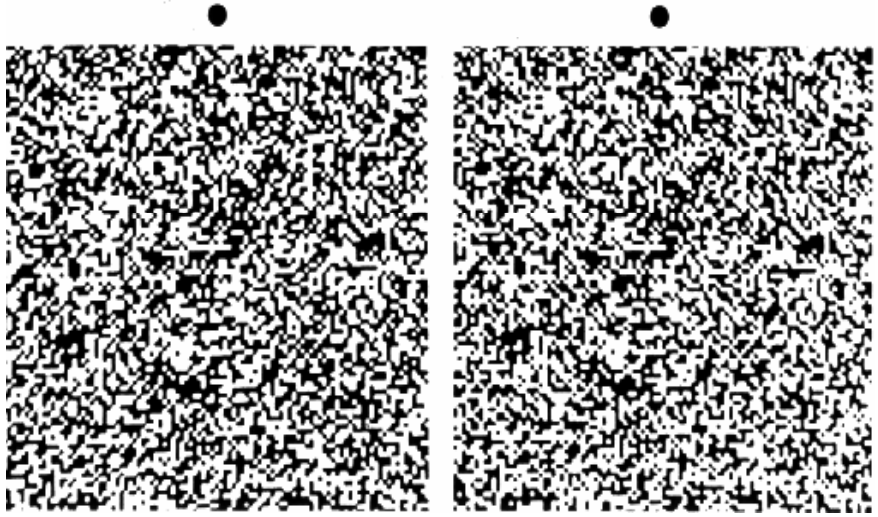


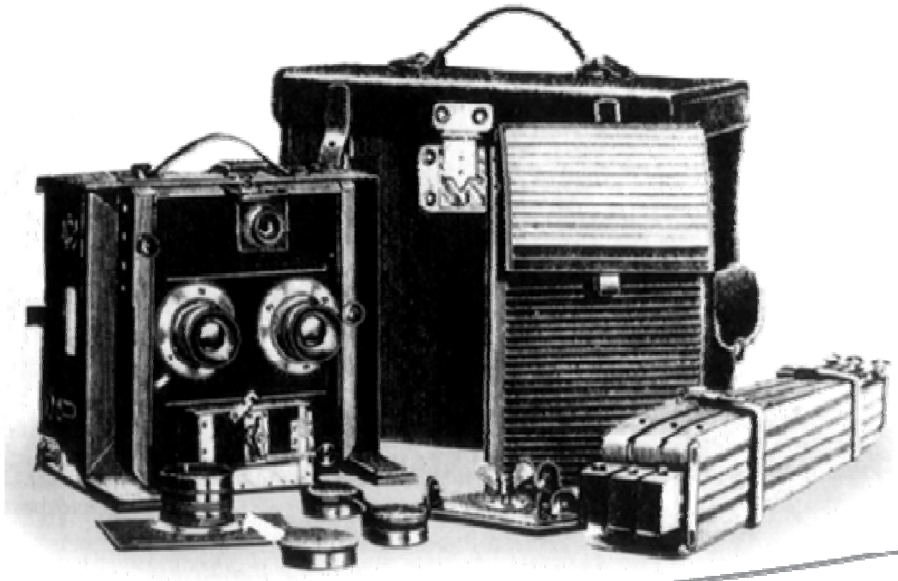
Random Dot Stereogram

Stereo Vision



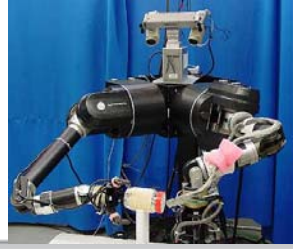
- 3D vision is a natural product of our visual perception:
  - Learned capability
  - Is learned in the first month in life: Hand - eye problem
  - Stereo emerges in the brain => proof: Random Dot Stereograms
  - Also in entertainment industry and art
  - Around 1890 first stereo camera



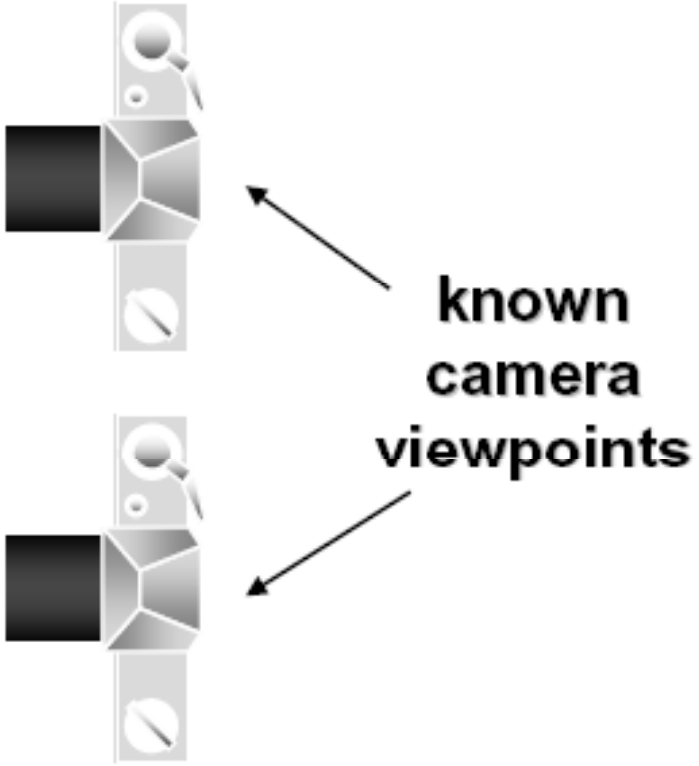


Mark Twain at Pool Table", no date, UCR Museum of Photography

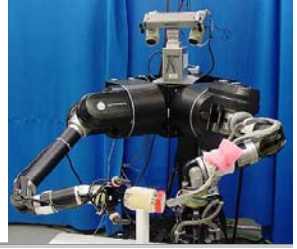
Stereo Reconstruction



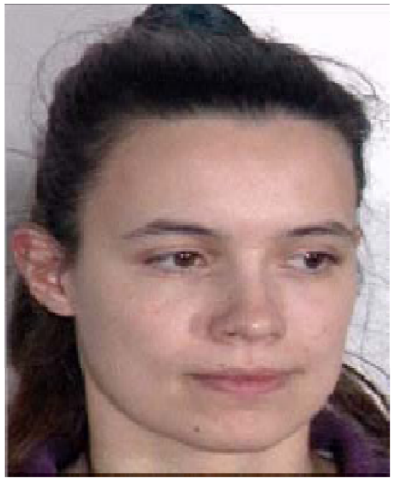
- Shape (3D) from two (or more) images

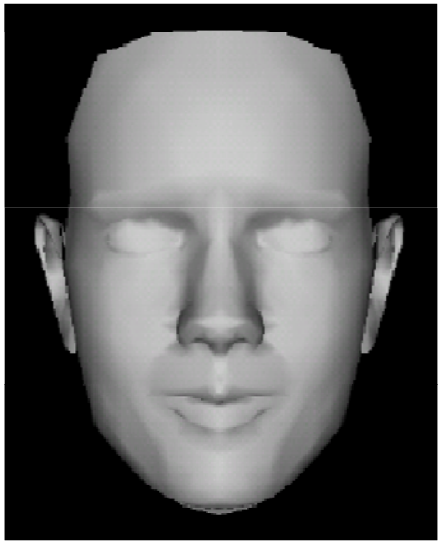


Example



images



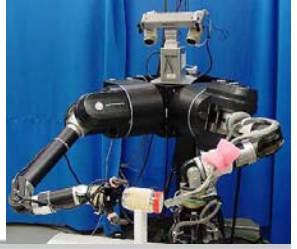


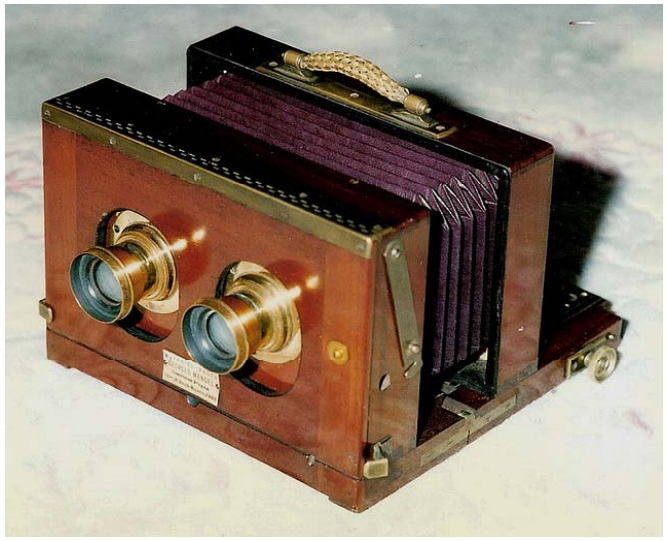
shape

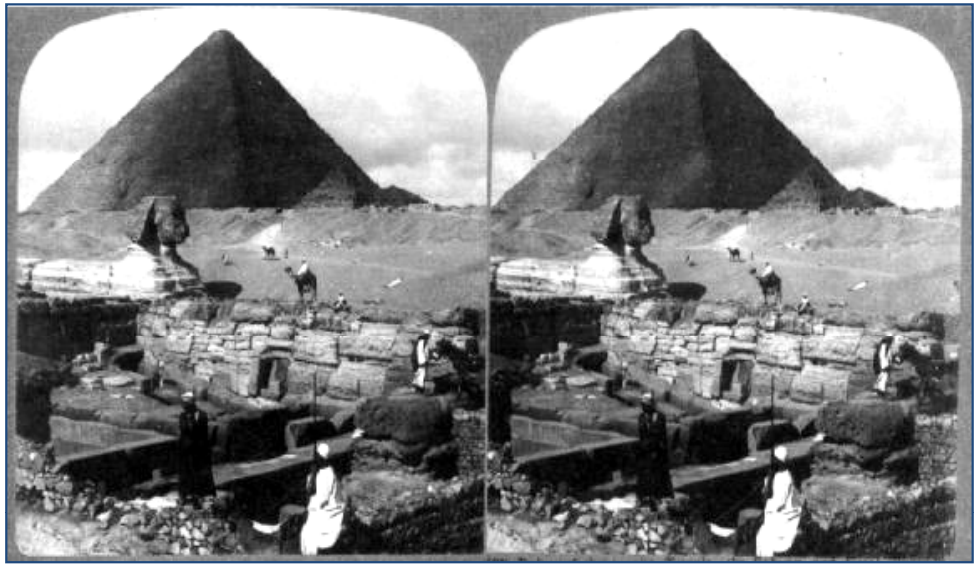
surface
reflectance

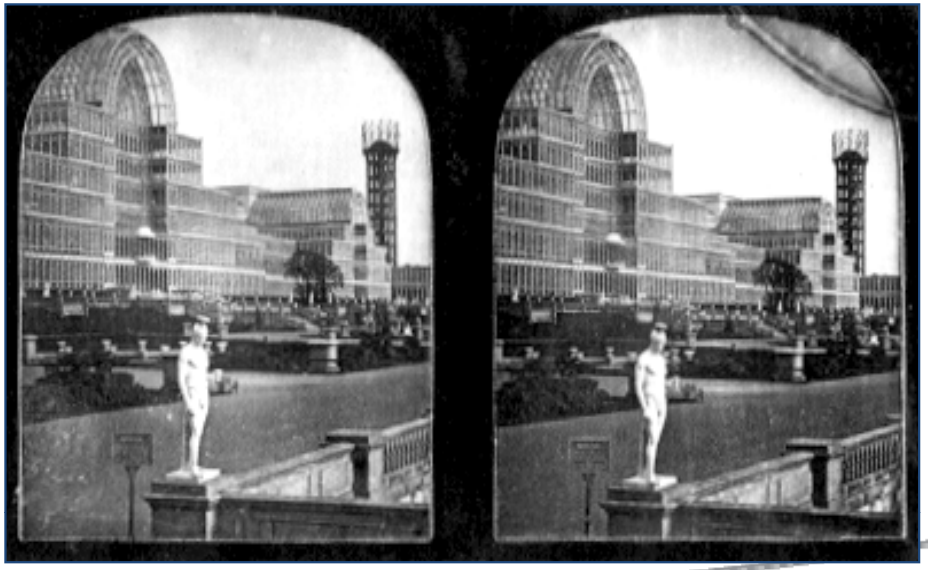
Stereoscopy

Stereo Camera: 1890

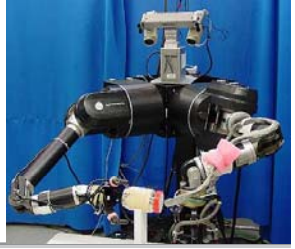




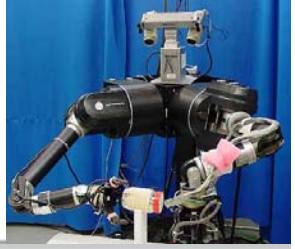




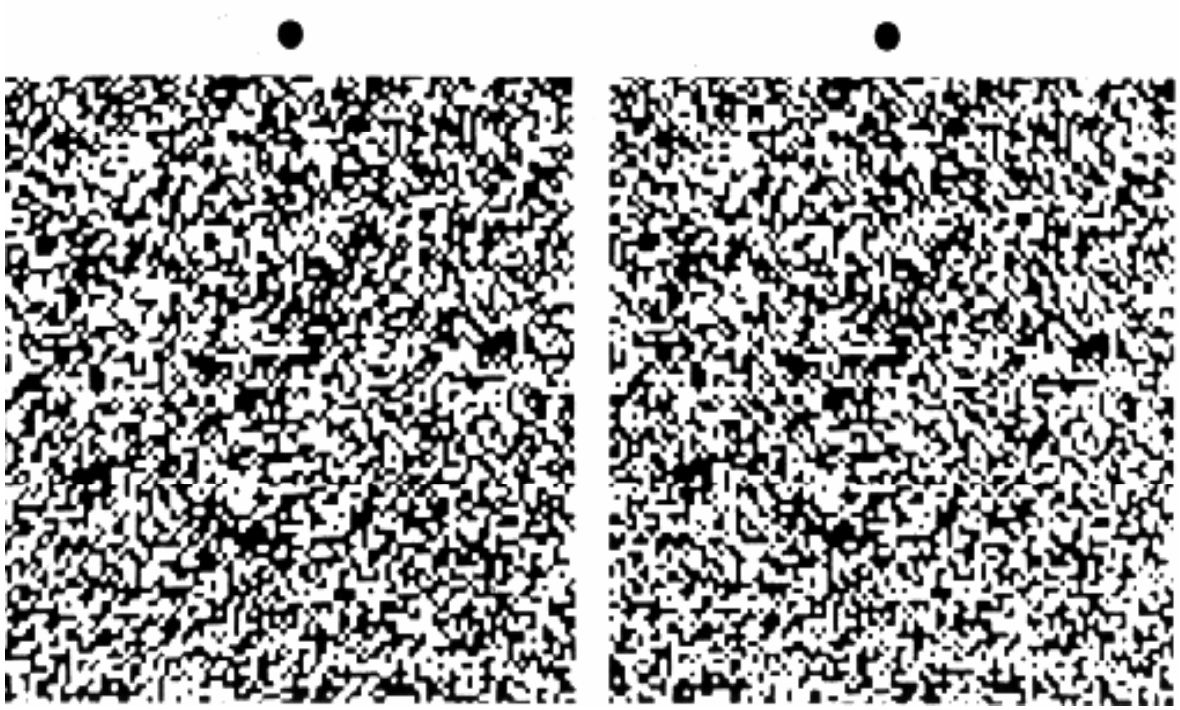
Stereo Camera: 120 years later



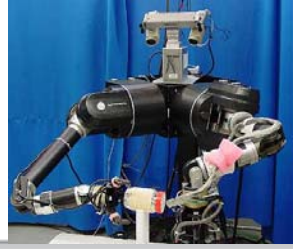
Random Dot Stereograms



- 1959: Evidence that human brain generates 3D impressions by first random dot stereogram [Julez59]
  - Revolutionized psychology of perception
  - „modern“ from time to time

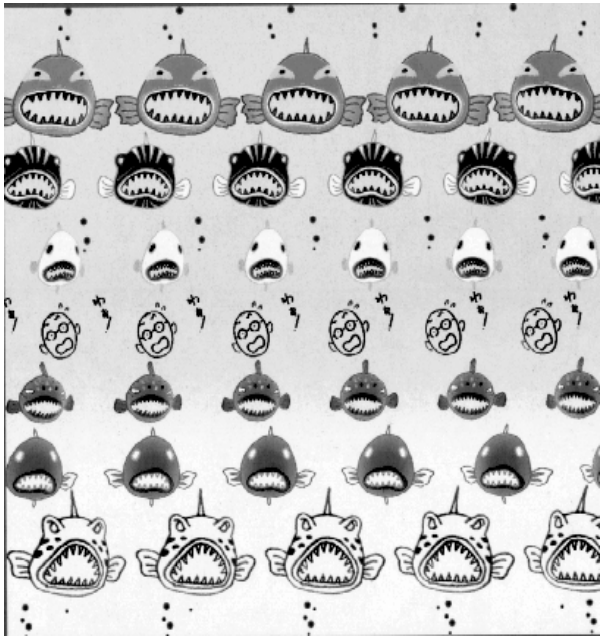


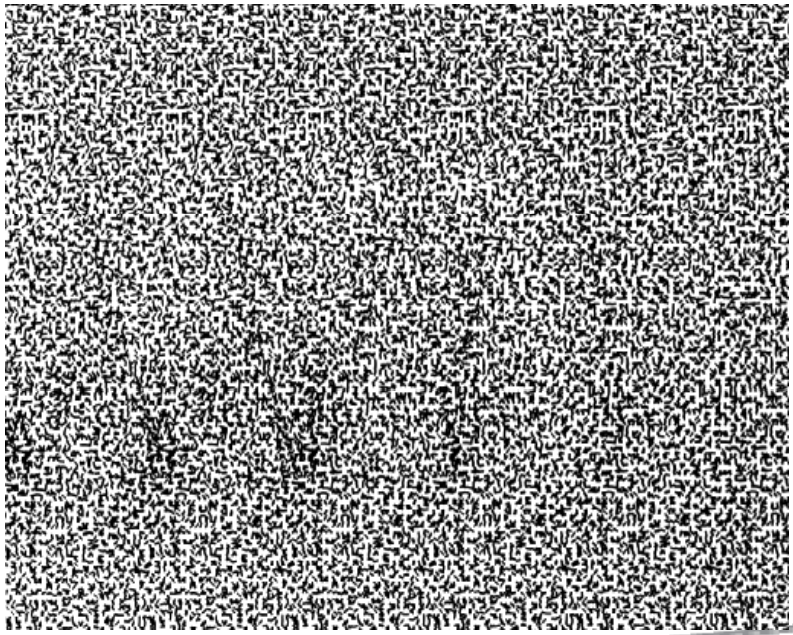
Autostereograms



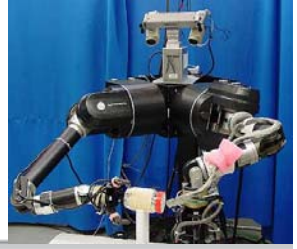
For some people Random Dot Stereograms are complicated to view: Autostereogramme [Tyler79]:

- Also called single image Stereogram
- Form of Art
- Is formed by repetition of patterns in specific intervals



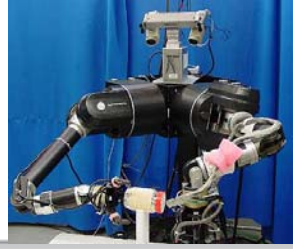


Stereoscopes

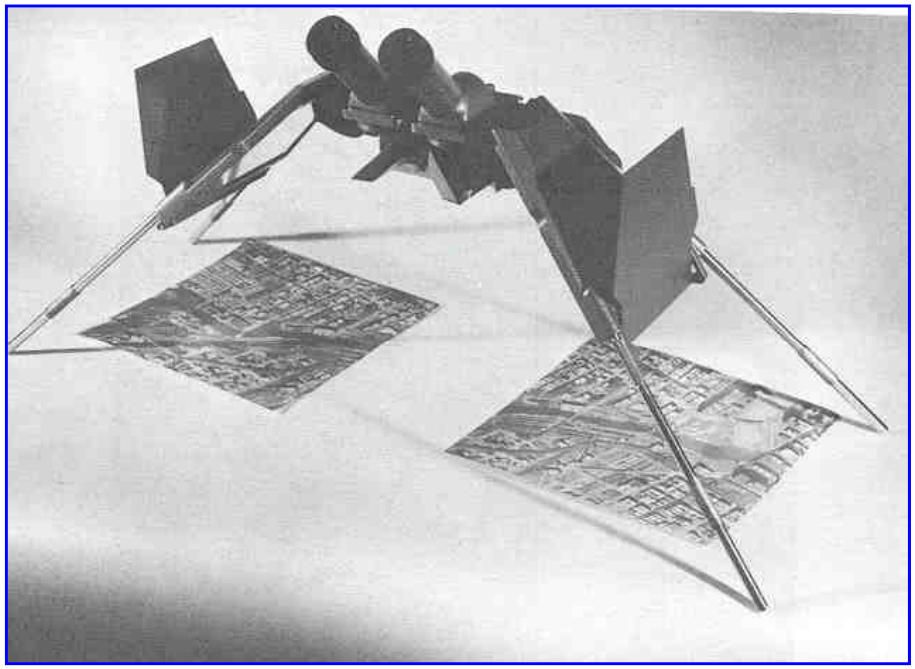


- A binocular optical instrument that helps us view two properly oriented photos to
- obtain a 3-dimensional model.
- Lens (pocket) stereoscope
  - Simplest
  - Least expensive
  - Small
  - 2-4 x magnification

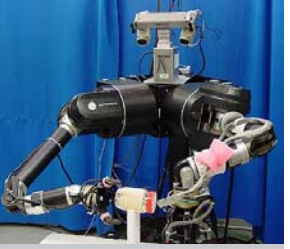
Stereoscopes

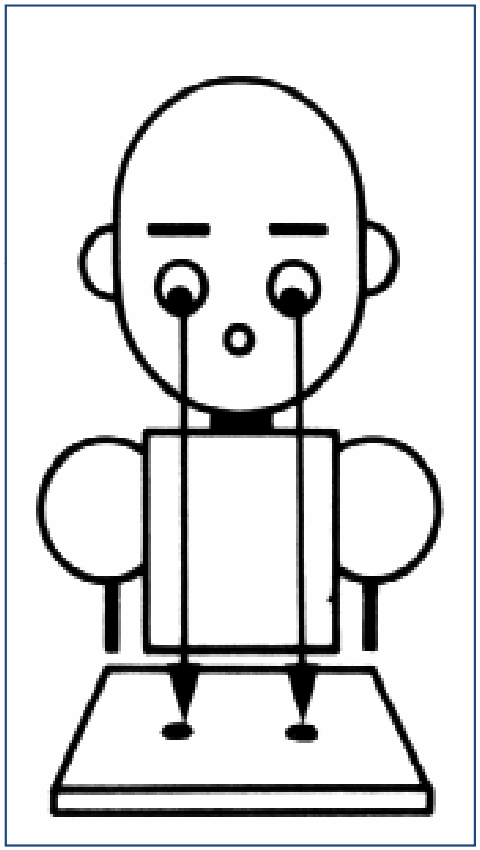


- Mirror stereoscope
  - Photos can be placed separately for viewing



Stereograms – Parallel Technique

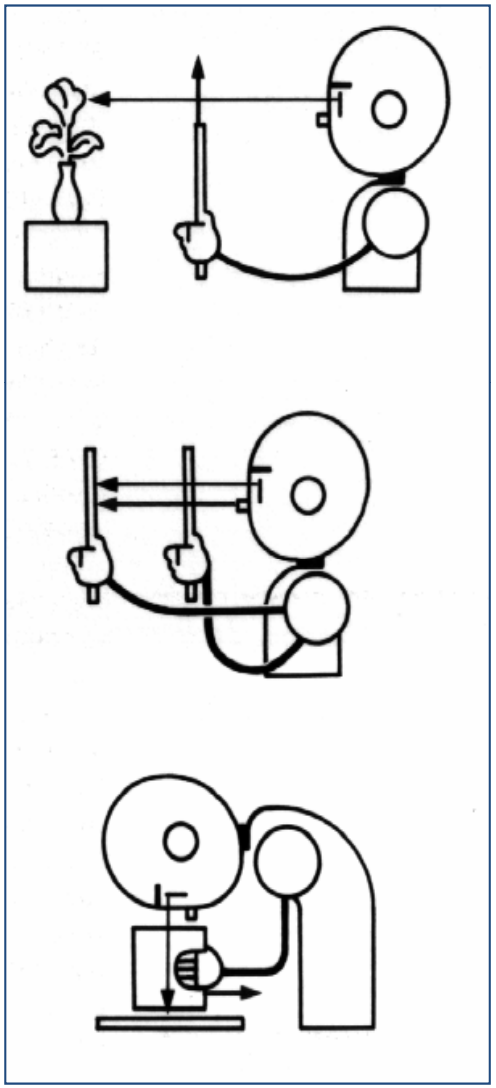


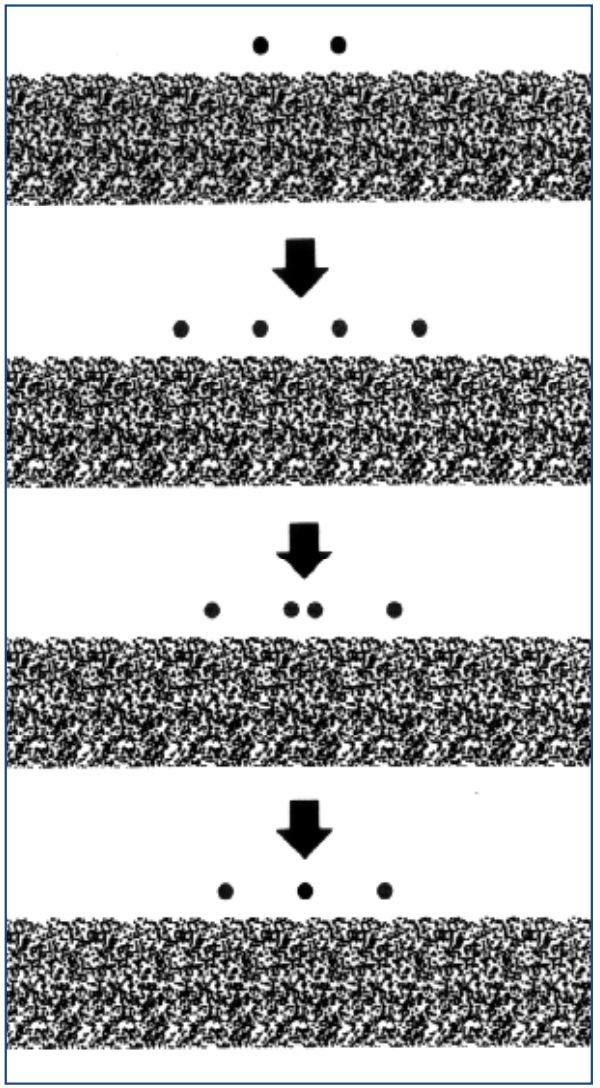


Insertion-technique

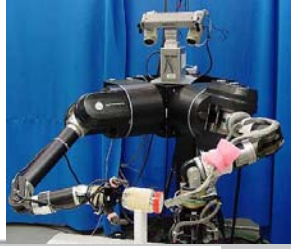
Tip of nose-technique

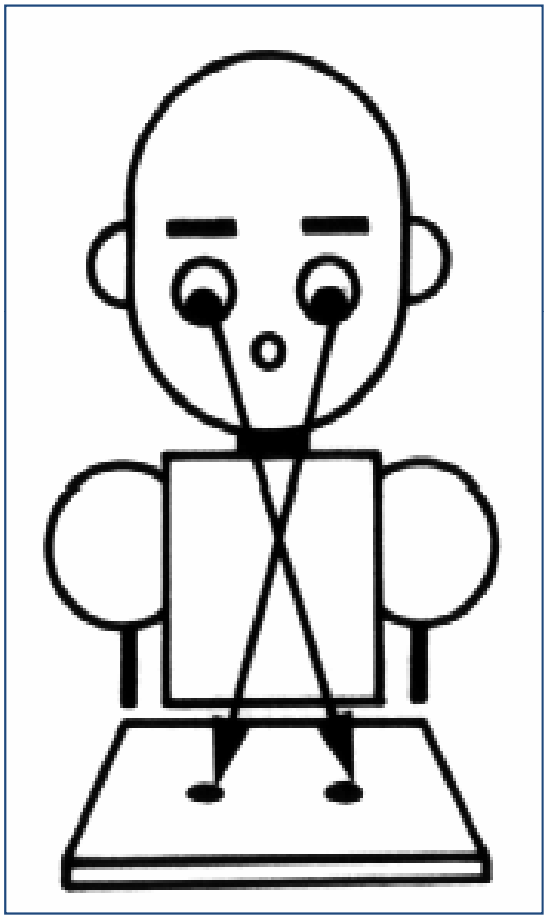
Separation-technique

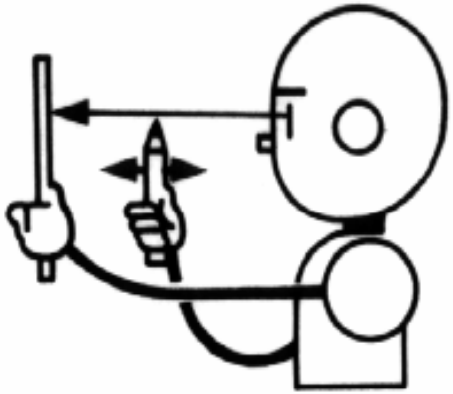




Stereograms – Cross-eye Technique

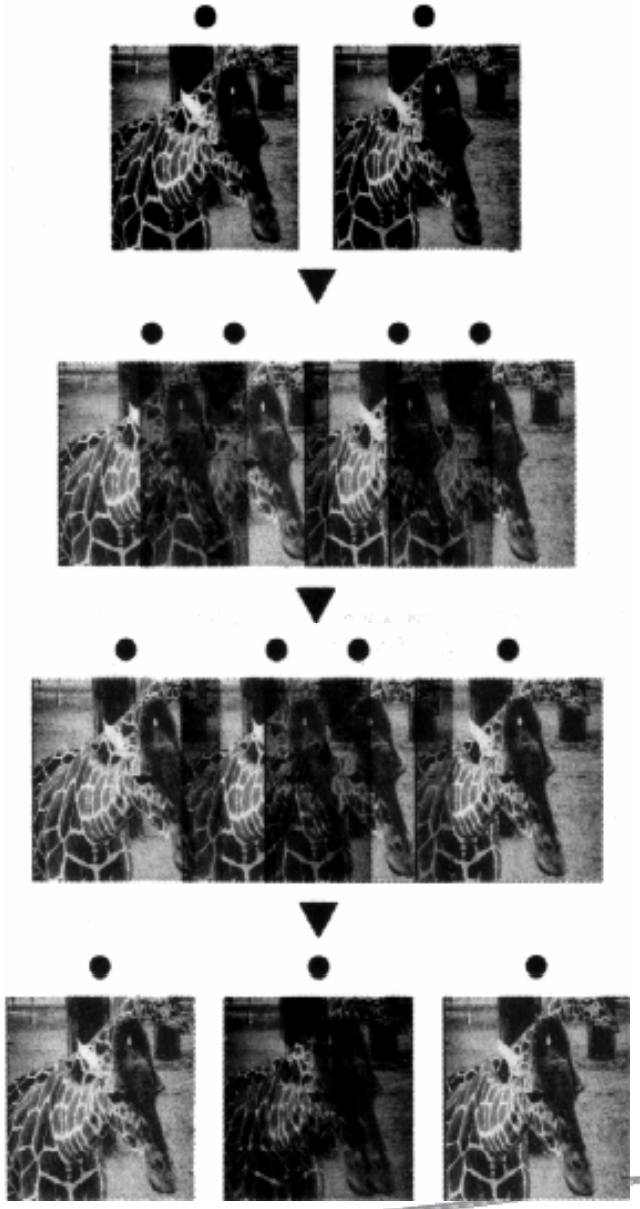






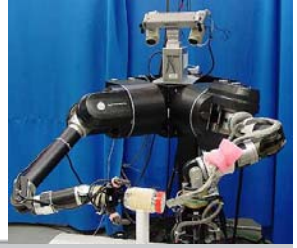
Pencil technique

Ring technique

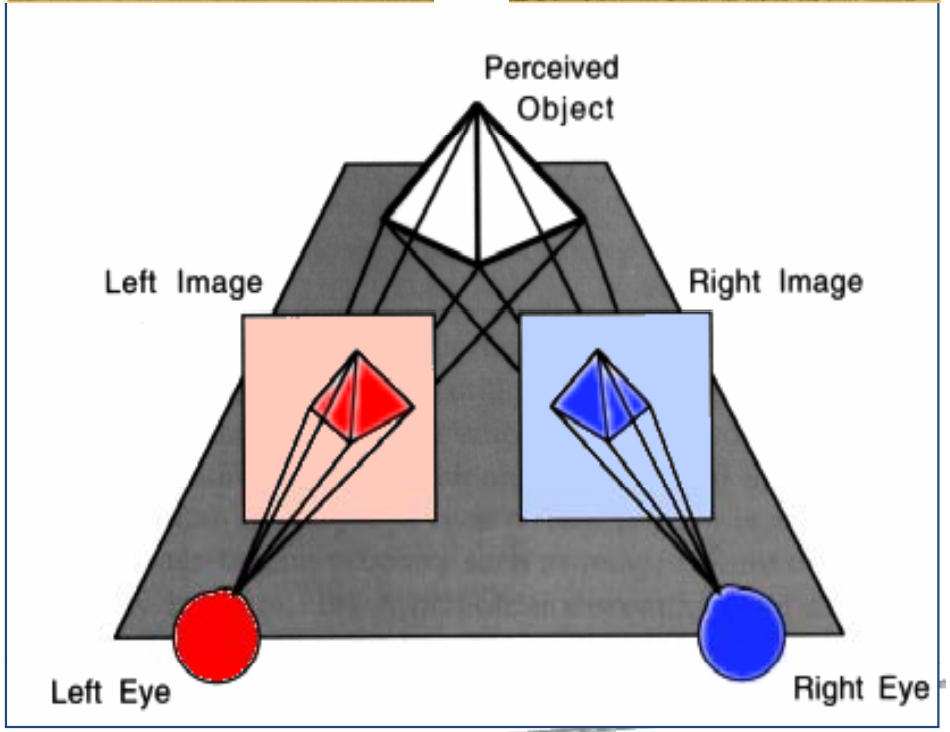


Stereo Analysis

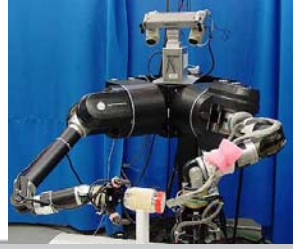
Stereo Analysis



- Using two views of an object from two different positions enables to reconstruct 3d shape of the object out of the geometric differences of the two 2d projections:
  - two 2d images
  - geometric relation between cameras

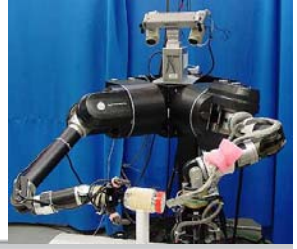


Challenges

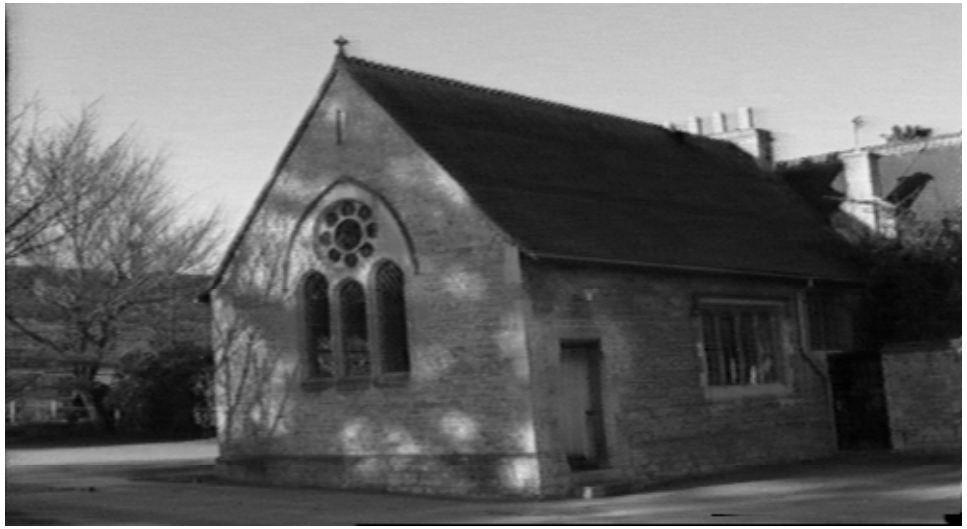


- Ill-posed inverse problem
  - Recover 3-D structure from 2-D information
- Difficulties
  - Uniform regions
  - Half-occluded pixels

The Objective

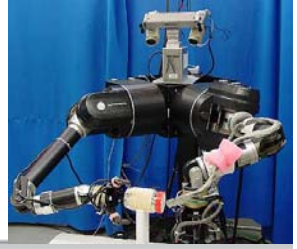


- **Given** two images of a scene acquired by known cameras compute the **3D position of the scene** (structure recovery)



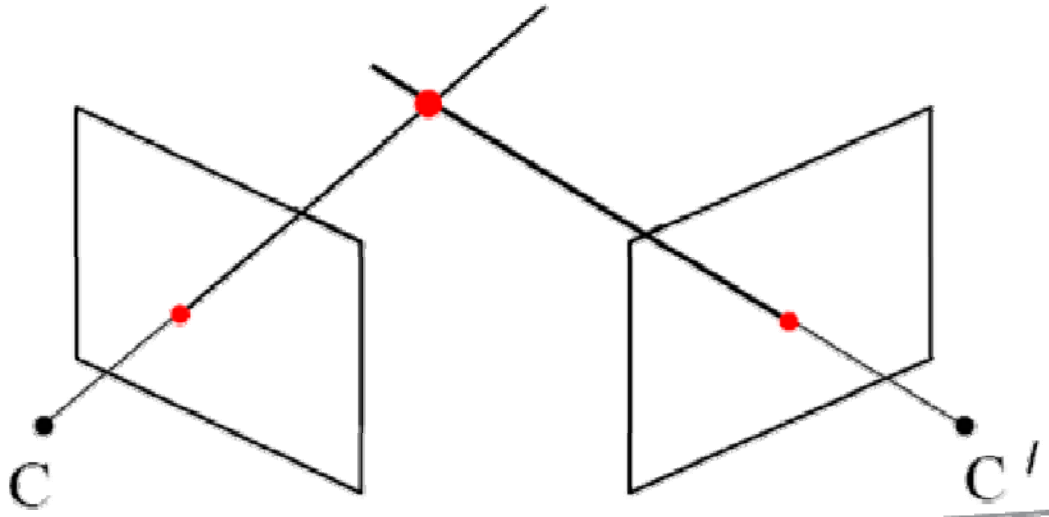
- Basic principle: triangulate from corresponding image points
  - Determine 3D point at intersection of two back-projected rays

The Solution

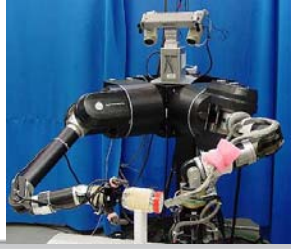


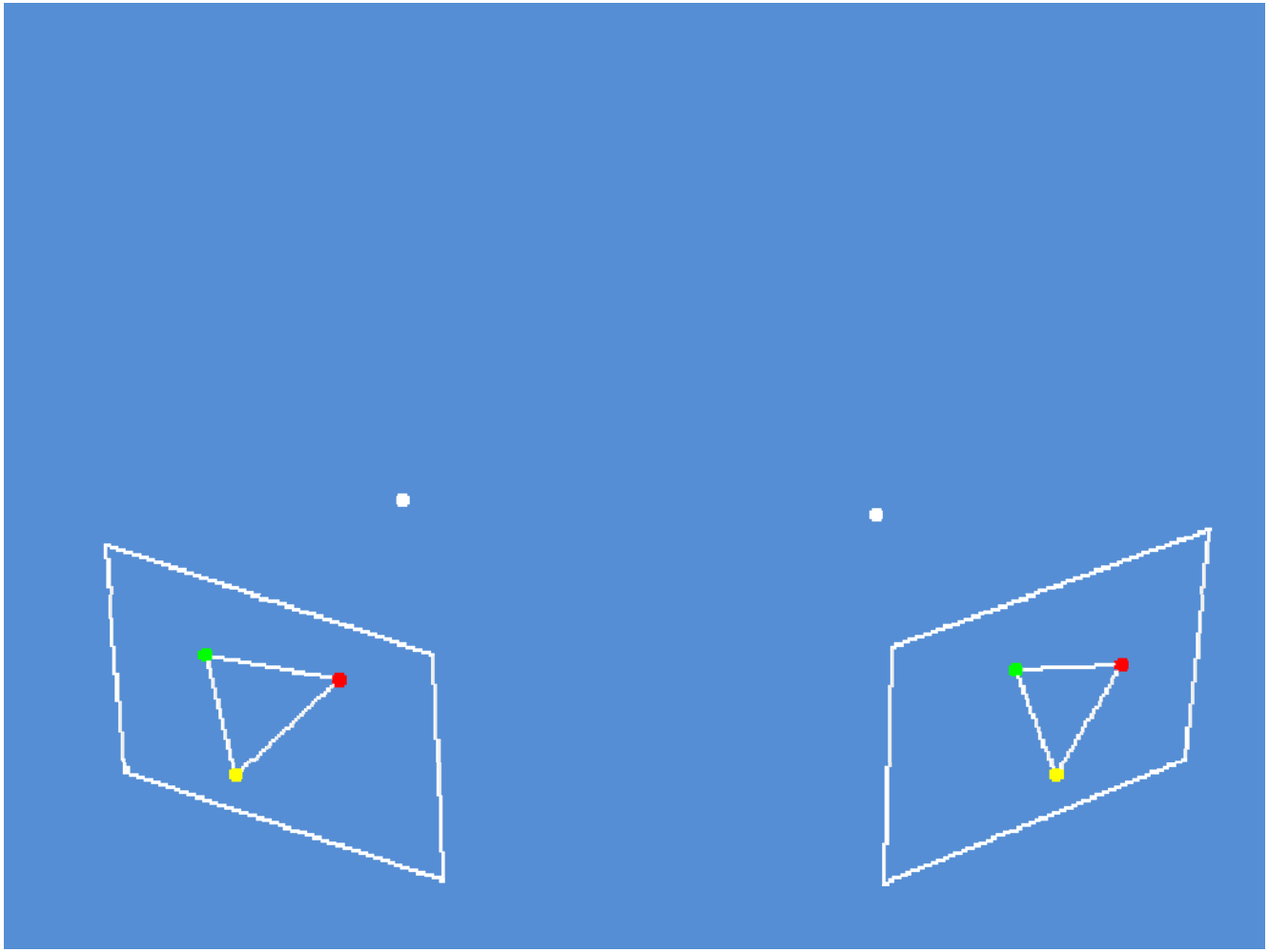
- Corresponding points are images of the same scene point

Triangulation



Fundamentals of Stereo Vision





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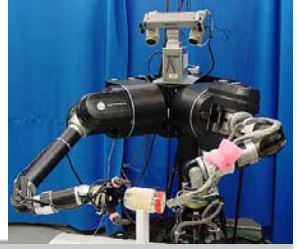

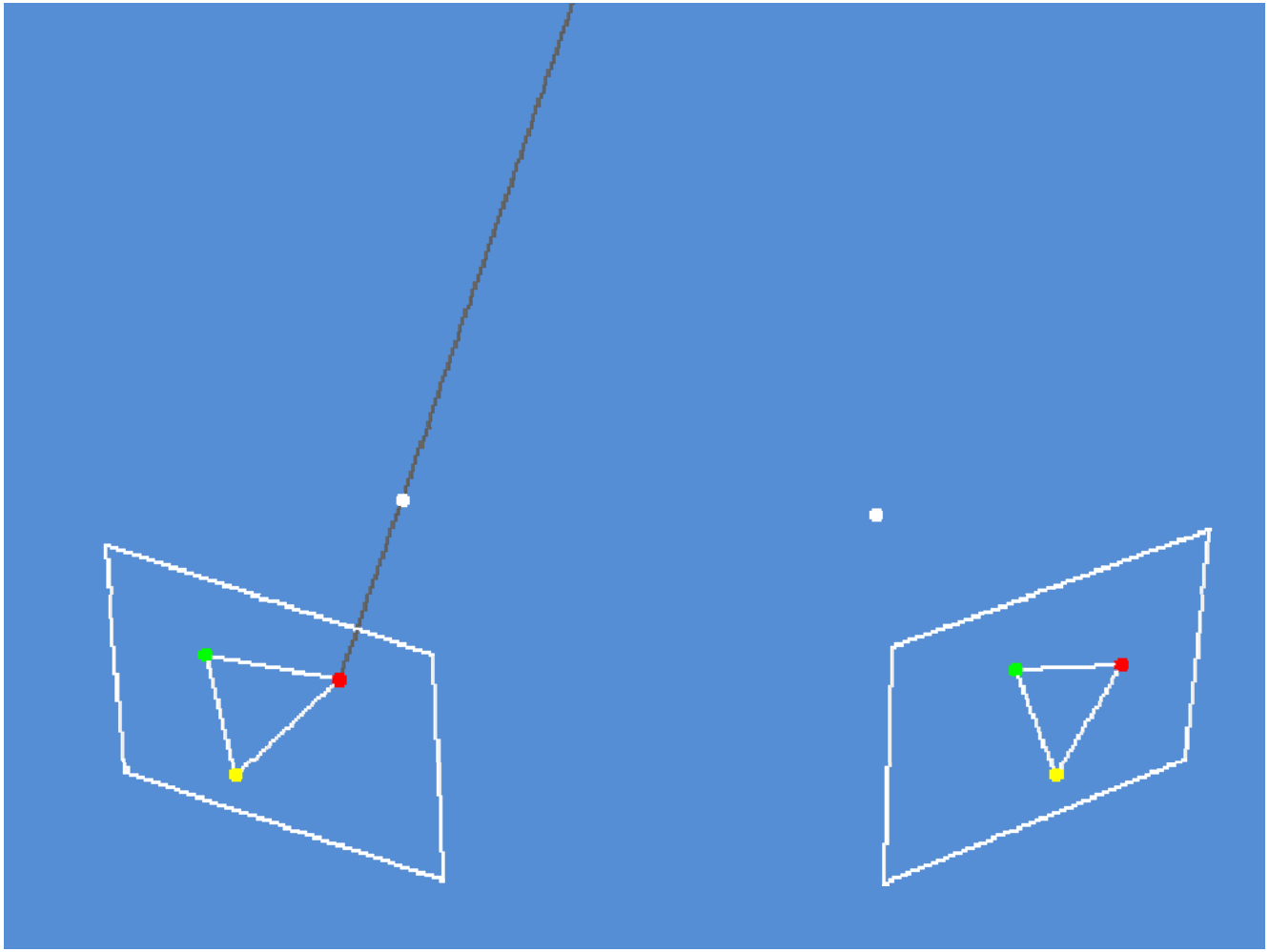

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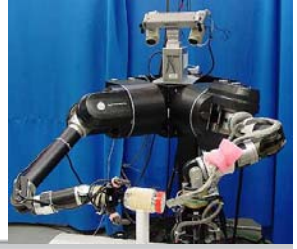

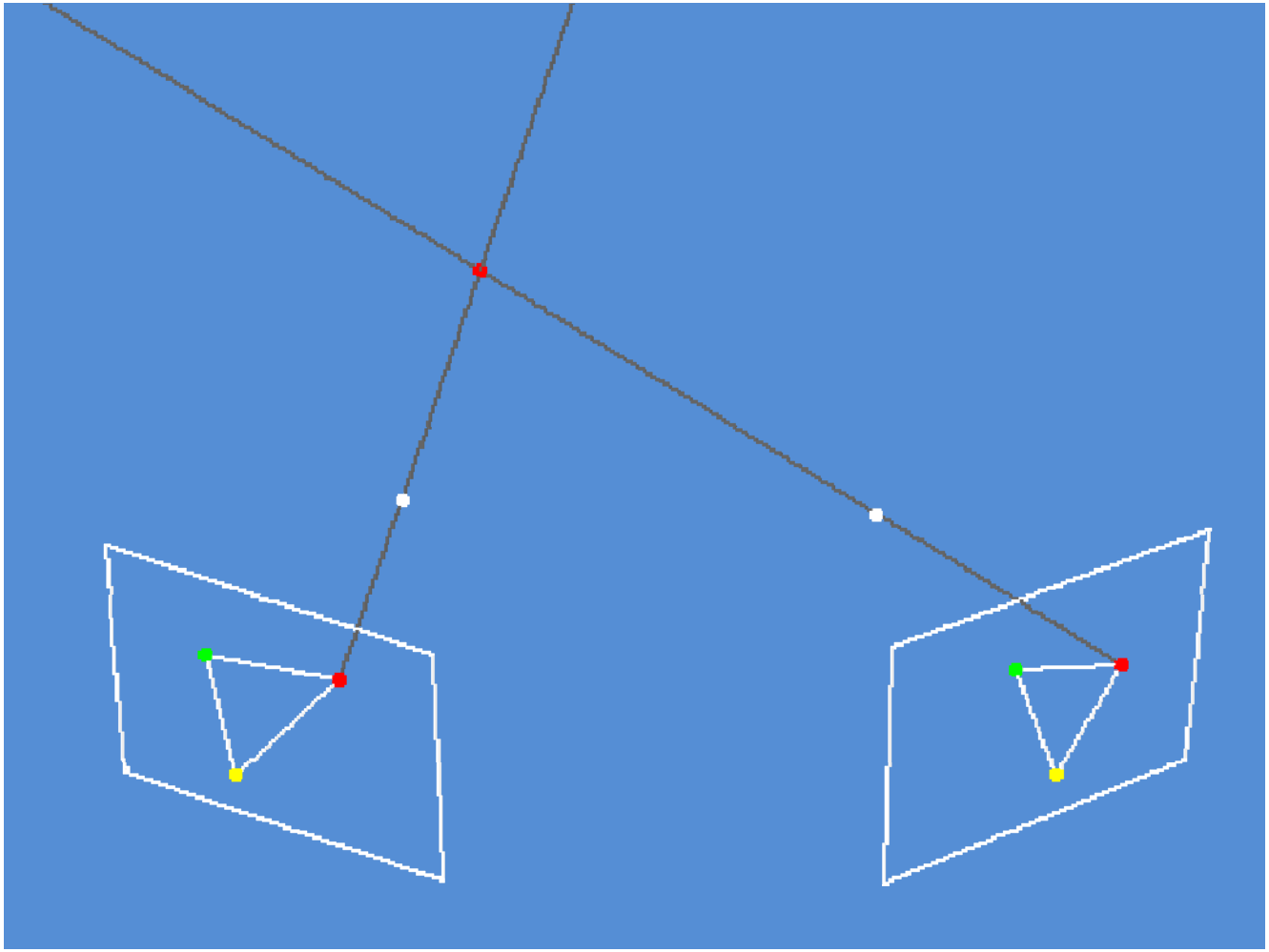

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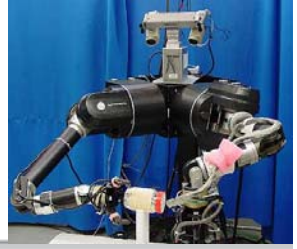

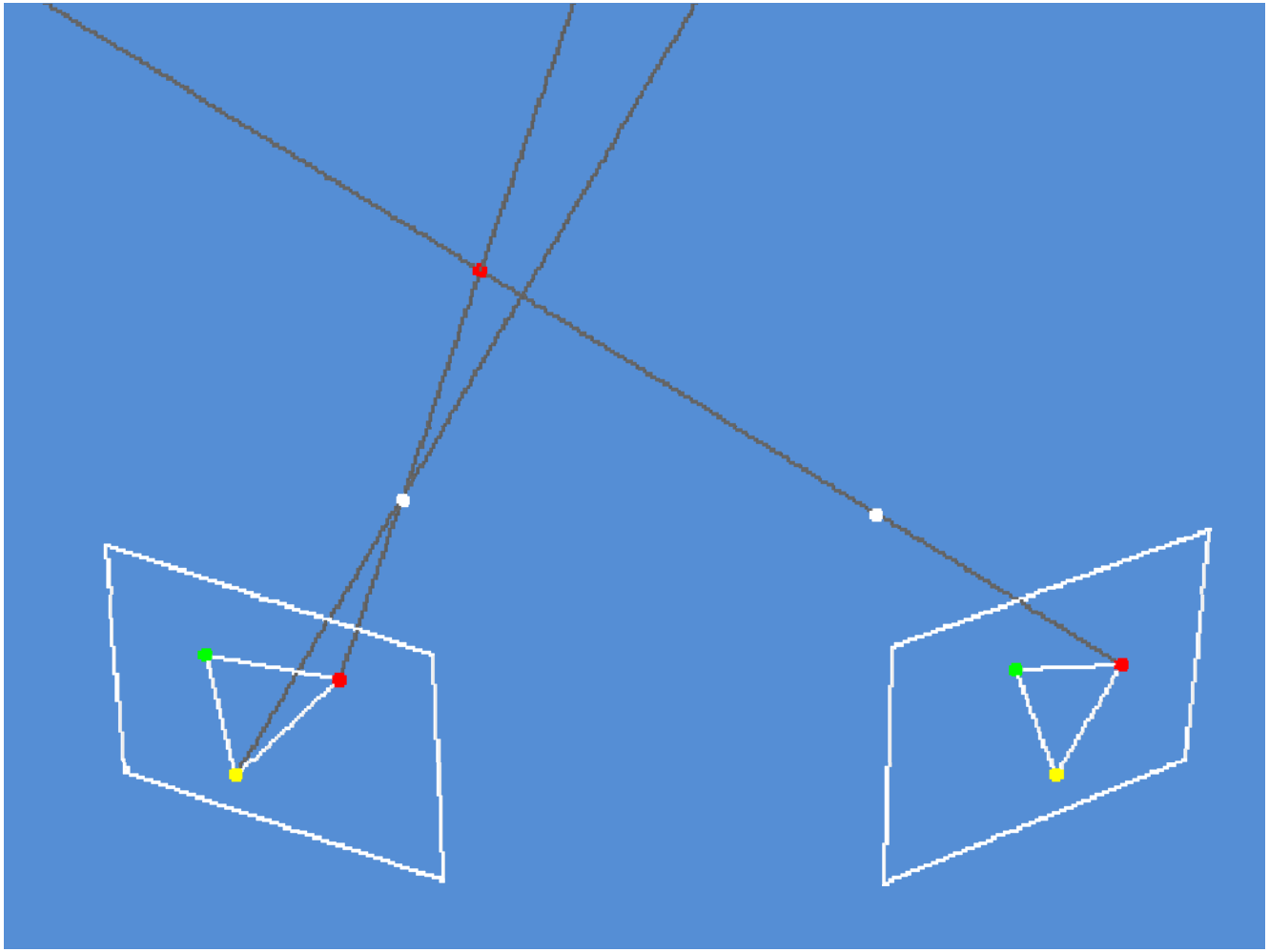

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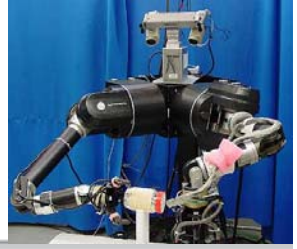
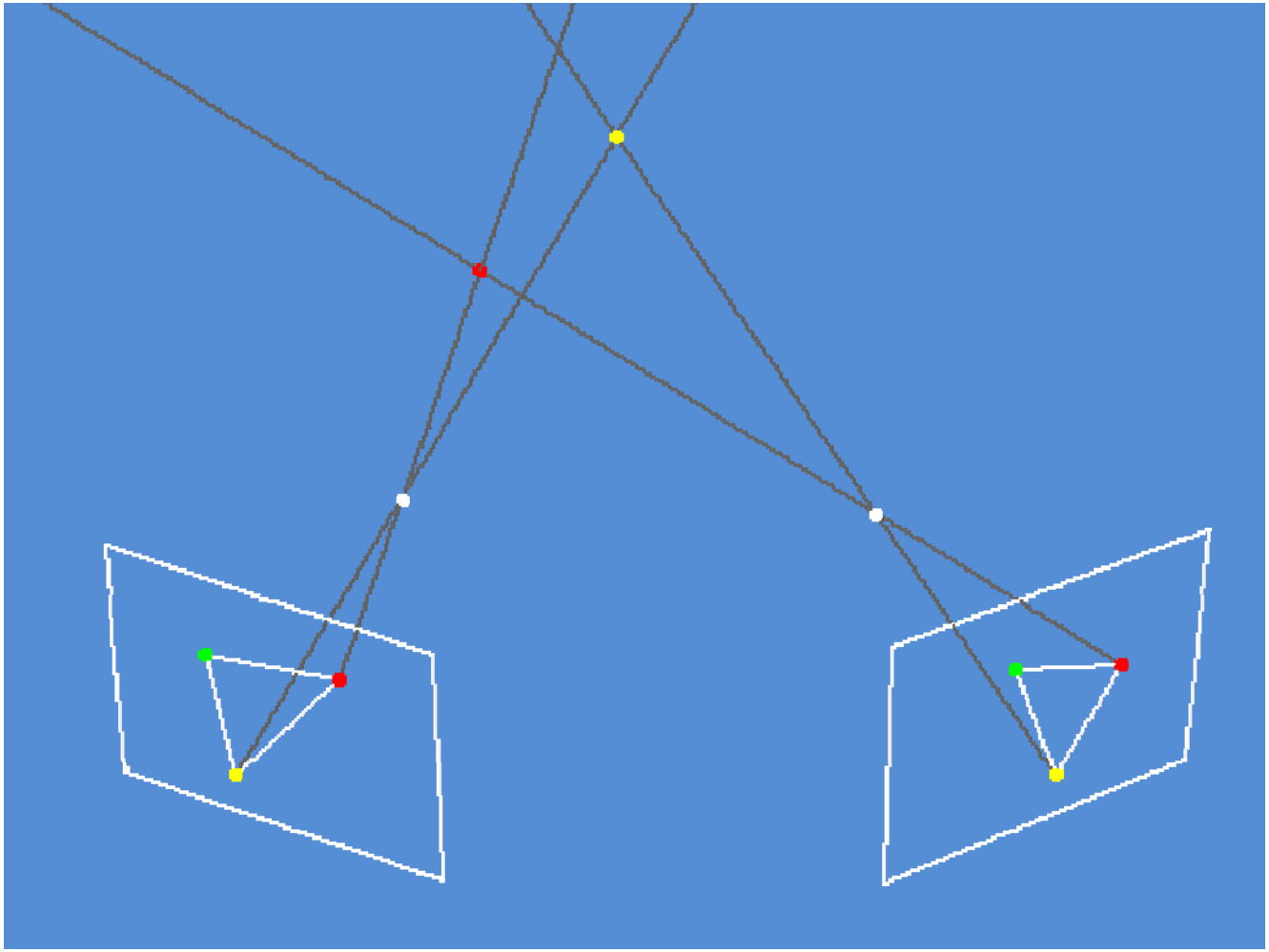
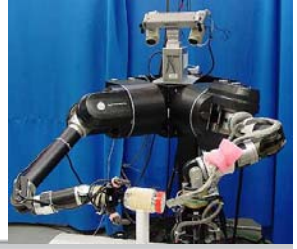
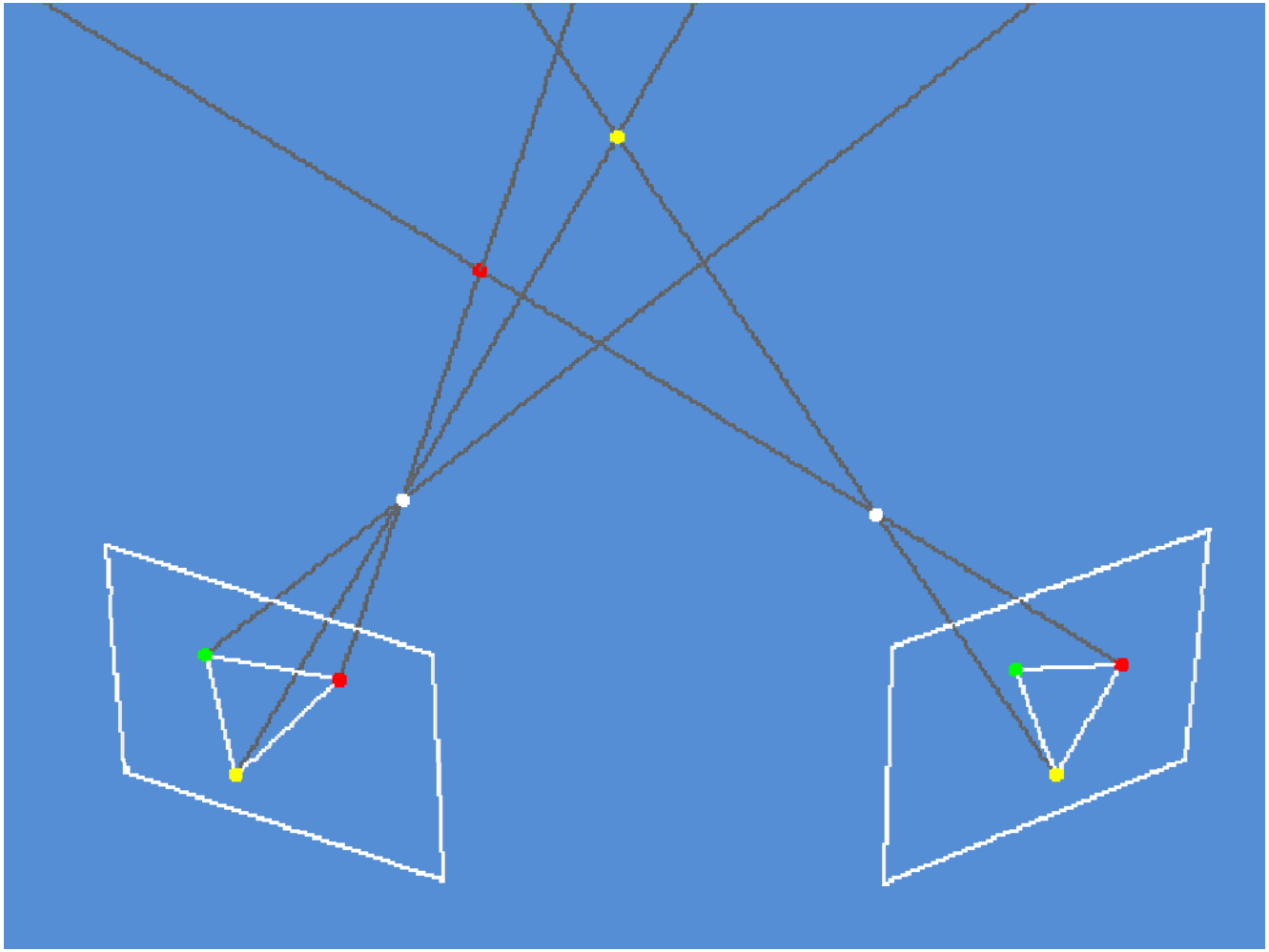


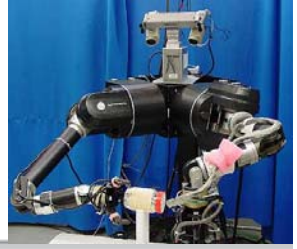


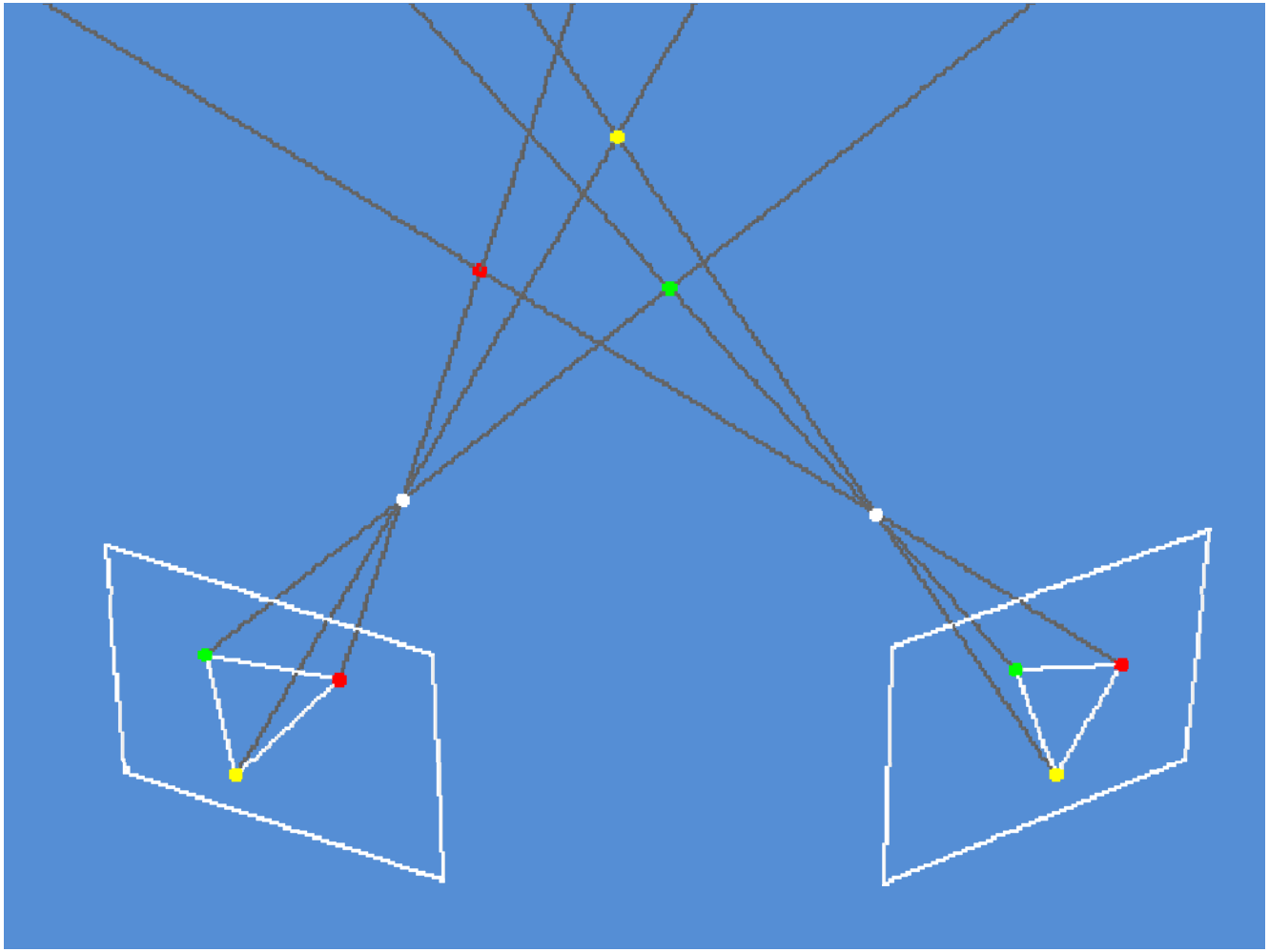
Fundamentals of Stereo Vision



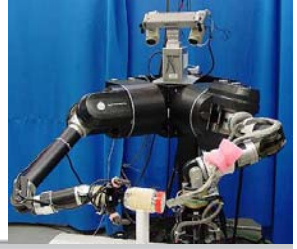


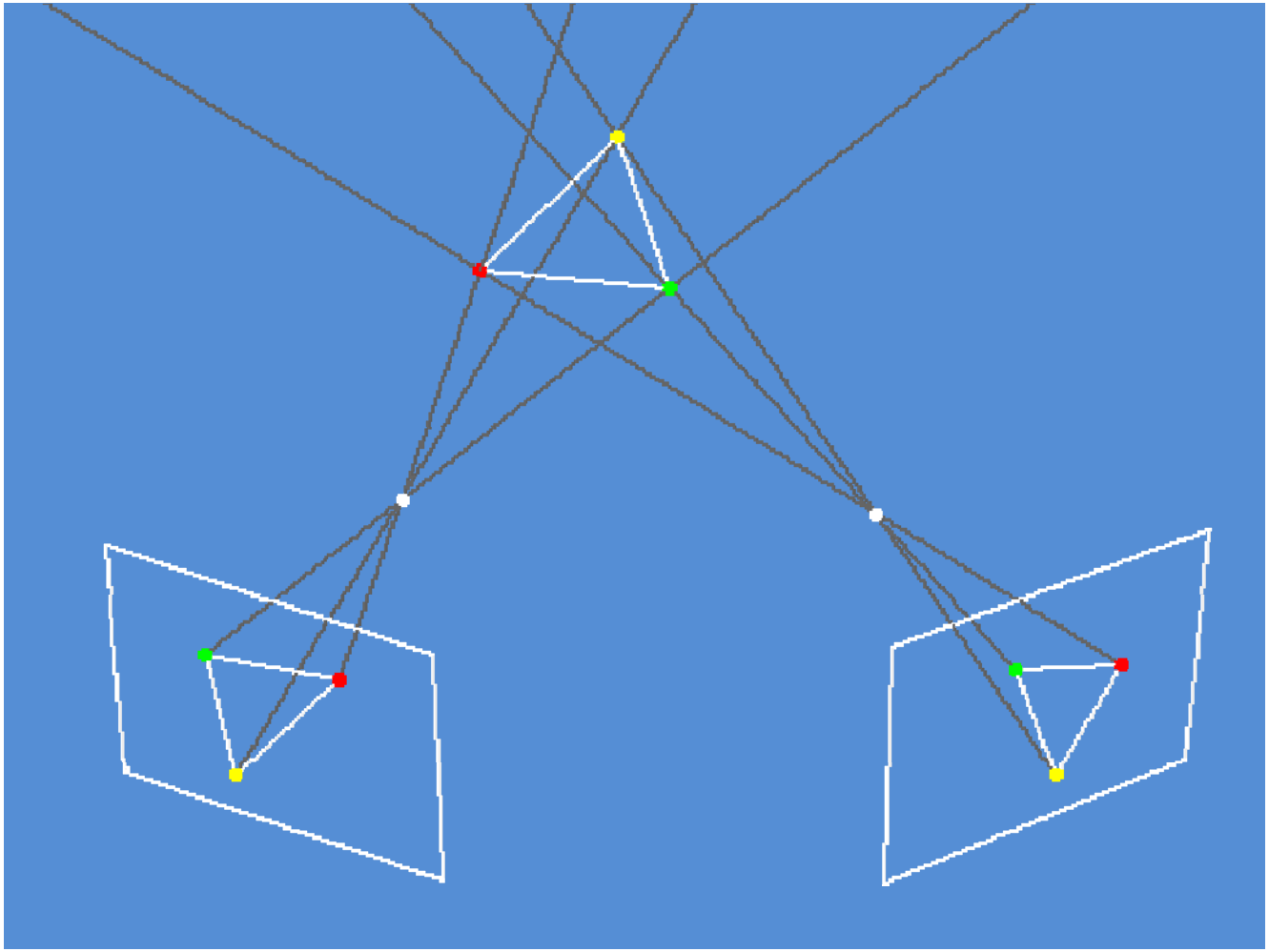
Fundamentals of Stereo Vision



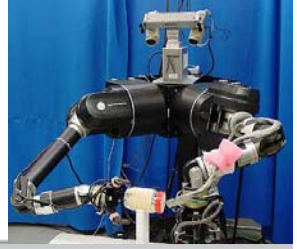


Fundamentals of Stereo Vision

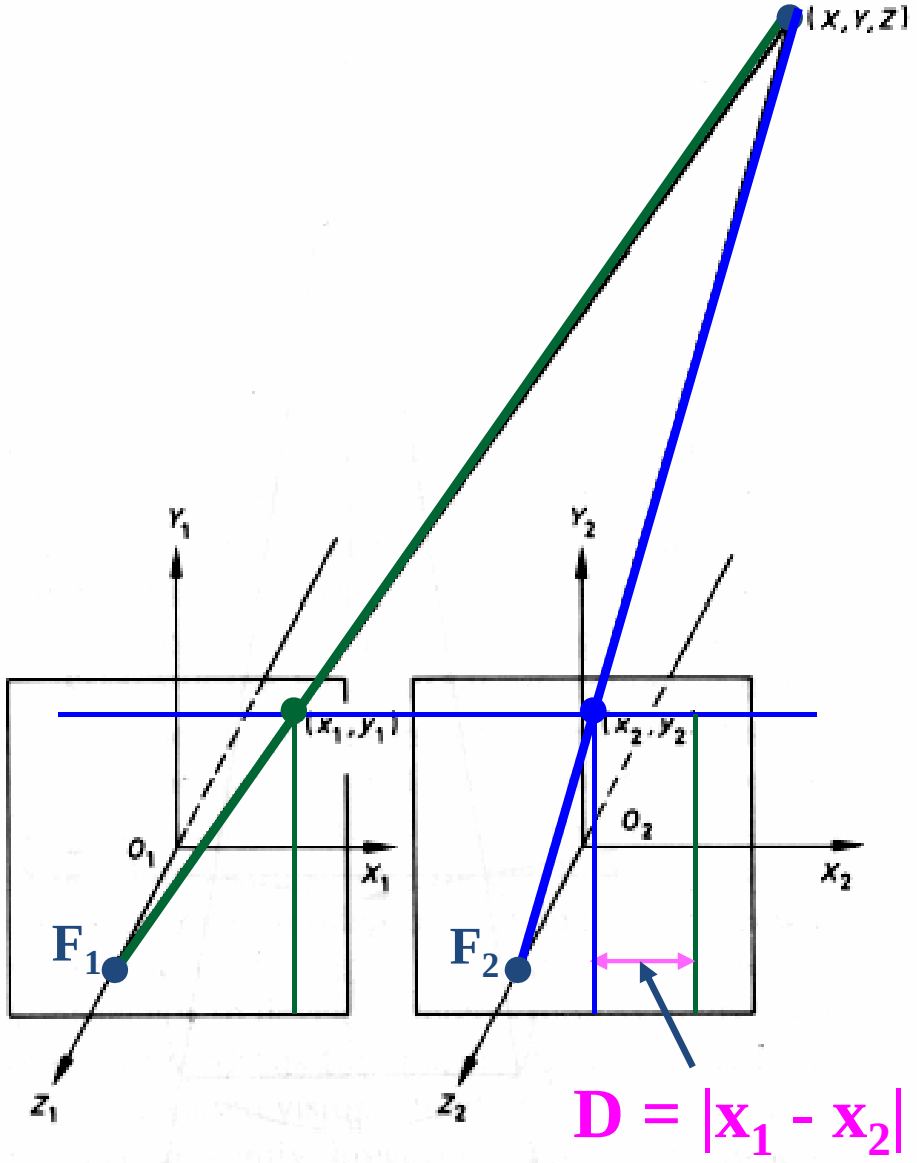




Stereo Geometry

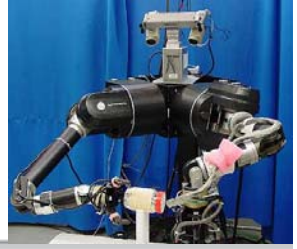


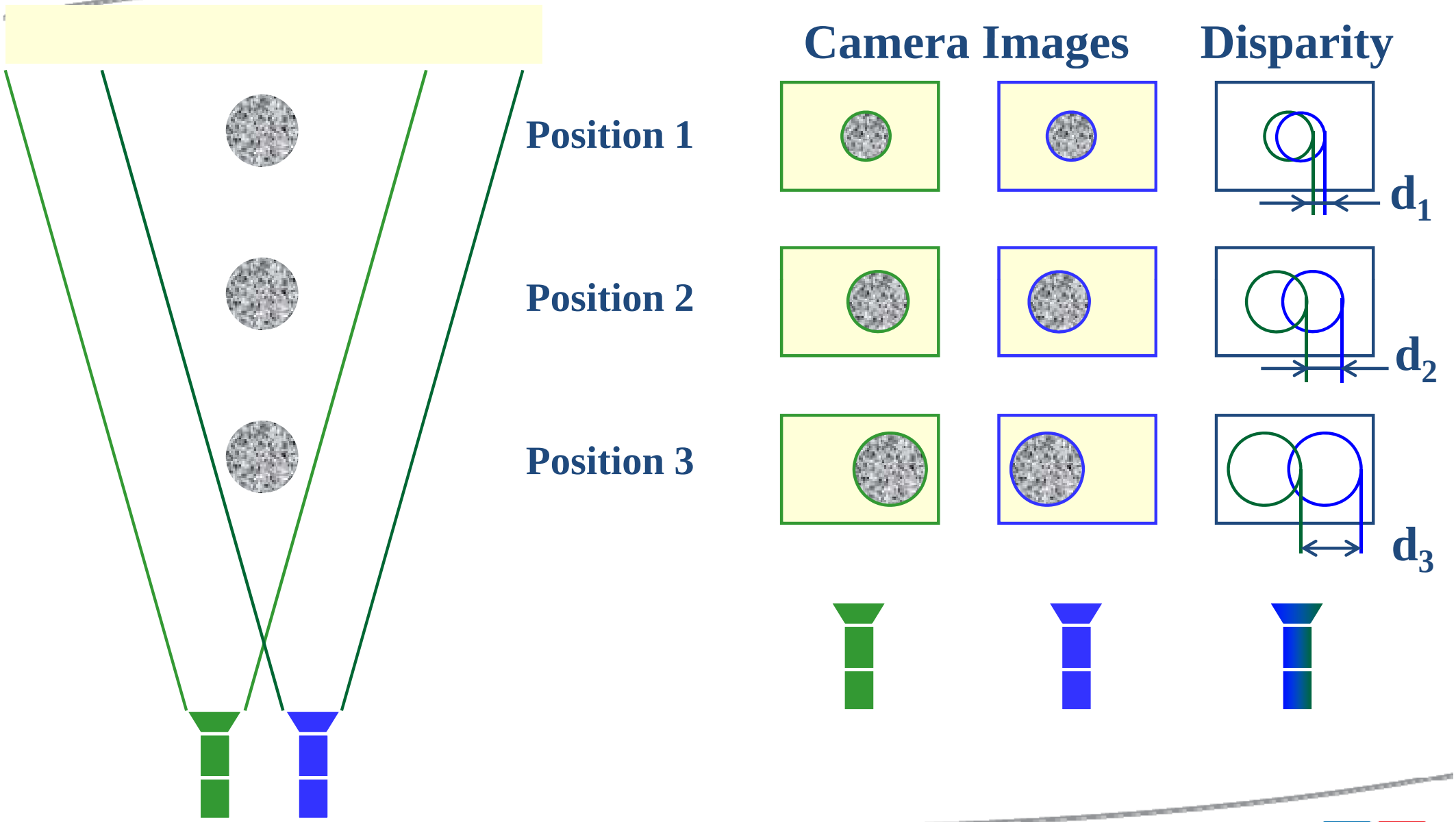
- Perspective **projections** of object points
- Specific case: both image planes are parallel => **normal case**
- Using **geometric** position of images planes and object **projection** depth information is computed



Disparity

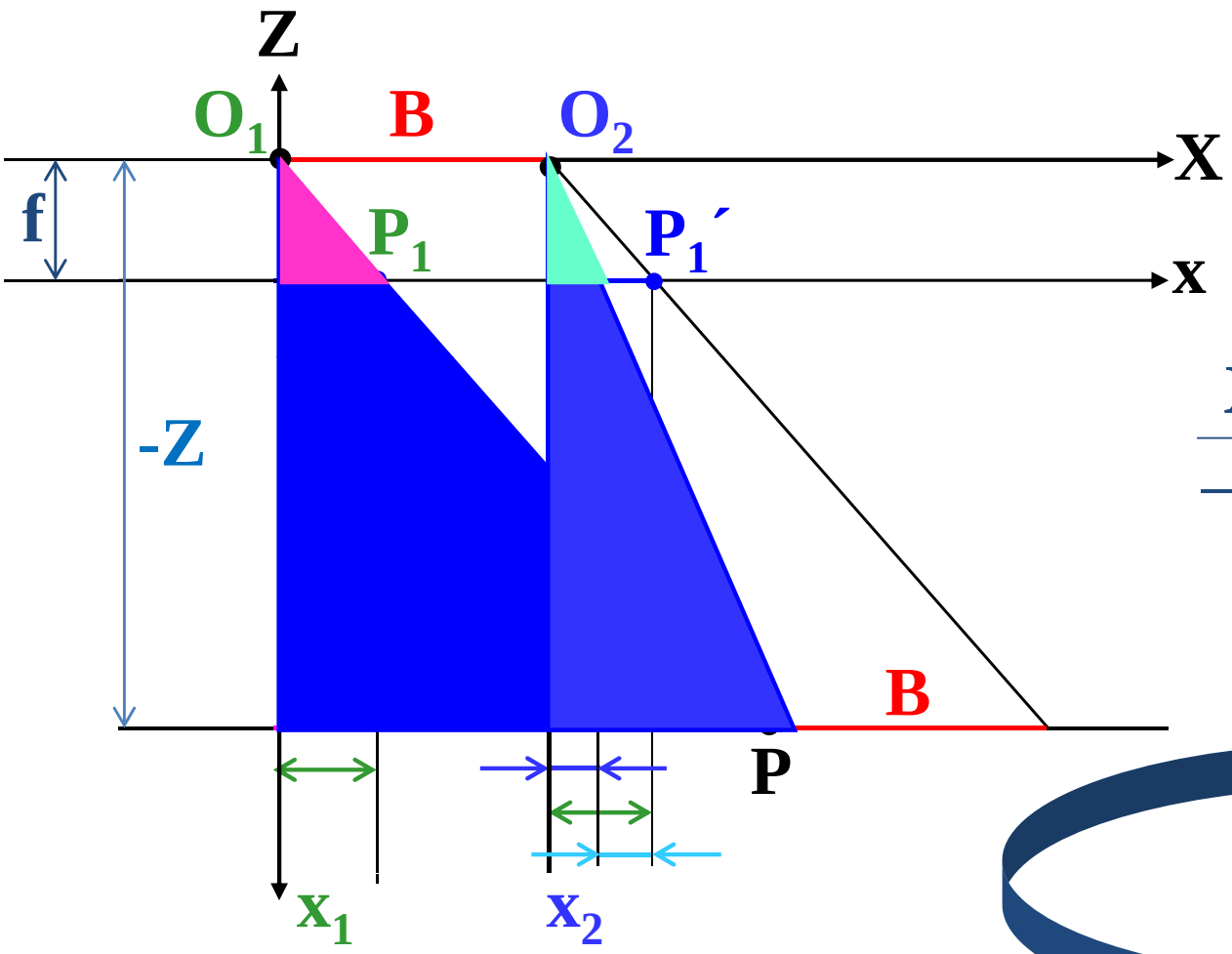
Disparity




Camera Images
Disparity
Position 1
Position 2
Position 3
d_1
d_2
d_3

Stereo Analysis

F: center of projection
X: world coordinate
x: image coordinate
f: focal length
Z: distance to center of projection
B: basis, distance between centers of projection



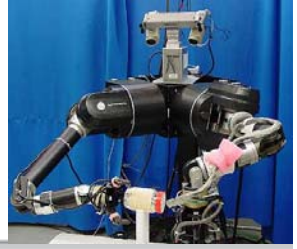
$$\frac{X}{-Z} = \frac{x_1}{f} \qquad \frac{X-B}{-Z} = \frac{x_2}{f}$$

$$X = -Z\frac{x_1}{f} \qquad X = B - Z\frac{x_2}{f}$$

$$-Z = \frac{f\,B}{x_1 - x_2}$$

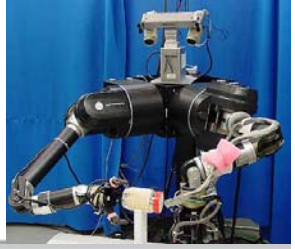
Epipolar Geometry

Epipolar Geometry

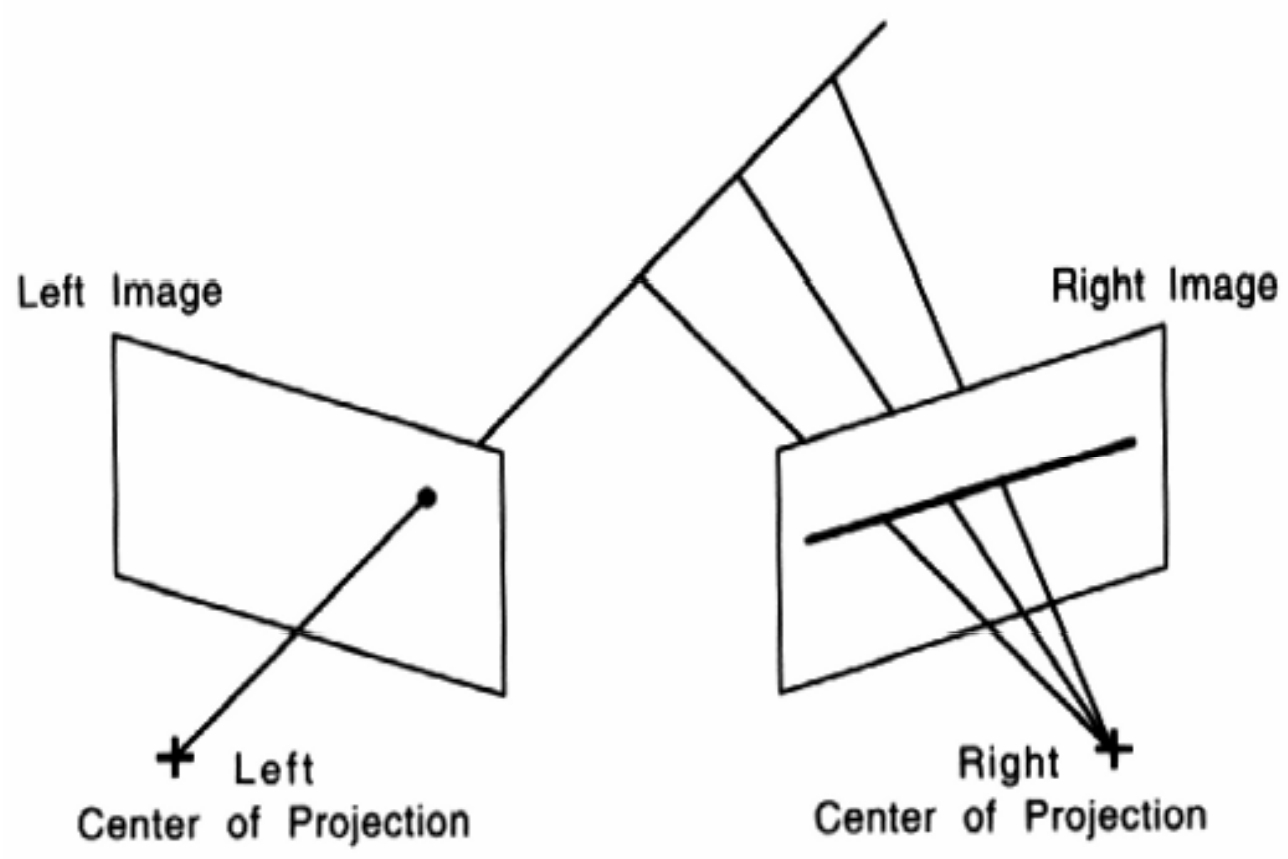


- Epipolar constraint
  - Reduces correspondence problem to 1D search along an epipolar line

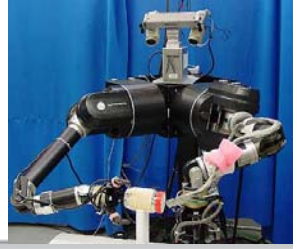
Epipolar Line



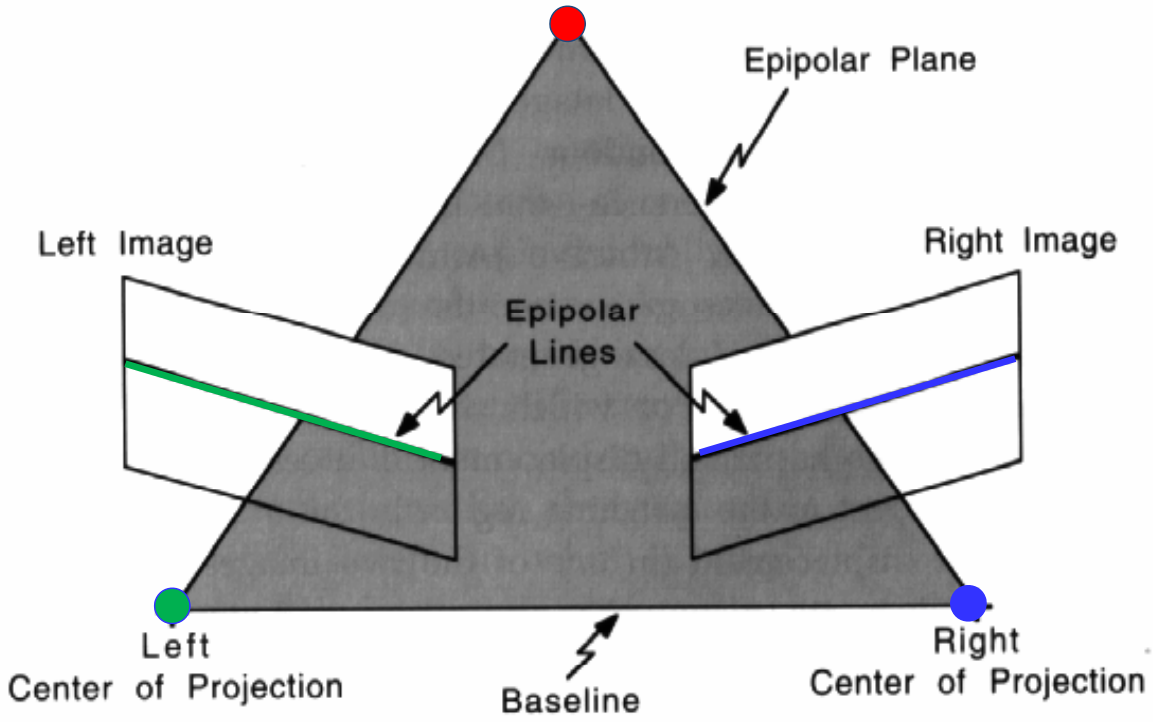
- Epipolar Constraint: Each point of the left image can lie only on a specific line in the right image: the Epipolar Line



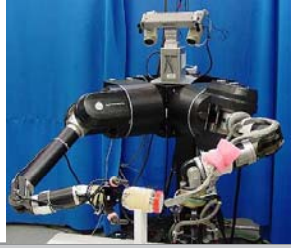
Epipolar Geometry

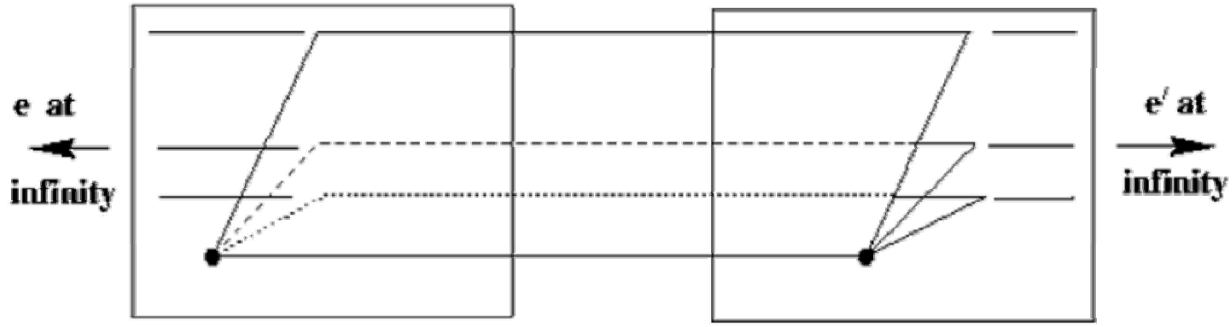


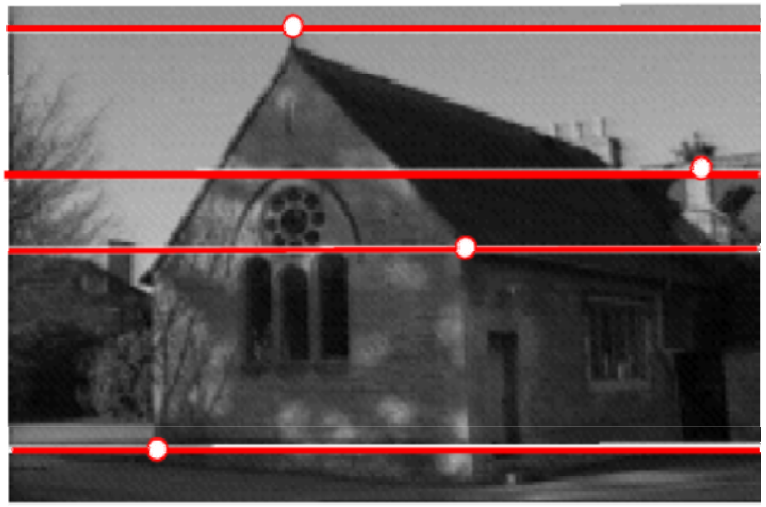
- Epipolar geometry is a consequence of the coplanarity of the camera centers and scene point
- The camera centers, corresponding points and scene point lie in a single plane, known as the epipolar plane



Epipolar Geometry

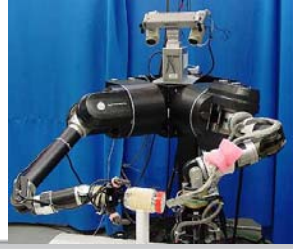




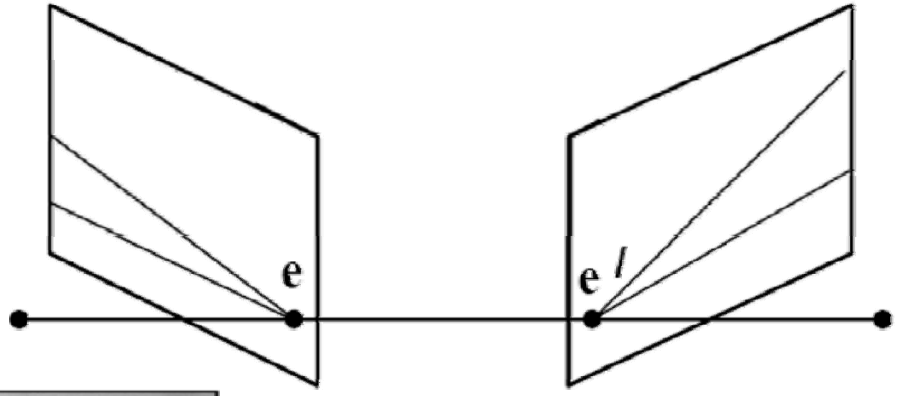


- Epipolar geometry depends only on the relative pose (position and orientation) and internal parameters of the two cameras, i.e. the position of the camera centers and image planes.
- It does not depend on the scene structure (3D points external to the camera).

Epipolar Geometry

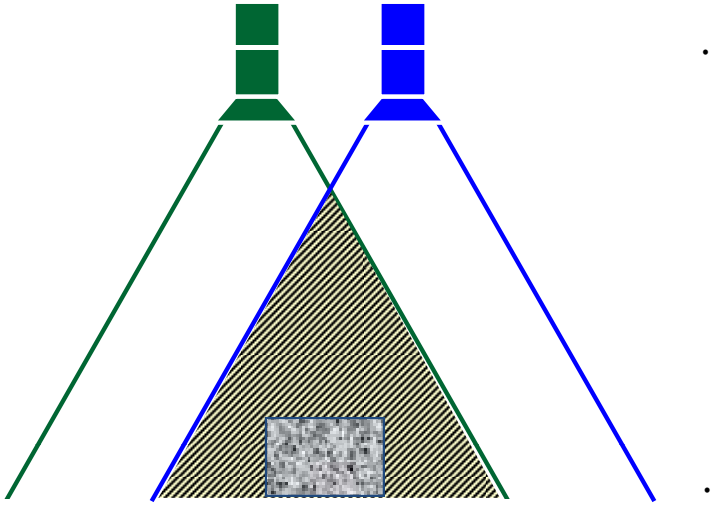


- Note, epipolar lines are in general not parallel

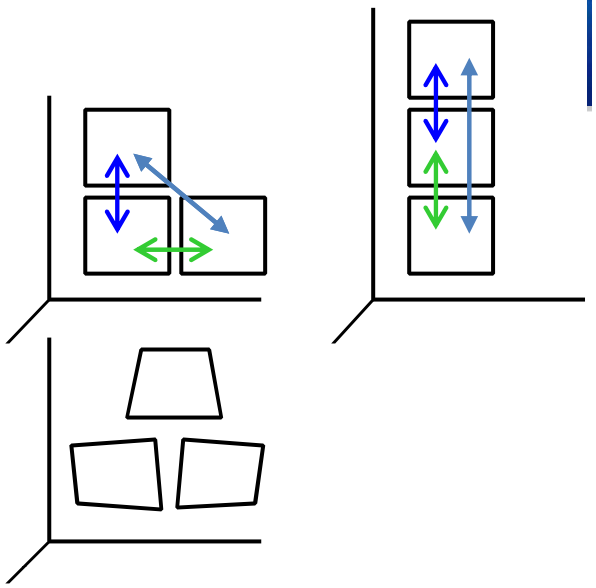


Camera Setup

Static Stereo:

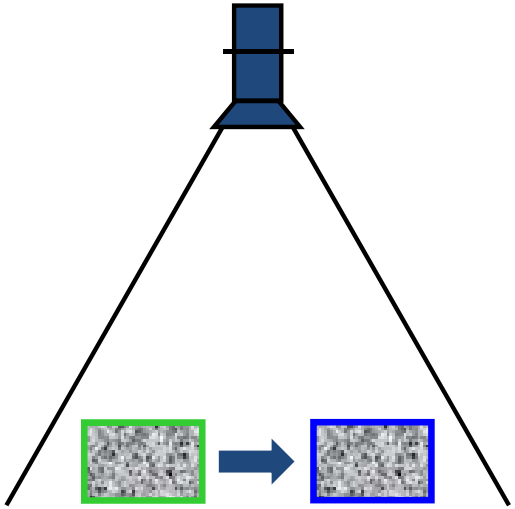


Binocular Stereo

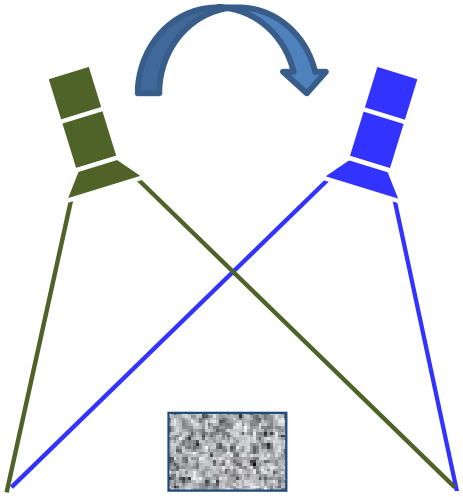


Trinocular Stereo

Dynamic Stereo:

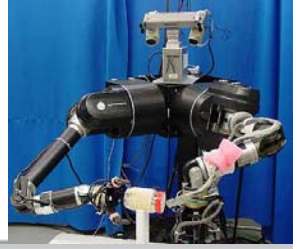


Moving Object

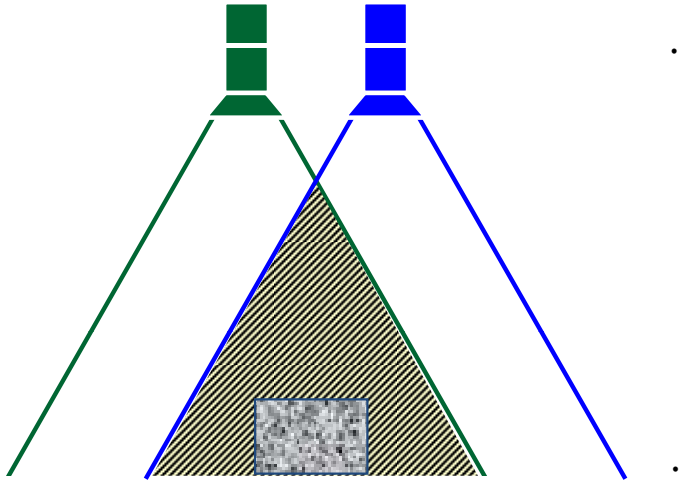


Moving Camera

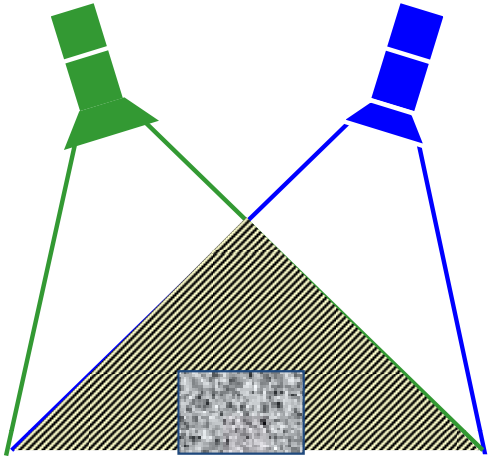
Choice of Camera Setup



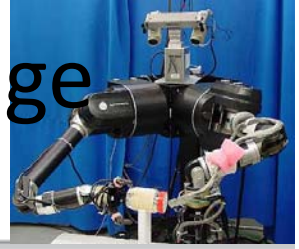
- Baseline
  - distance between cameras (focal points)



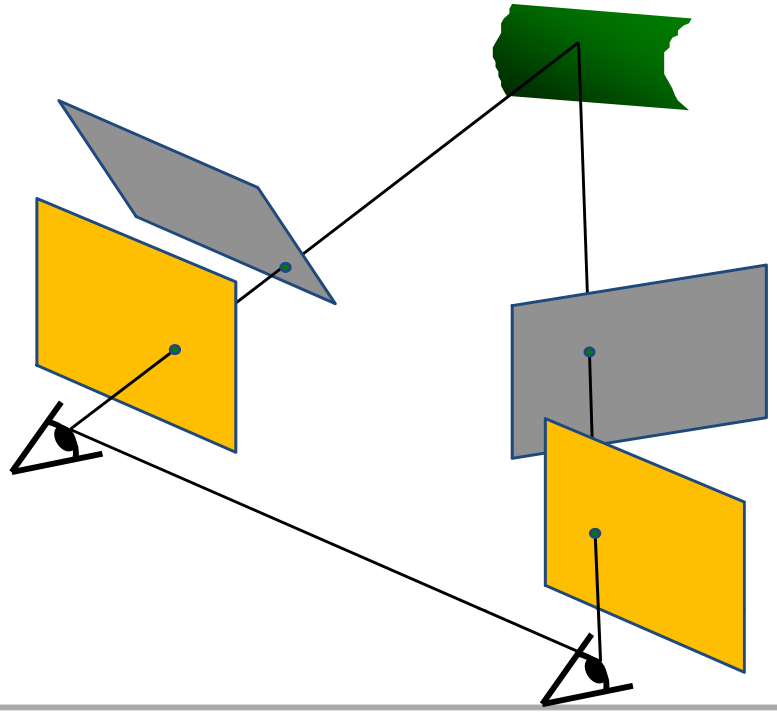
- Trade-off
  - Small baseline: Matching easier
  - Large baseline: Depth precision better



We can always achieve this geometry with image rectification



- Image Re-projection
  - Re-project image planes onto common plane parallel to line between optical centers
  - Notice, only focal point of camera really matters



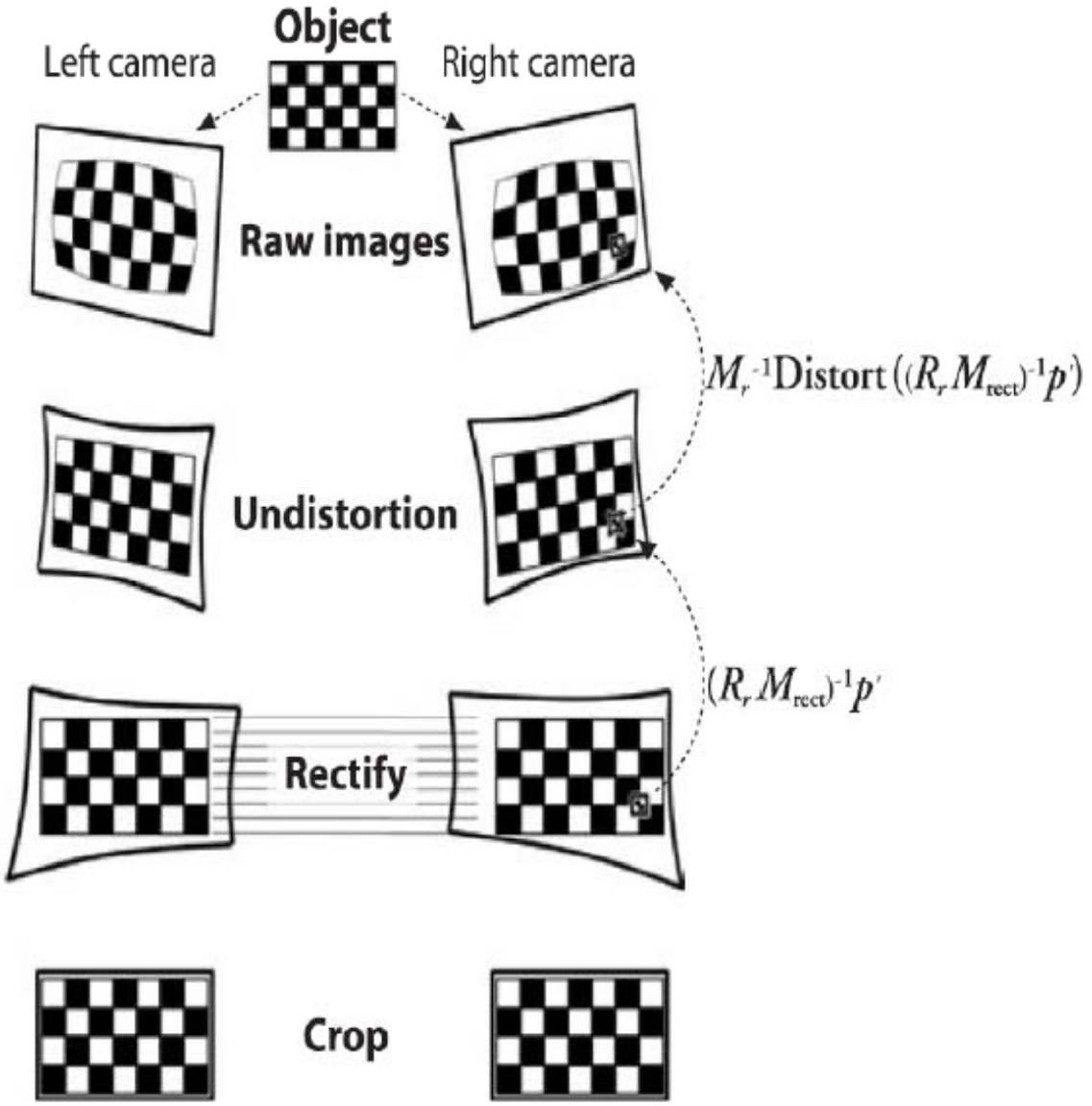
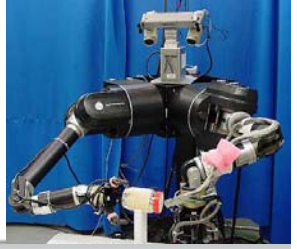
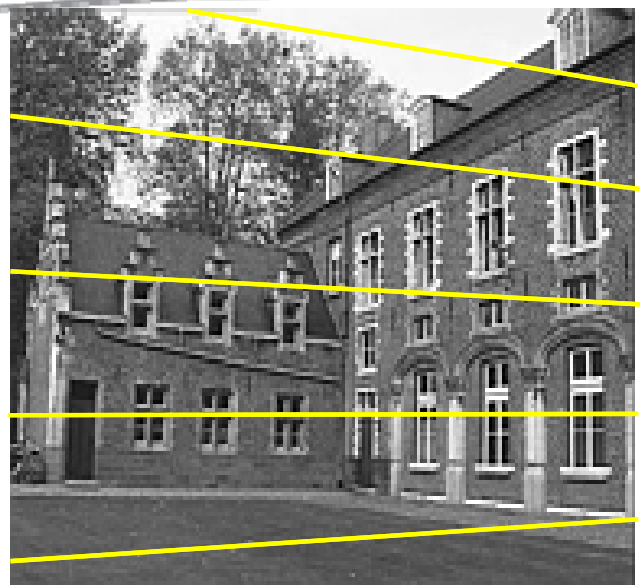
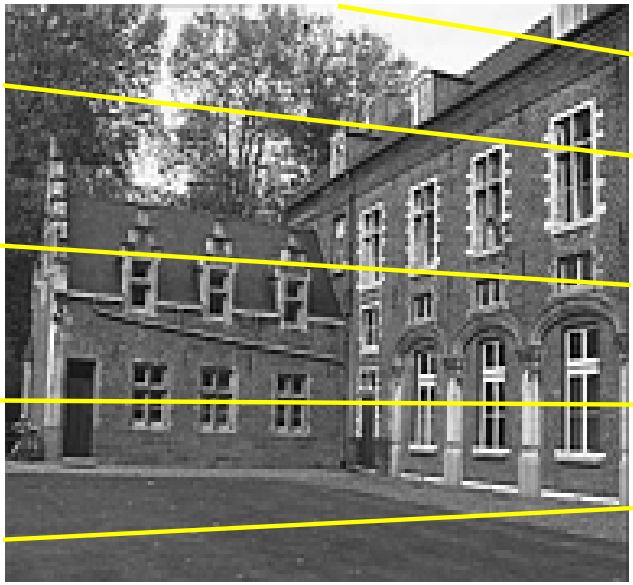
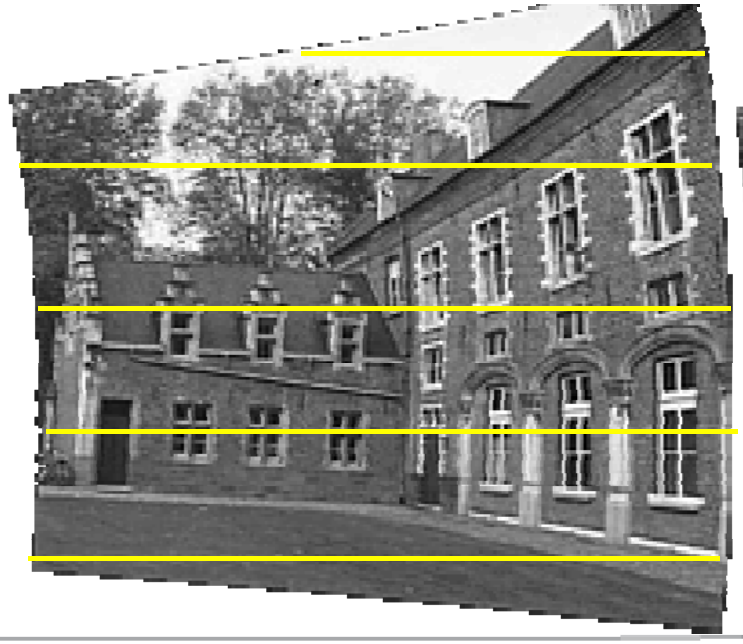


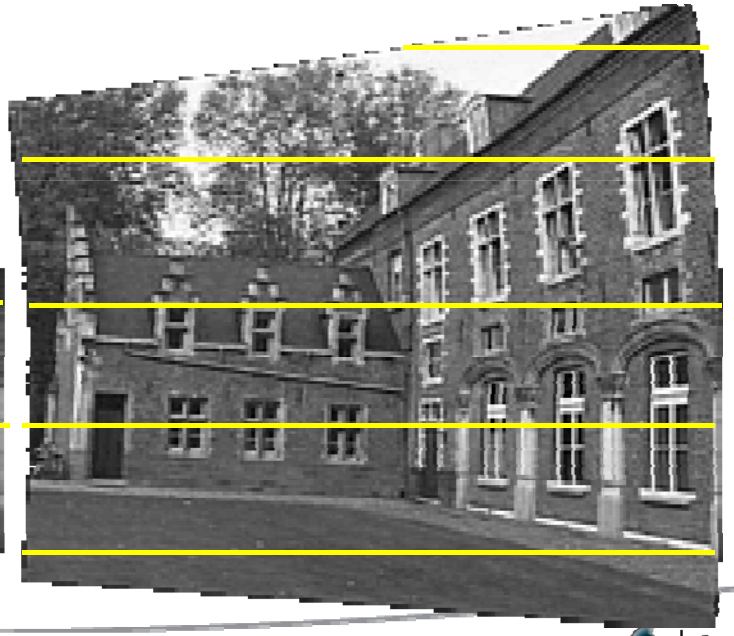
Image Rectification



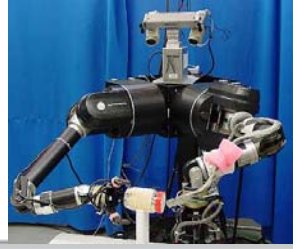




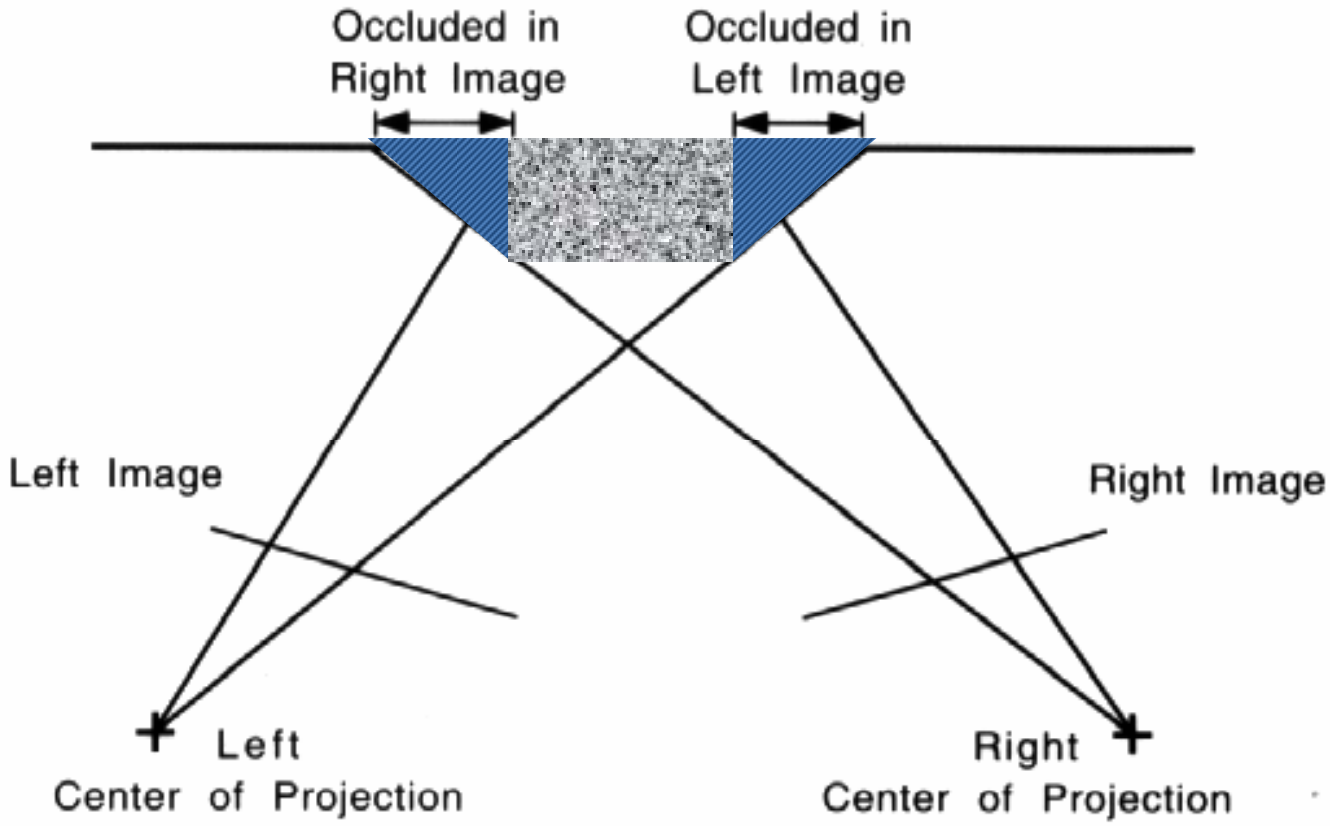




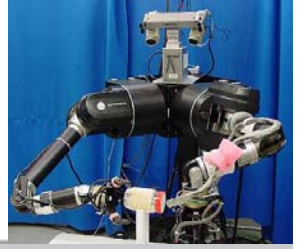
Occlusions



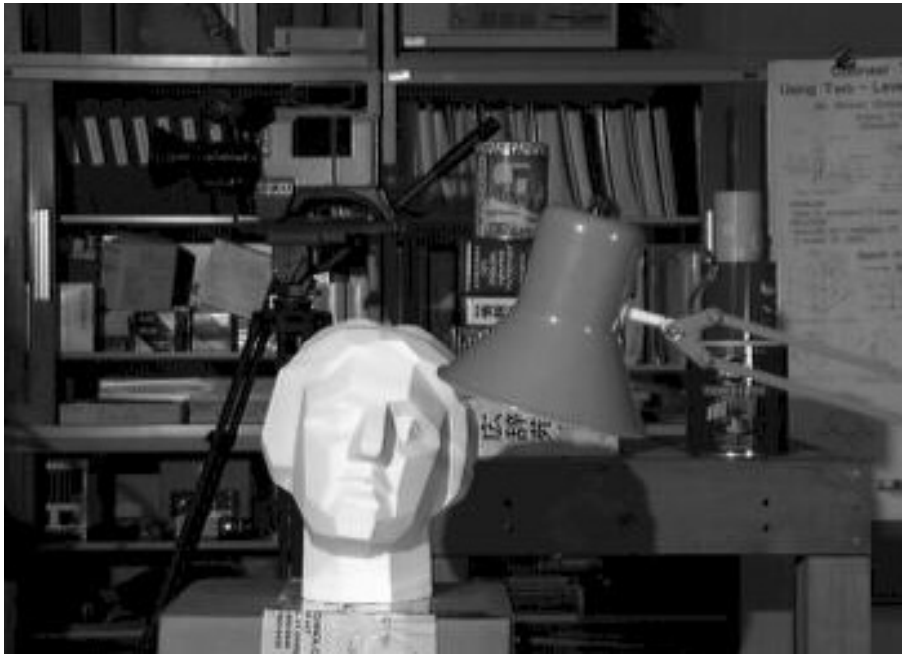
- View dependent
- Occluded points cannot be computed

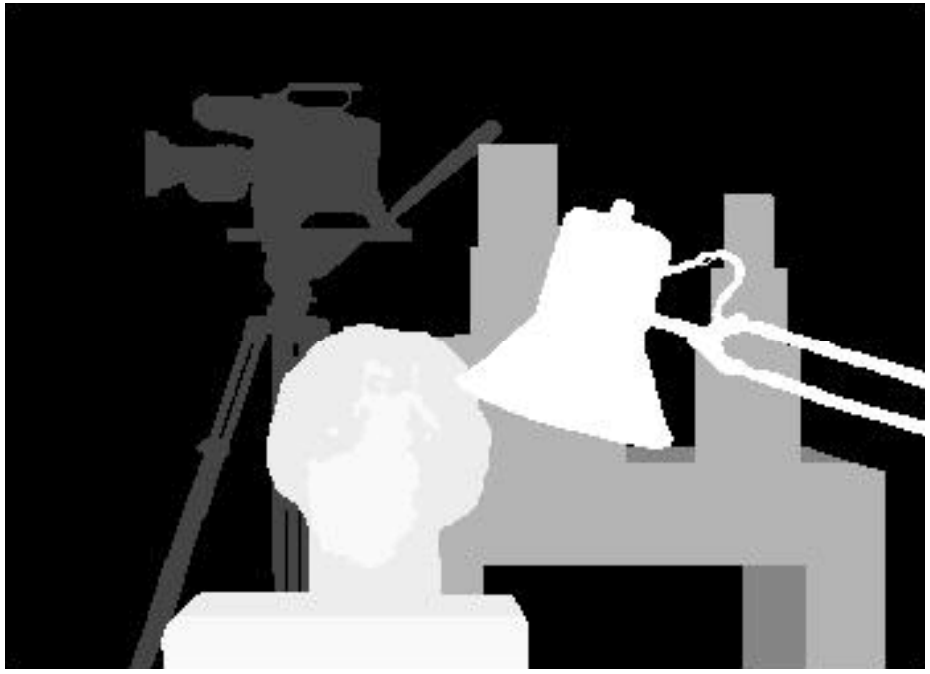


Goal: Disparity Map

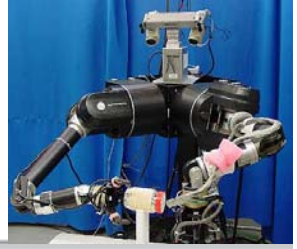


- Disparity:
  - The horizontal displacement between corresponding points
  - Closely related to scene depth



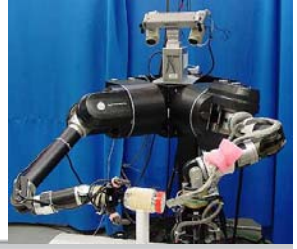


Prerequisites

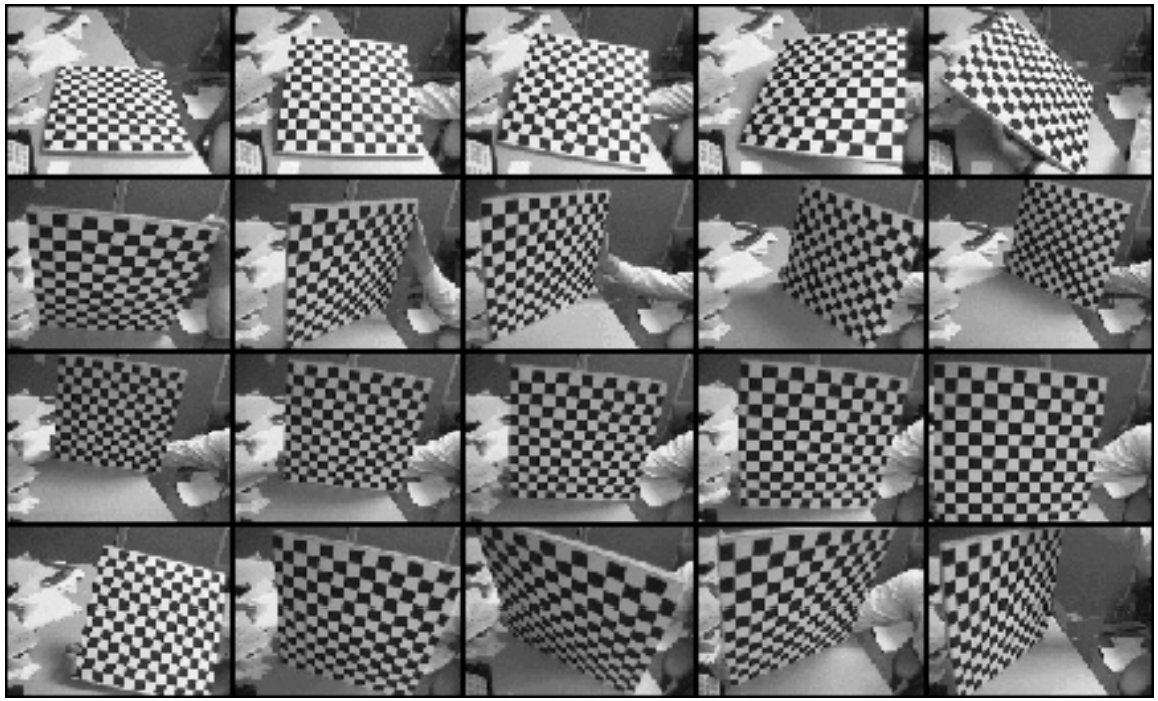


- Camera model parameters must be known:
  - **External** parameters:
    - Positions, orientations
  - **Internal** parameters:
    - Focal length, image center, distortion, etc..

Prerequisites



- Camera calibration



Correspondence Problem

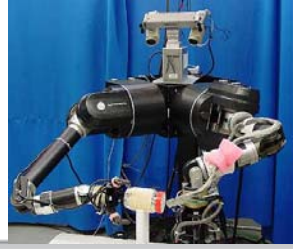
Correspondence Analysis

Left Stereo Image

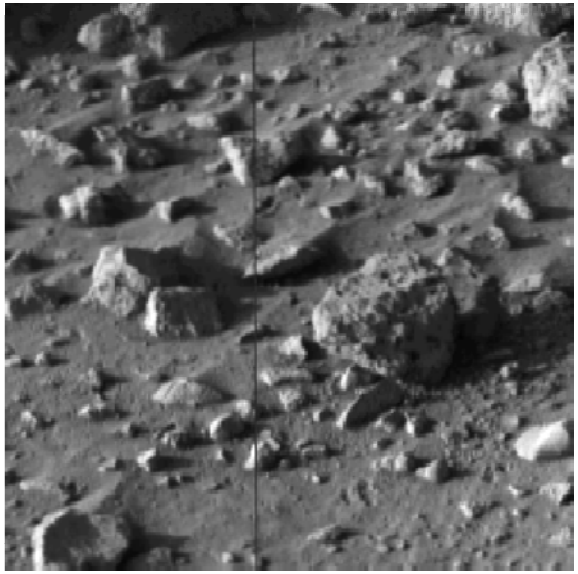
Right Stereo Image

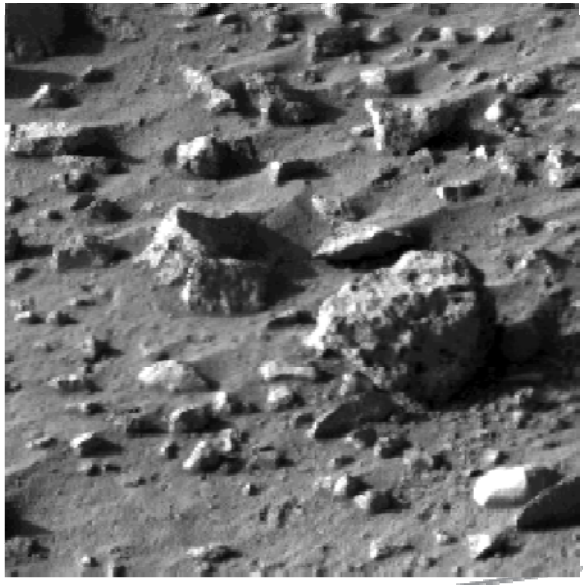
- Area Based
  - Comparison of **intensity values** in the left and right image
  - Correspondence due to the **similarity** between the **intensity values**
  - Correspondence **for each pixel**
- Feature Based
  - Comparison of **features** in left and right image
  - Correspondence on the basis of **selected characteristics** of features (edge orientation, edge length, gradient, etc.)
  - Correspondence only for **selected pixels**
  - **more accurate** because of sub-pixel positioning of features

Matching Challenges

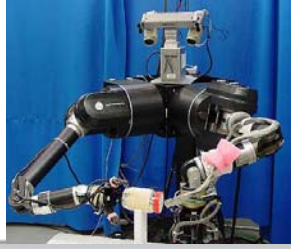


- Scene elements do not always look the same in the two images
  - Camera-related problems
    - Image noise, differing gain, contrast, etc..
  - Viewpoint-related problems:
    - Perspective distortions
    - Occlusions
    - Specular reflections

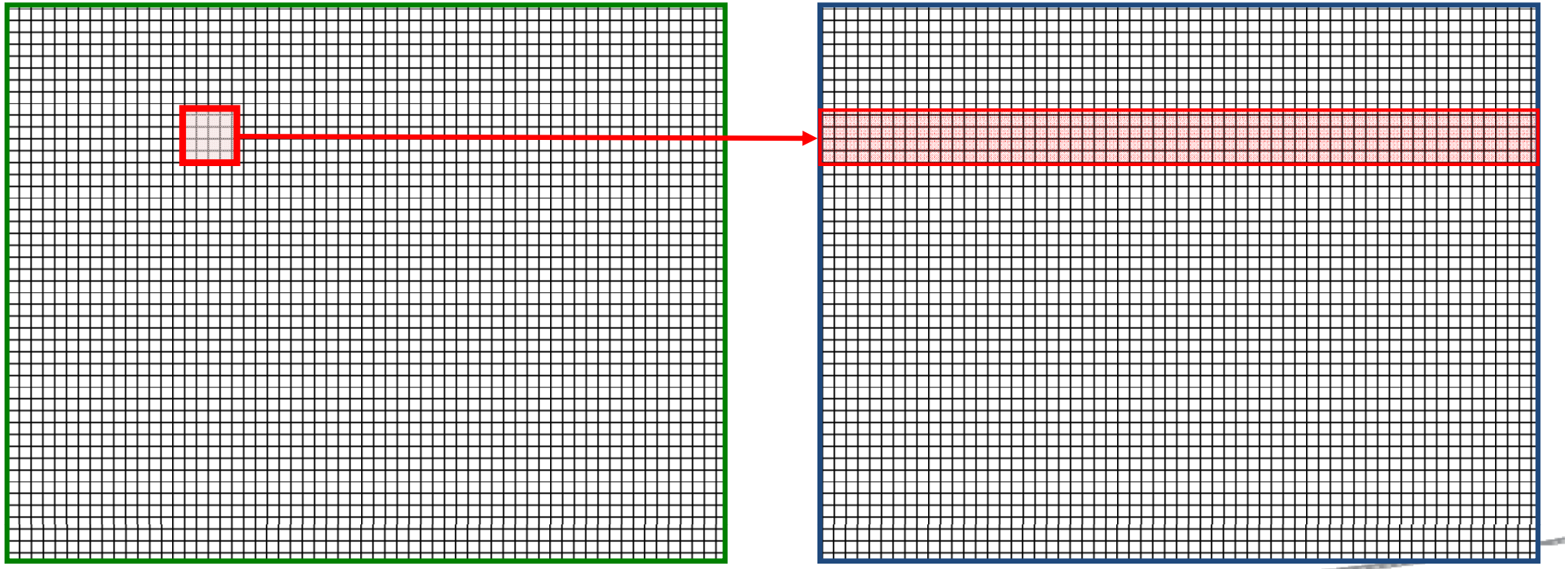




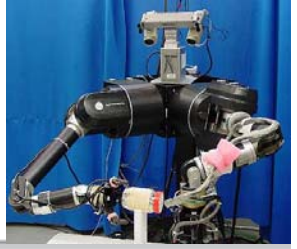
Area-based Matching



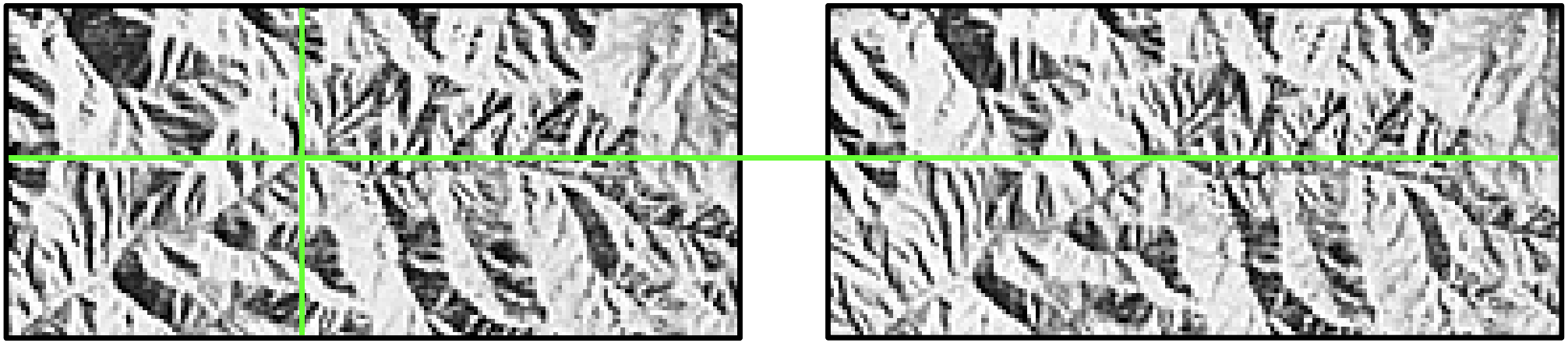
- Observation window in the left image fix
- for each position in the right image the correlation function is calculated
- Window will be “slided" from left to right across the image
- is performed for each position in the left image



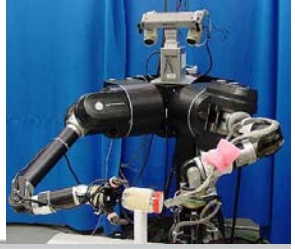
Area-based Matching



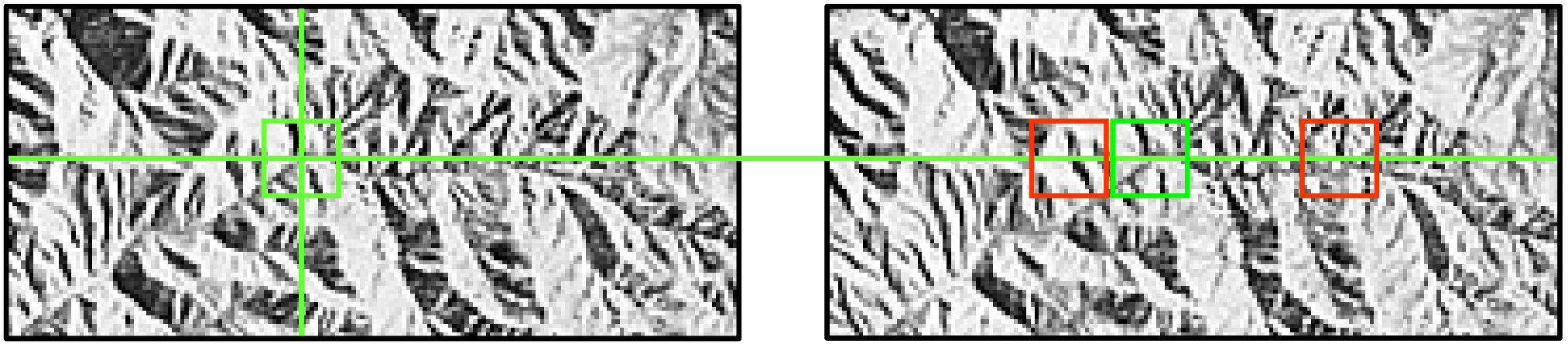
- Finding pixel-to-pixel correspondences
  - For each pixel in the left image, search for the most similar pixel in the right image



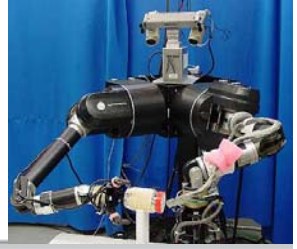
Area-based Matching



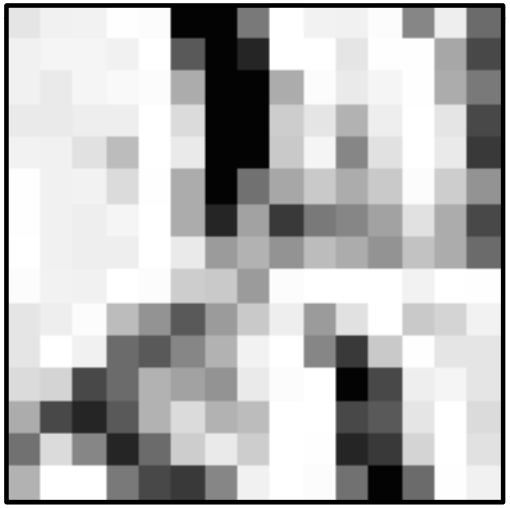
- Finding pixel-to-pixel correspondences
  - For each pixel in the left image, search for the most similar pixel in the right image
  - Using neighborhood windows

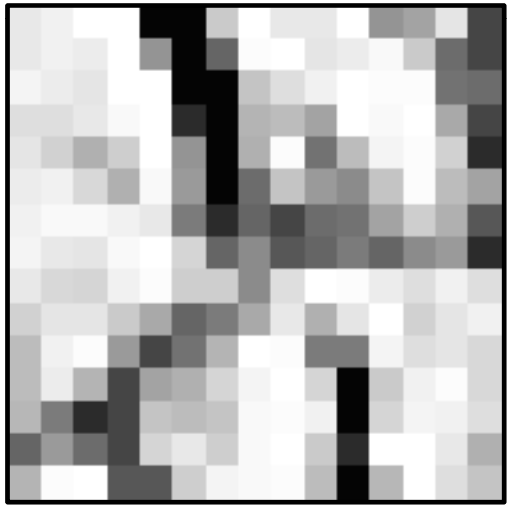


Area-based Matching



- Similarity measures for two windows
  - SAD (sum of absolute differences)
  - SSD (sum of squared differences)
  - CC (cross-correlation)
  - …

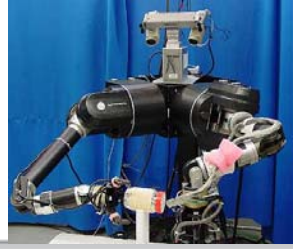




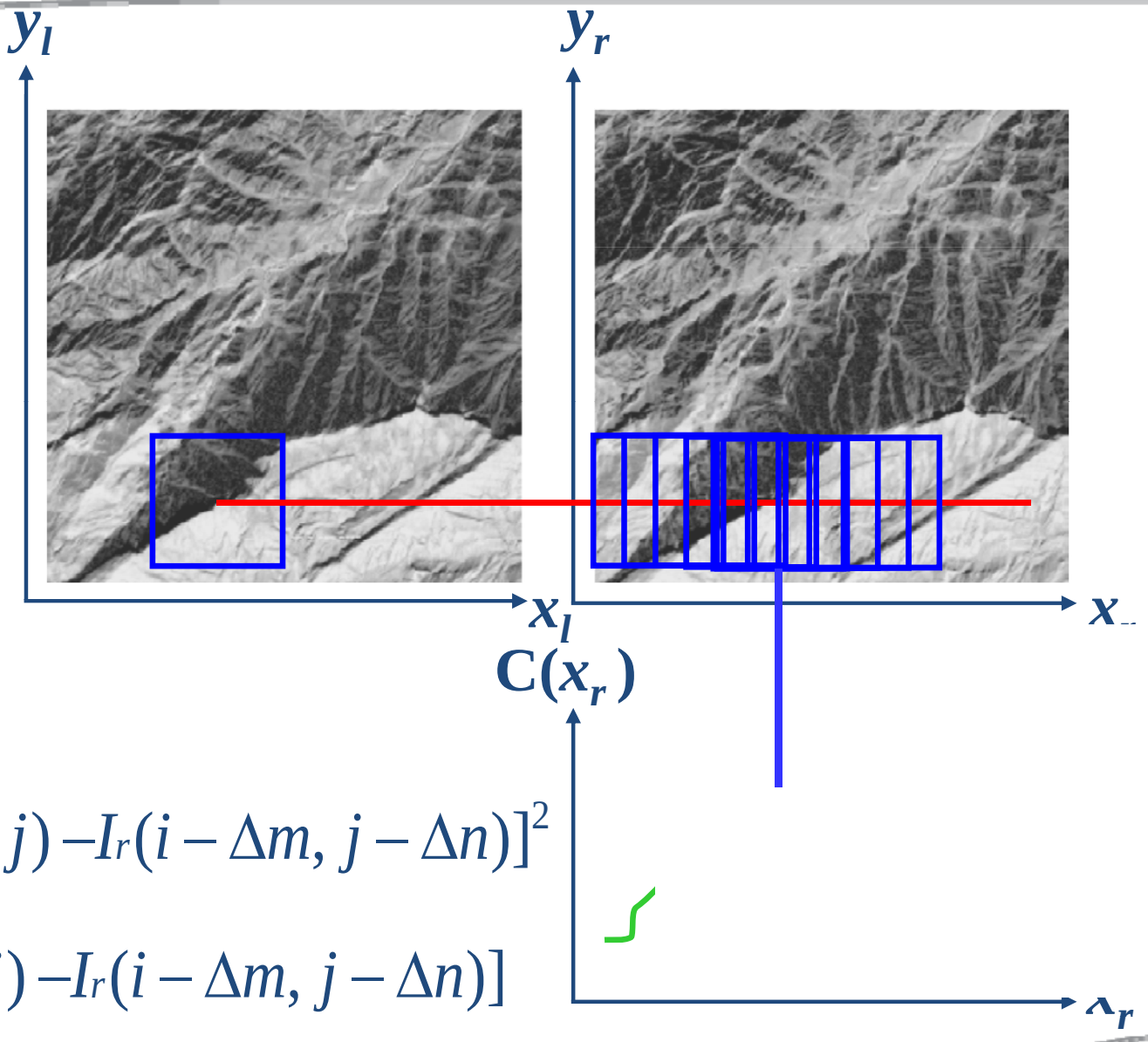
$$SSD(\Delta m, \Delta n) \hat{=} \sum_{i,j \in R} [I_l(i,j) - I_r(i-\Delta m, j-\Delta n)]^2$$

$$CC(\Delta m, \Delta n) \hat{=} \sum_{i,j \in R} [I_l(i,j) - I_r(i-\Delta m, j-\Delta n)]$$

Area-based Matching



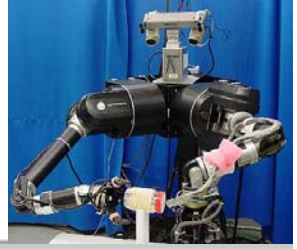
- Correspondence due to **similarity** between the gray values in the left and right image

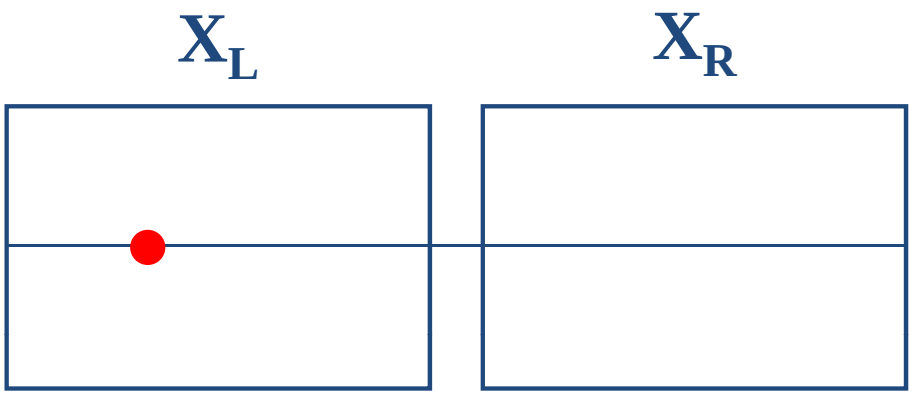


$$SSD(\Delta m, \Delta n) \hat{=} \sum_{i,j \in R} [I_l(i,j) - I_r(i-\Delta m, j-\Delta n)]^2$$

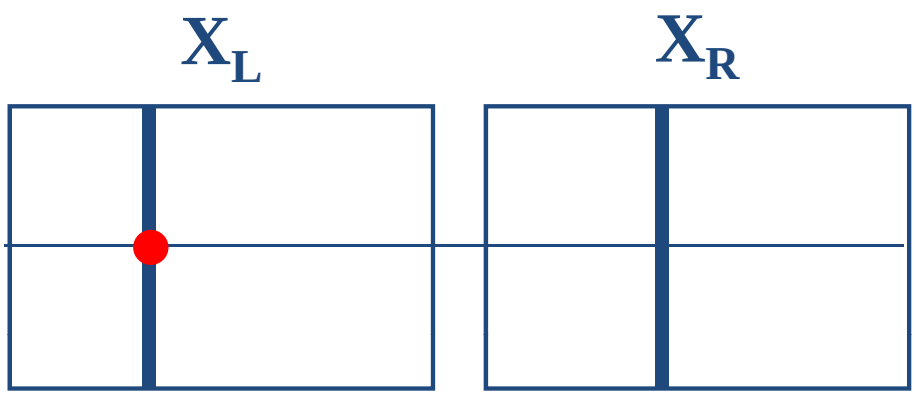
$$CC(\Delta m, \Delta n) \hat{=} \sum_{i,j \in R} [I_l(i,j) - I_r(i-\Delta m, j-\Delta n)]$$

Correspondence Problem

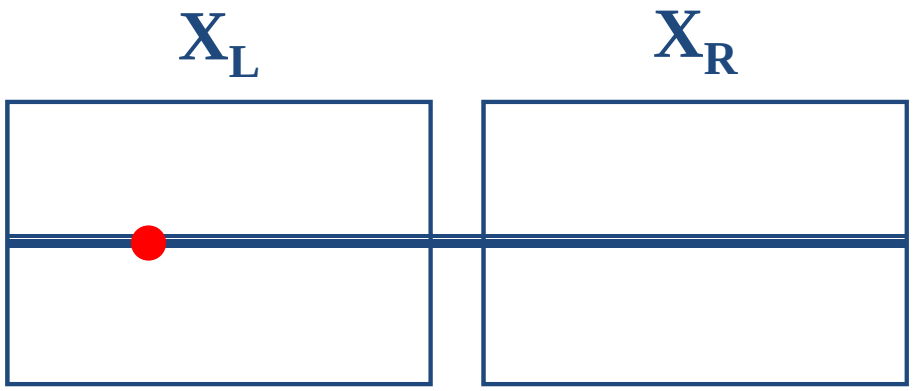




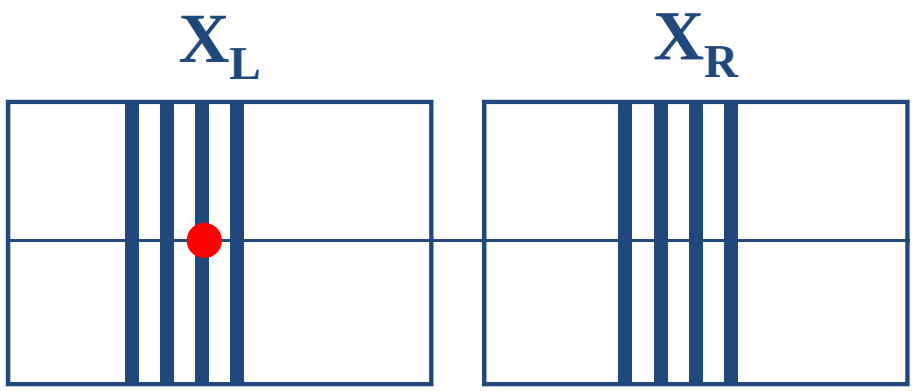
Point does not exist



Exact correspondence

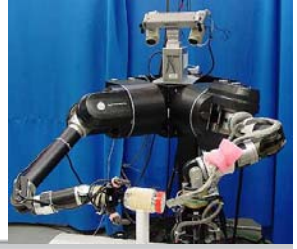


Horizontal lines



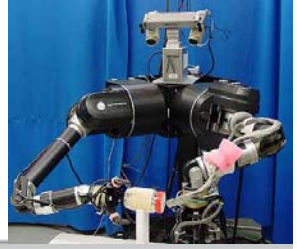
Ambiguous correspondence

Area-based Matching

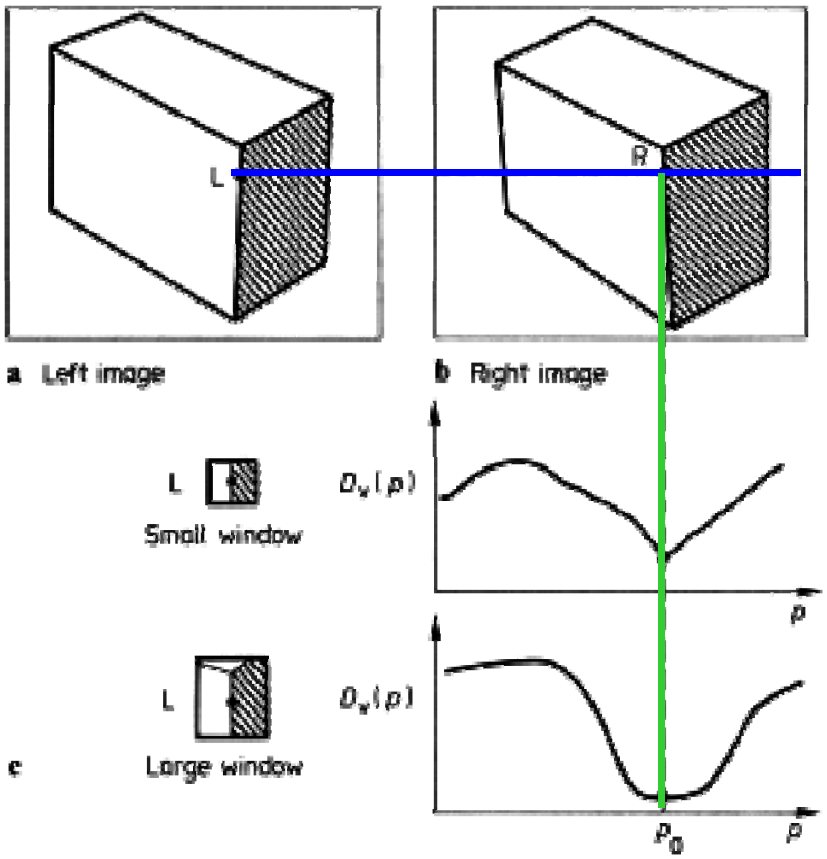


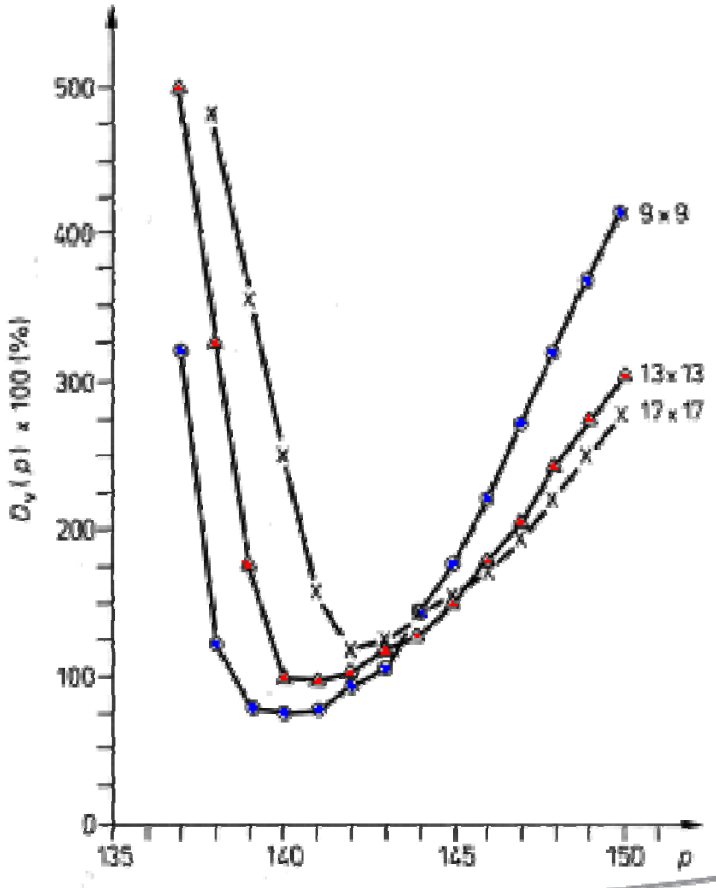
- Choice of window size
  - Factors to considers:
    - Ambiguity
    - Noise sensitivity
    - Sensitivity towards viewpoint-related distortions
    - Expected object sizes
    - Frequency of depth jumps

Correspondence Search

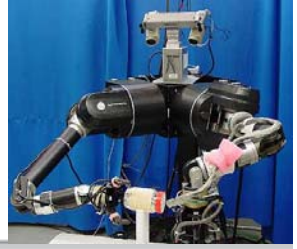


- Correspondence is strongly dependent on window size used
  - Different algorithms like adaptive matching, pyramids ….

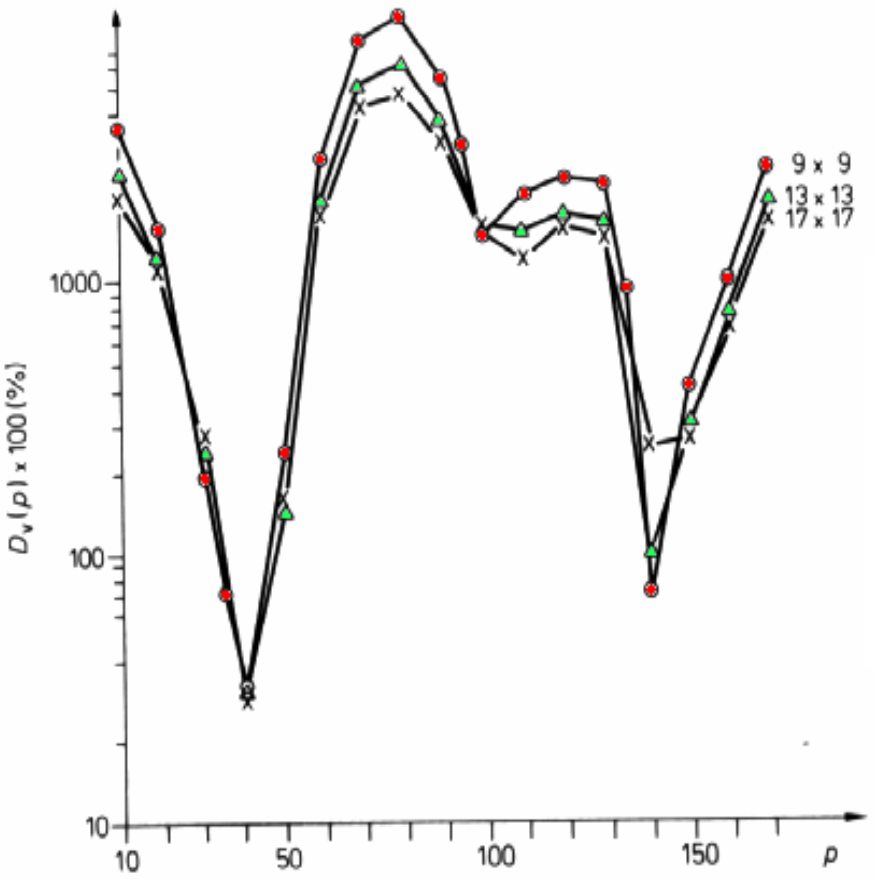


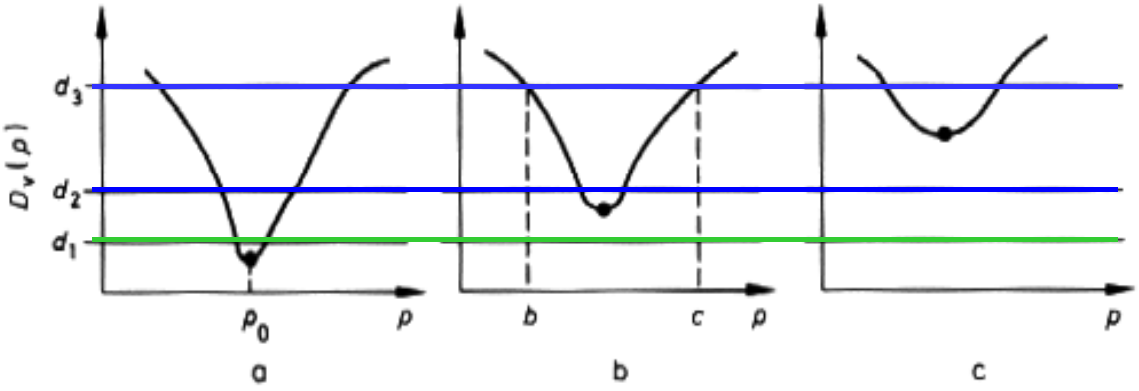


Correspondence Search



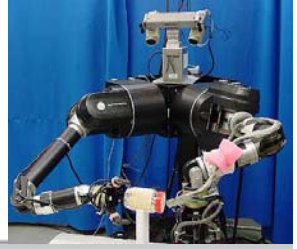
- Solution of ambiguity with threshold or additional constraints
- Different threshold values

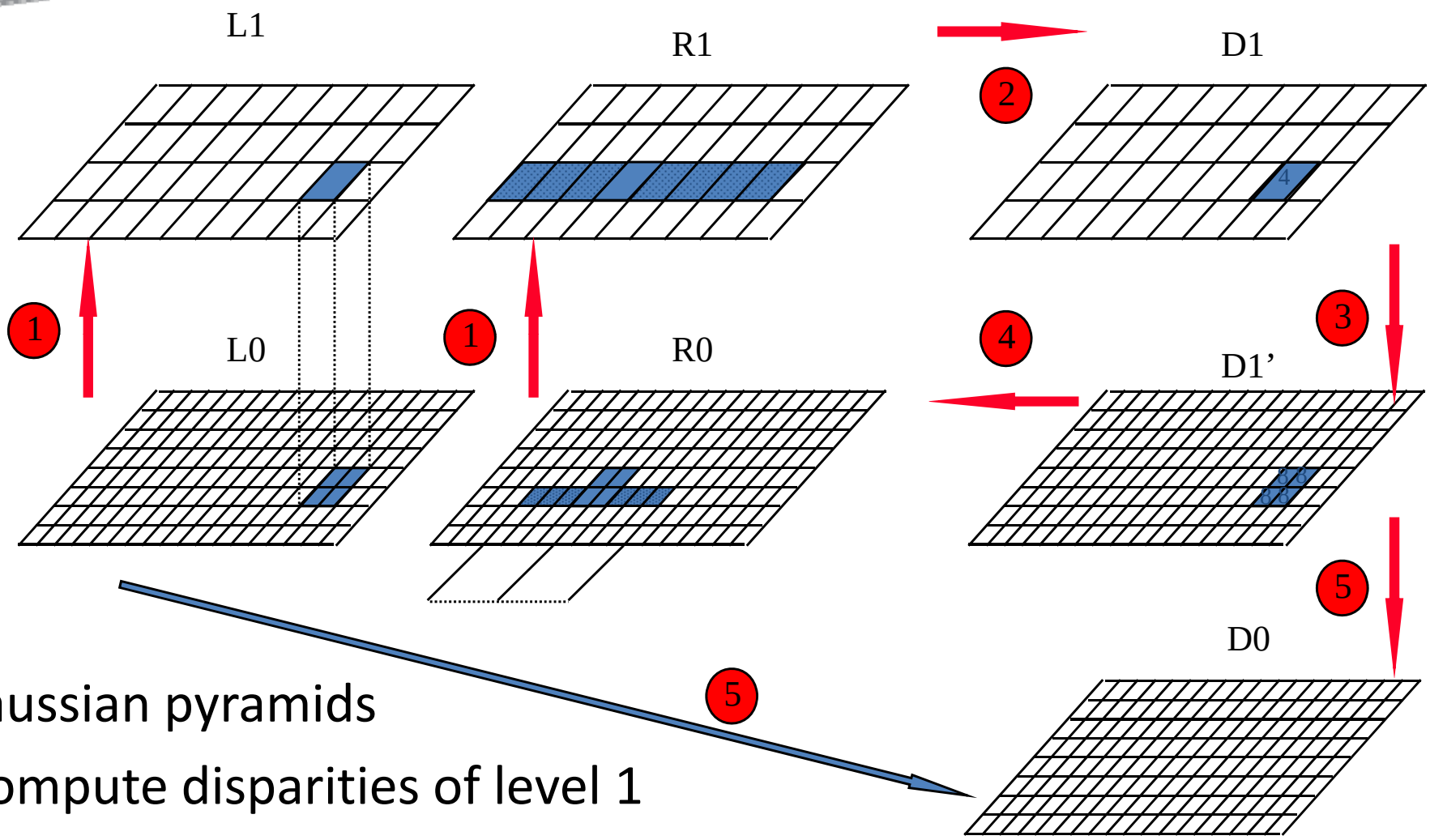




found **continue searching** **not found**

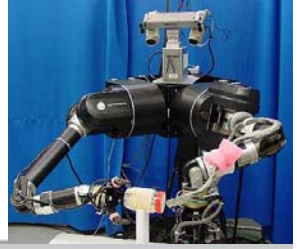
Hierarchical Matching



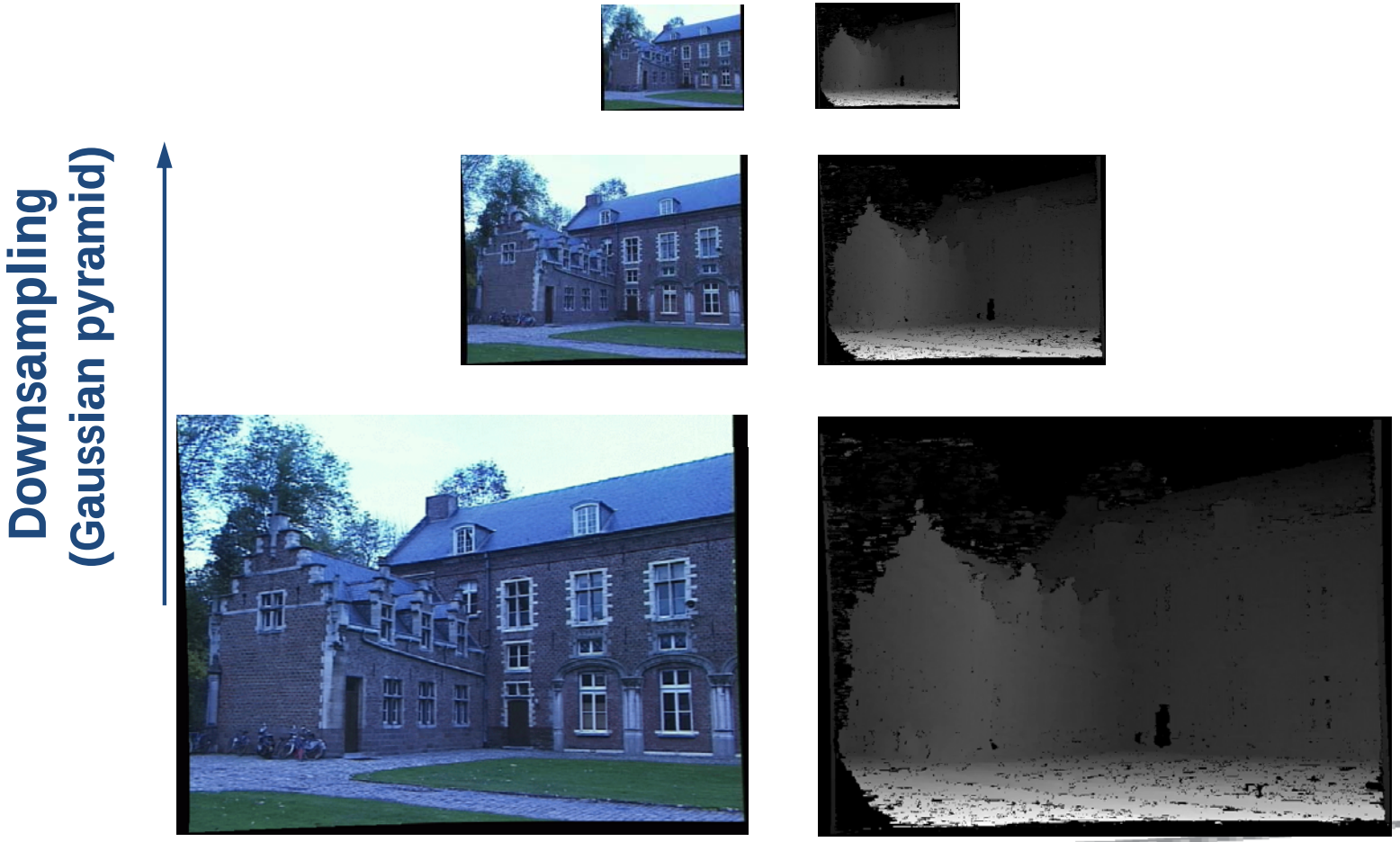


- Gaussian pyramids
- Compute disparities of level 1
- Project values
- Compute disparities of lower level

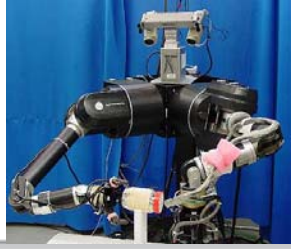
Hierarchical Stereo Matching



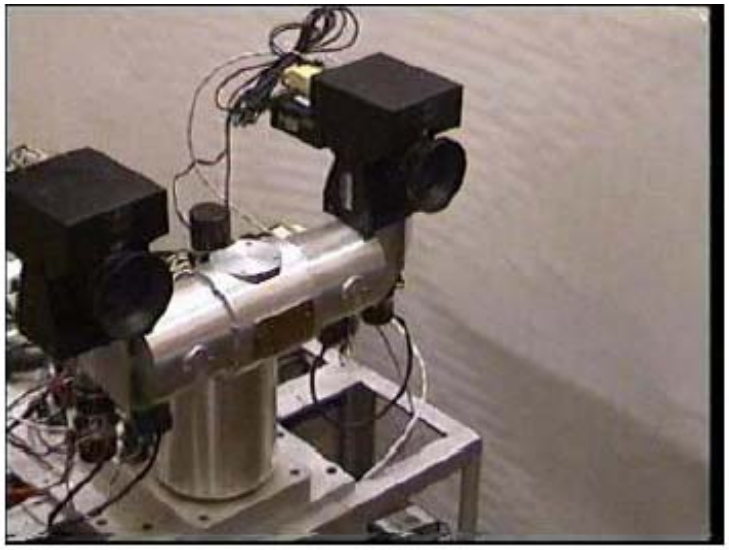
- Allows faster computation
- Deals with large disparity ranges



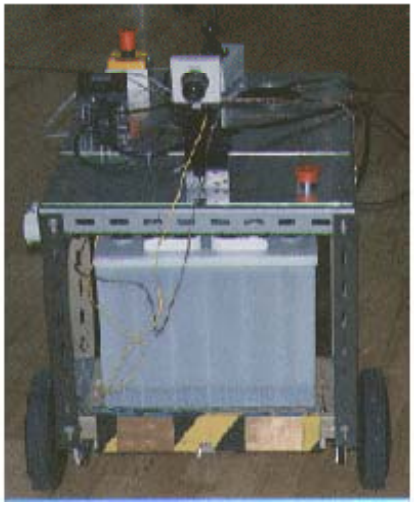
Example



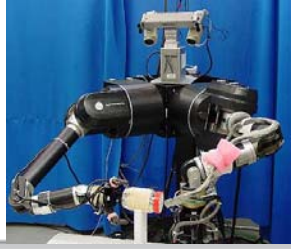
Stereo head



Camera on a mobile vehicle



Example



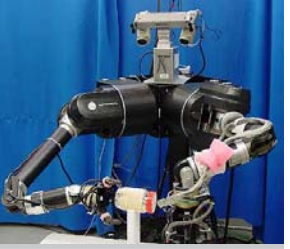
left image

right image

right image

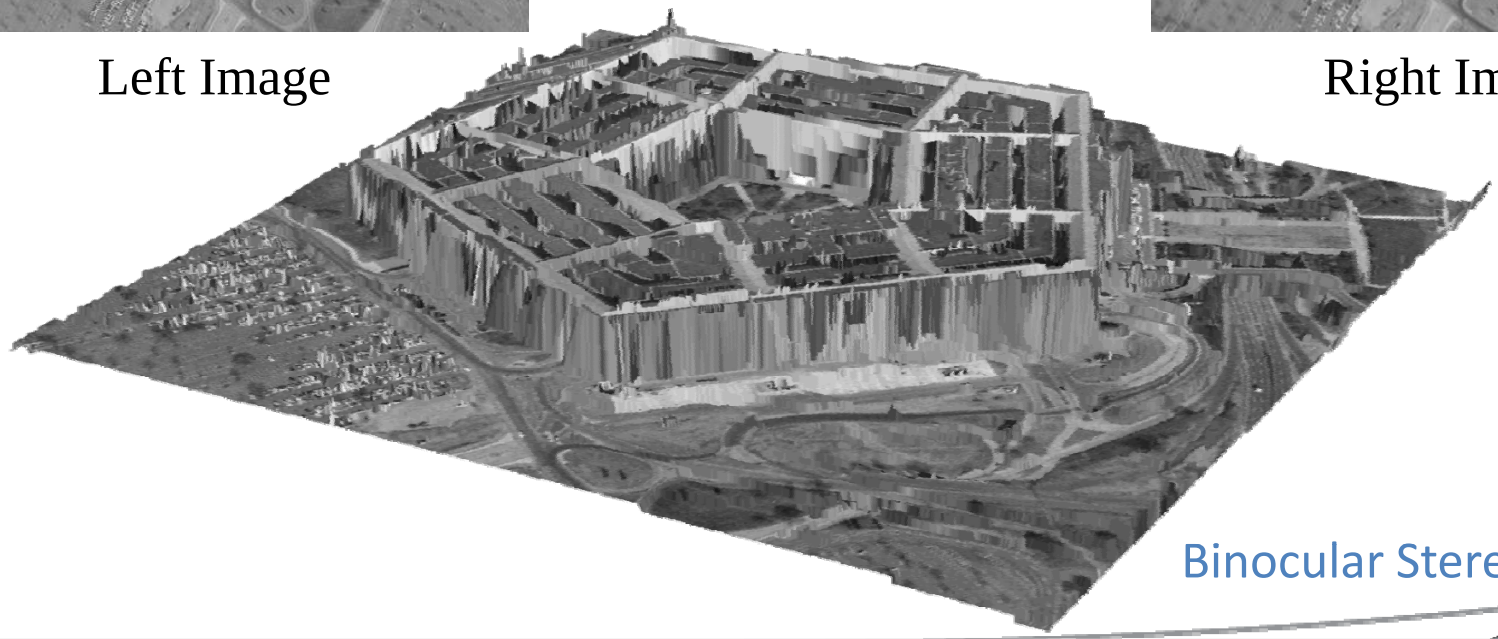
depth map

Pentagon Example



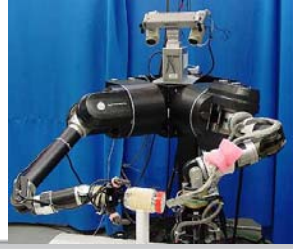
Left Image

Right Image



Binocular Stereo

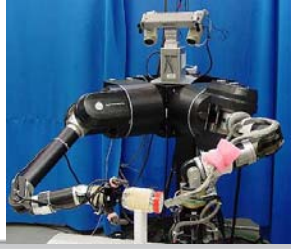
Problems with Window-based Matching

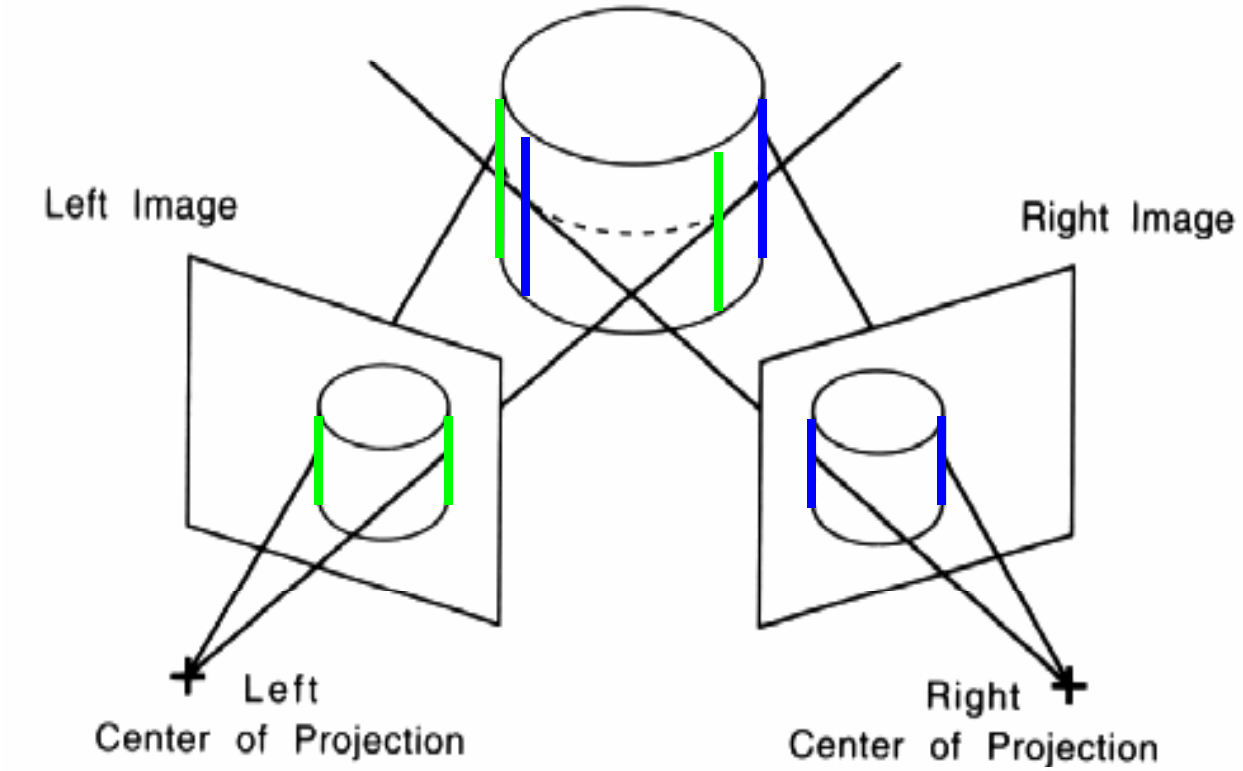


- Disparity within the window must be constant.
- Bias the results towards frontal-parallel surfaces.
- Blur across depth discontinuities.
- Perform poorly in textureless regions.
- Erroneous results in occluded regions

Feature-based Matching

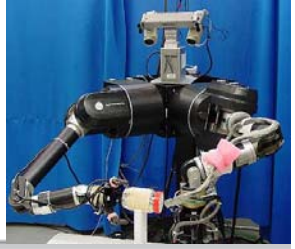
Feature-based Matching

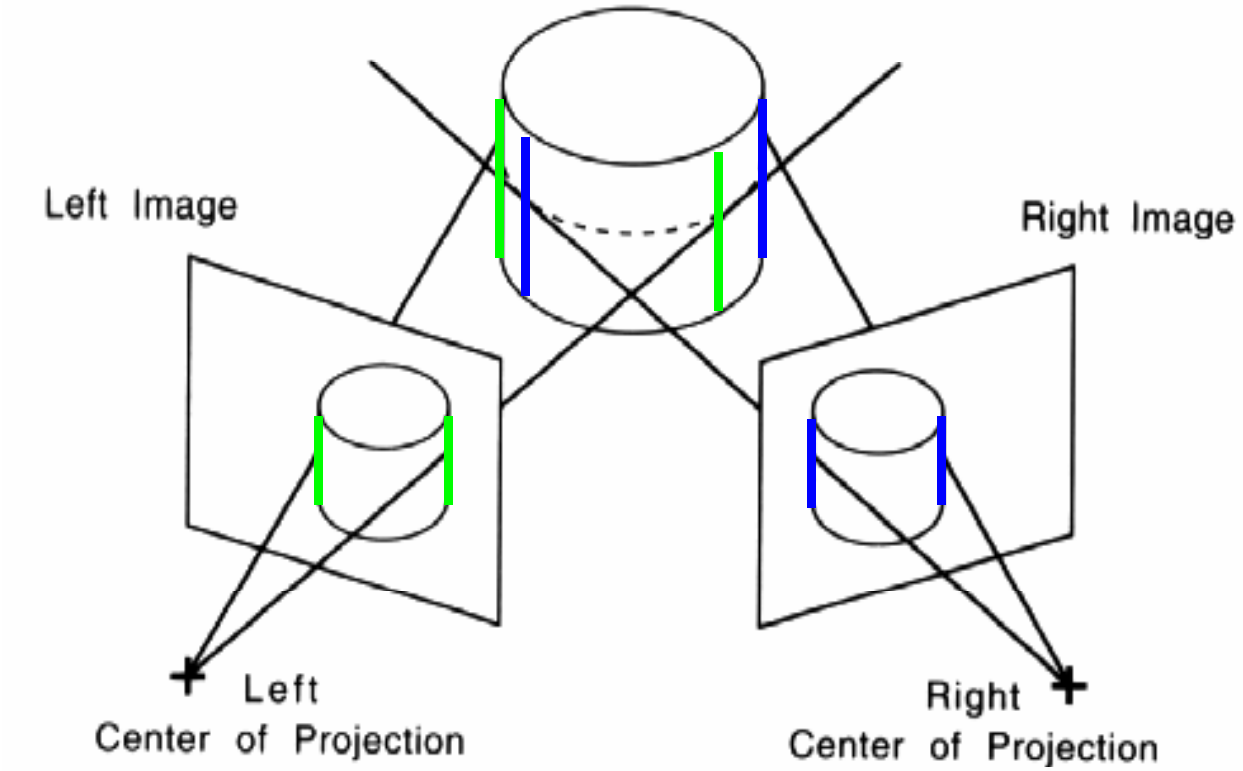




- Viewpoint-independent edges as a prerequisite for correct interpretation: violation = wrong values.
  - Edges are basis of evaluation
  - Advantage: very accurate
  - Disadvantage: very few range points

Feature-based Matching





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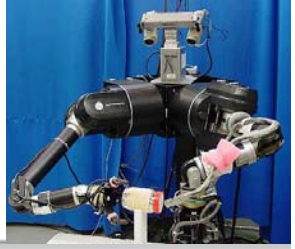
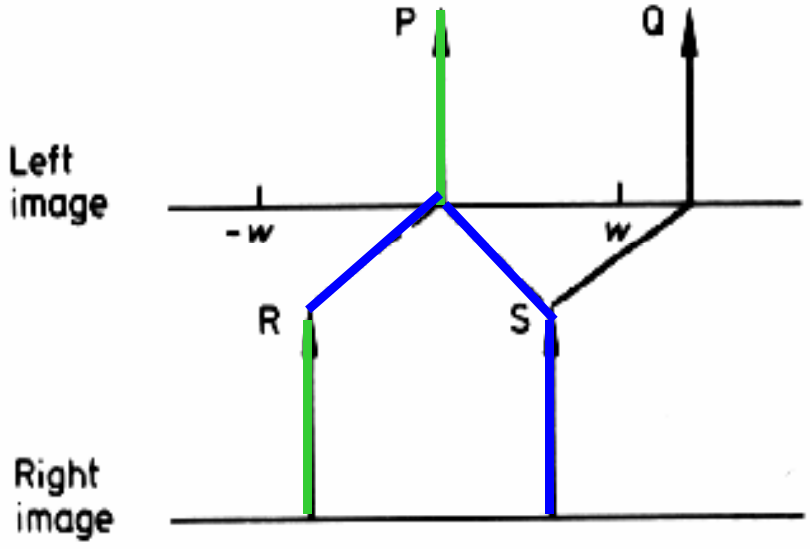
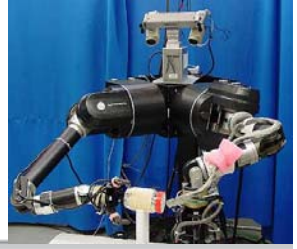
Feature-based Matching



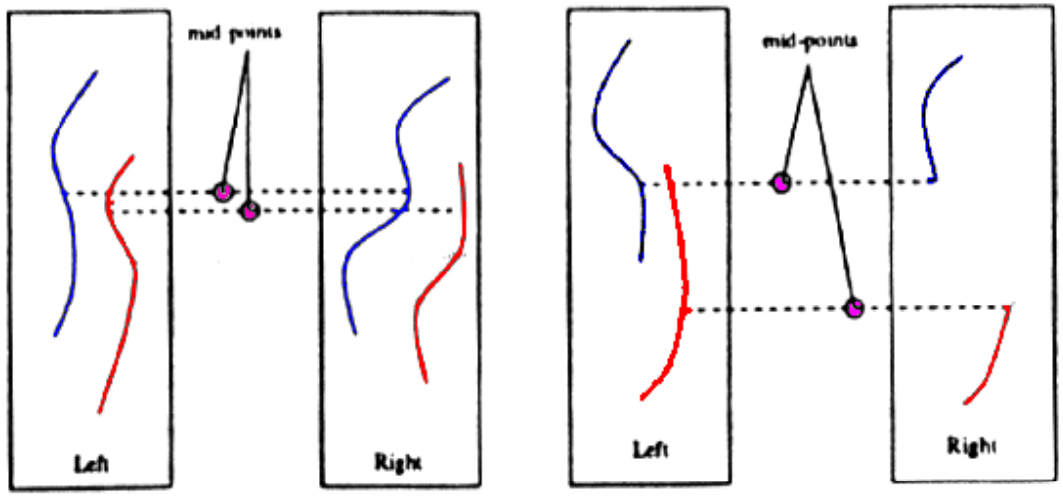
- Order of edges must be preserved
  - Pulling effect by shape and curve of edges
  - unique assignment possible



Contours as Features

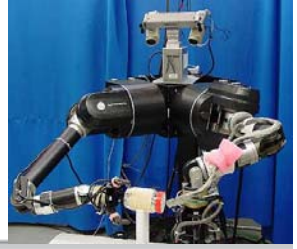


- Restrictions on the set of edges => Candidates for stereo
  - only vertical contours (> 30 to x-axis)
  - no intersecting contours
  - Epipolar line may be crossed only once
  - Contours must have minimum length



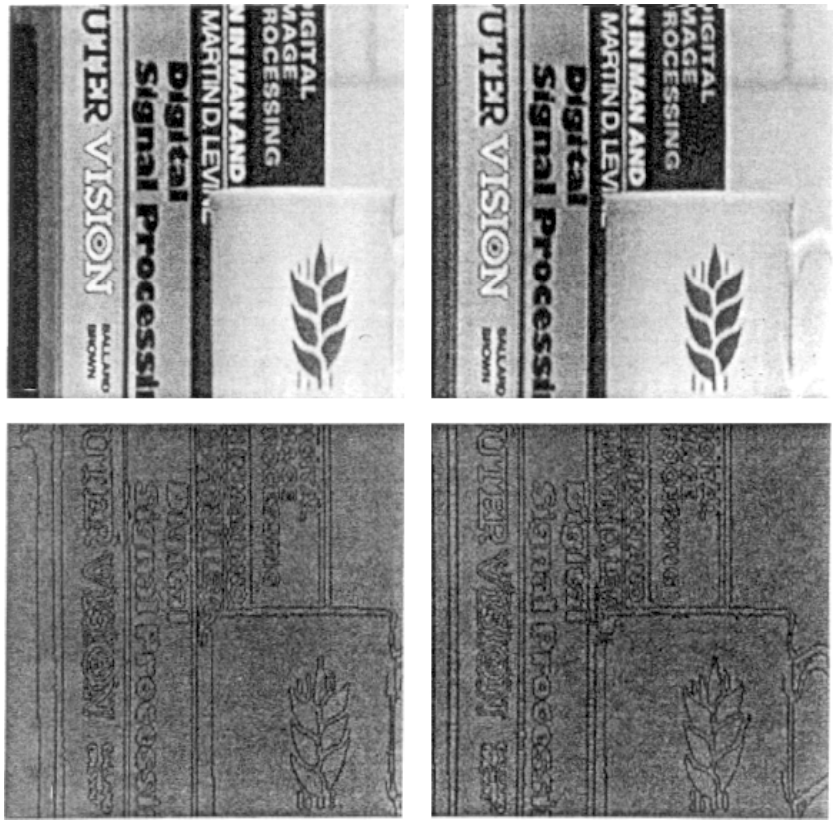
  - Contours must have similar shape
  - Contours must have similar angle to epipolar line
  - Contours have similar gradient magnitude
  - Order of the contours must be retained

Results



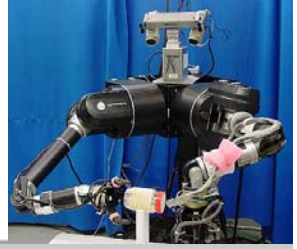
- Zero Crossings of the original images with a predefined threshold value are the basis for evaluation:

Left image **Right image** **Ground Truth**

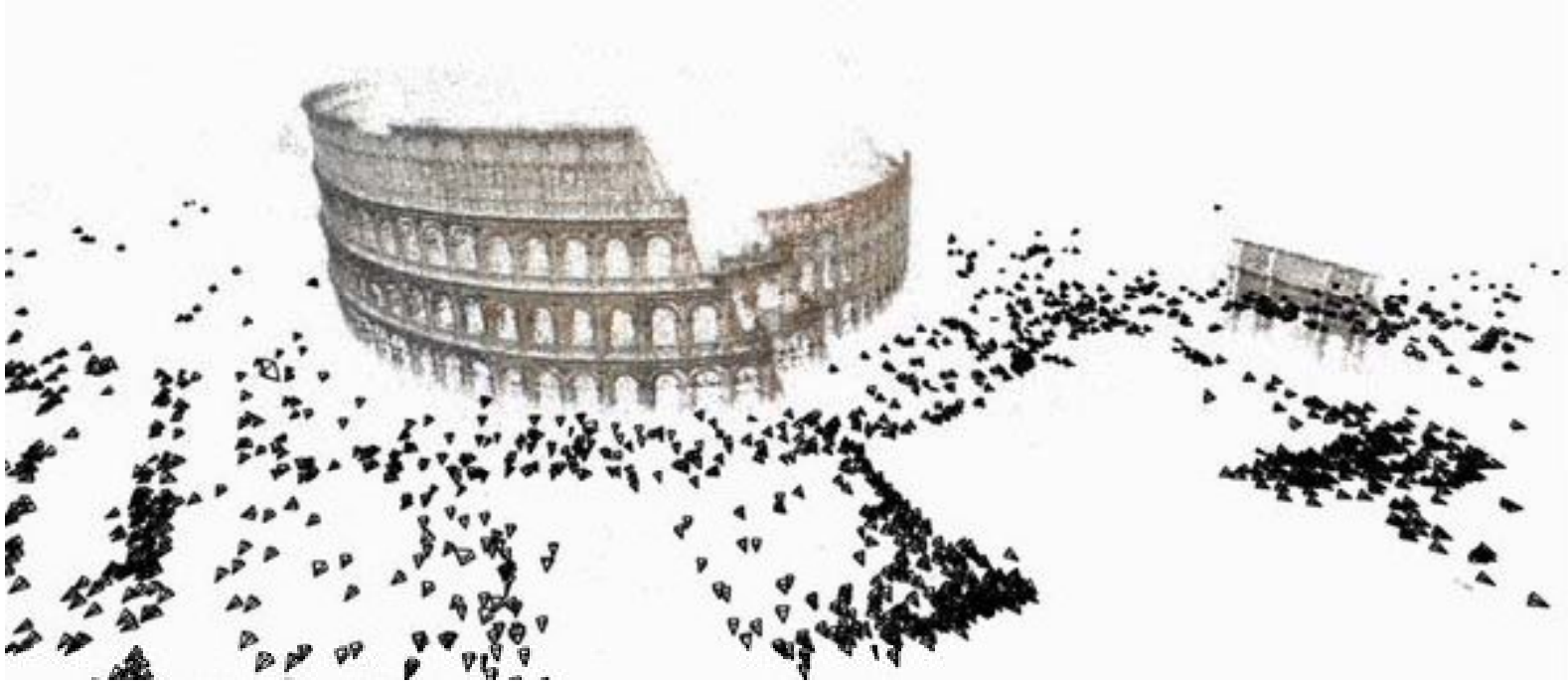


Zero crossings **Results**

Building Rome in a Day

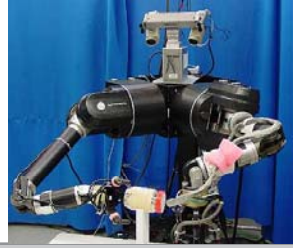


- Entering the search term Rome on Flickr returns more than two million photographs.
- reconstructing entire cities from images harvested from the web

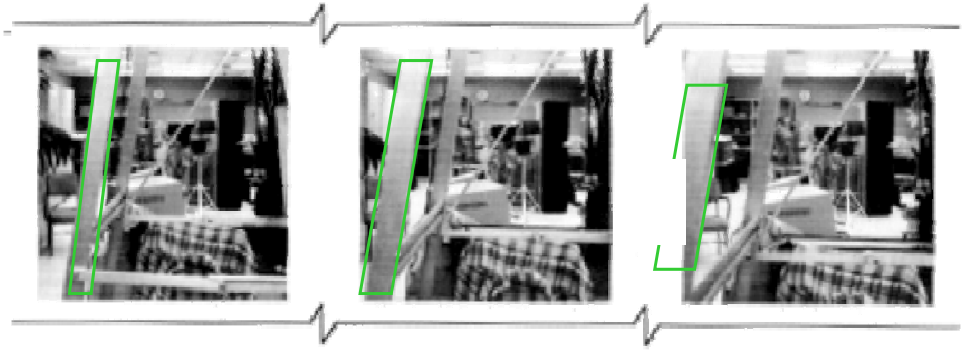


Structure from Motion (SfM)

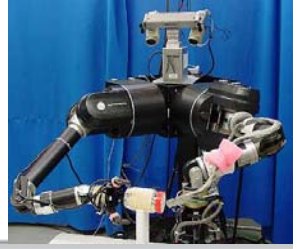
Structure from Motion



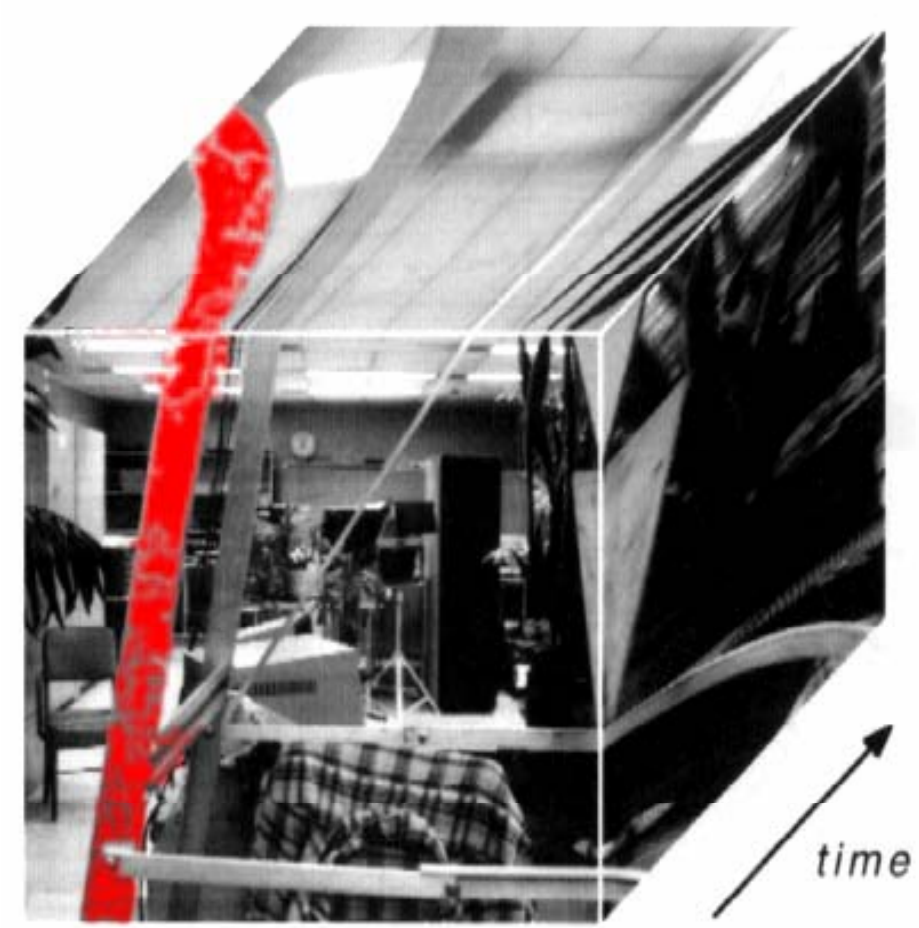
- Motion of an observer relative to the environment:
  - Information about **movement** of viewer
  - **Depth information** of the environment (cf. stereo)
  - Motion parallax = **Motion disparity**
- Problem: direction and amount of camera movement
  - Motion field **estimation**
  - Motion field **analysis**
  - Shift of viewpoint => motion of objects



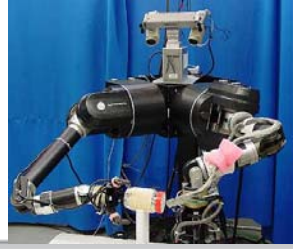
Assumptions for Motion



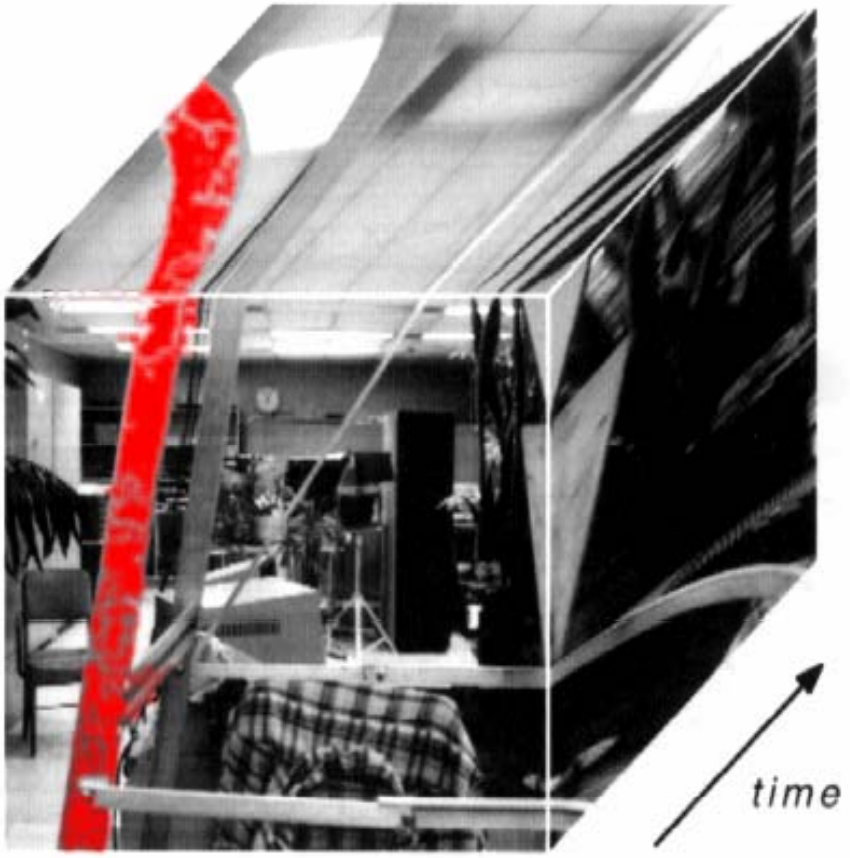
- Camera moves uniformly
- Camera moves along a displacement vector
- Time intervals between images are the same
- Objects are stationary
- Objects may not change temporarily
- Third Dimension = Time dimension
- Spatio-temporal greyscale
  - Spatio = image space
  - Temporal = time space



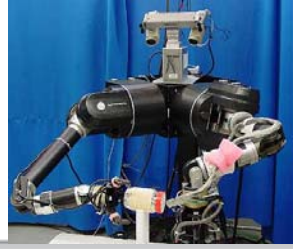
Motion – Range Image Computation



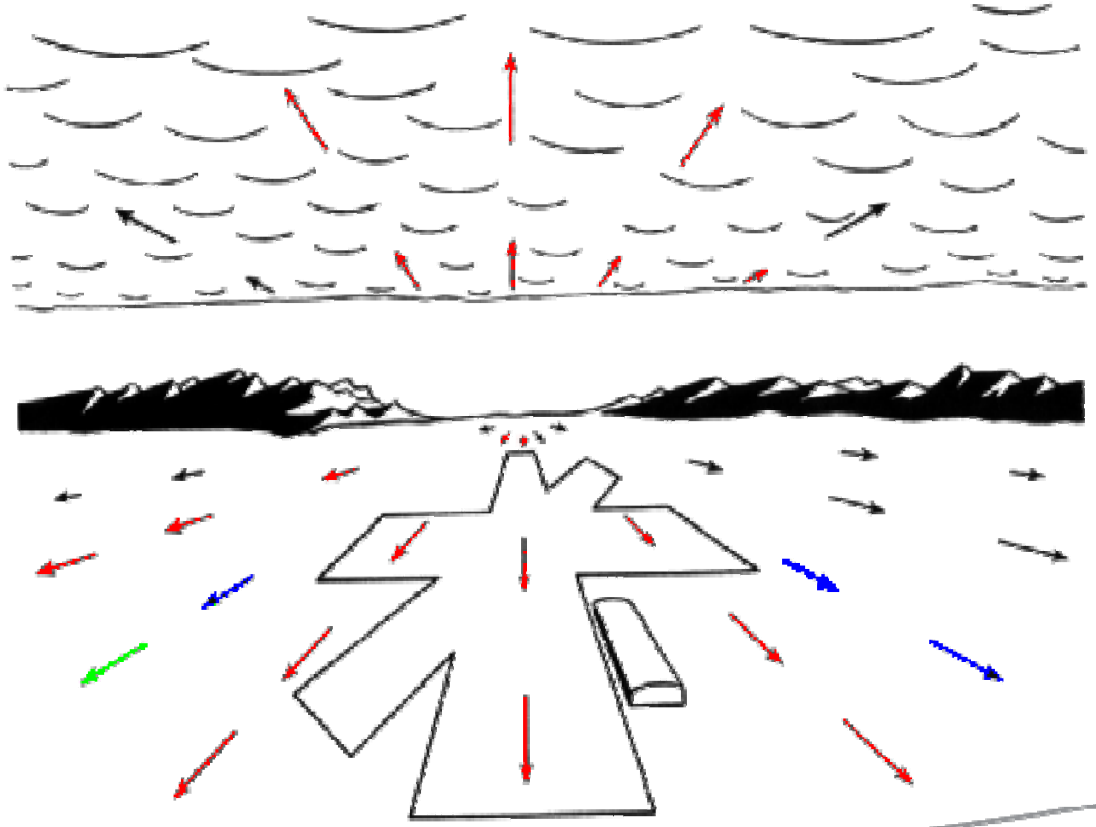
- Range Image Computation possible if (prerequisites):
  - Knowledge of the direction of movement of the camera
  - Knowledge of the speed of the camera
- Algorithm: **Geometric Stereo**



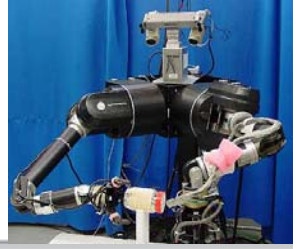
Motion Field



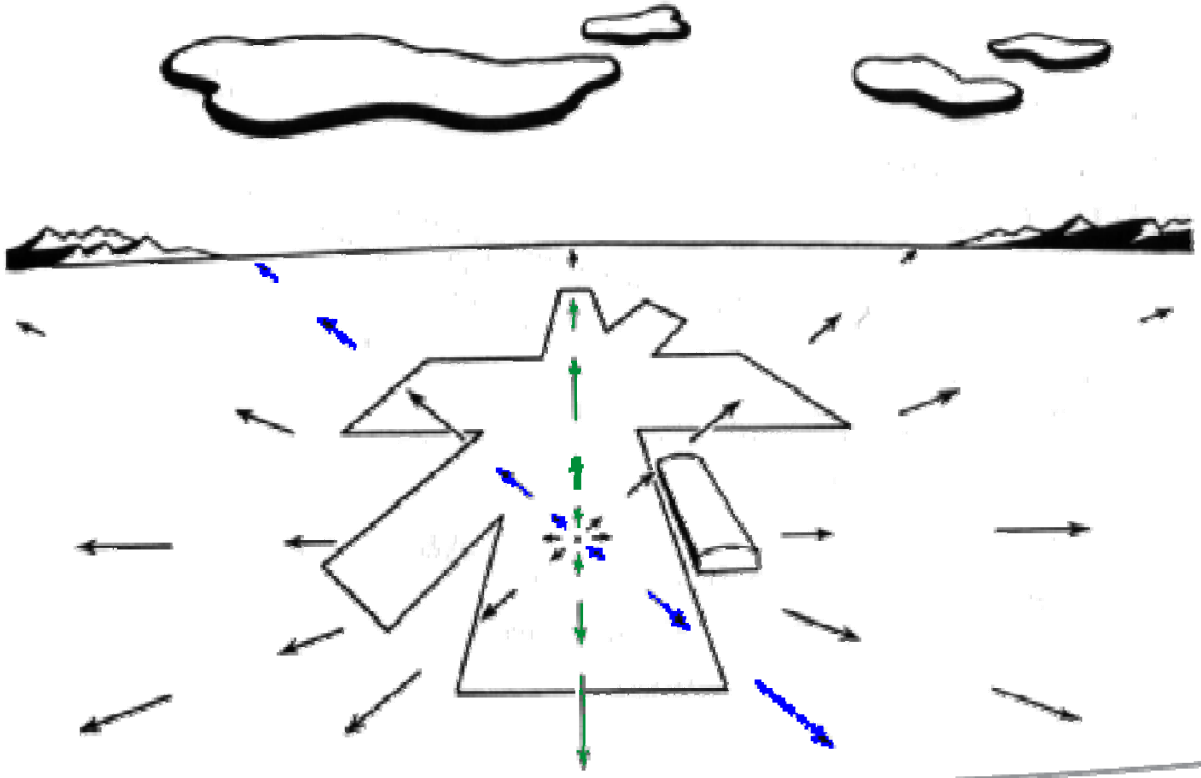
- The motion field of a camera which is in motion relative to the scene is characterized by vectors representing the motion of the corresponding scene points.
- Camera that does not rotate:
  - Vectors point radially to or from a focus
  - FOE: Focus Of Expansion
  - FOC: Focus Of Contraction
  - Point where the motion vector of the camera intersects image plane



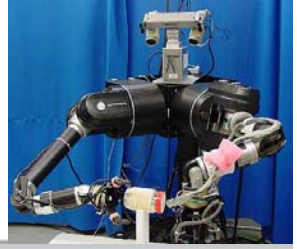
Motion Field



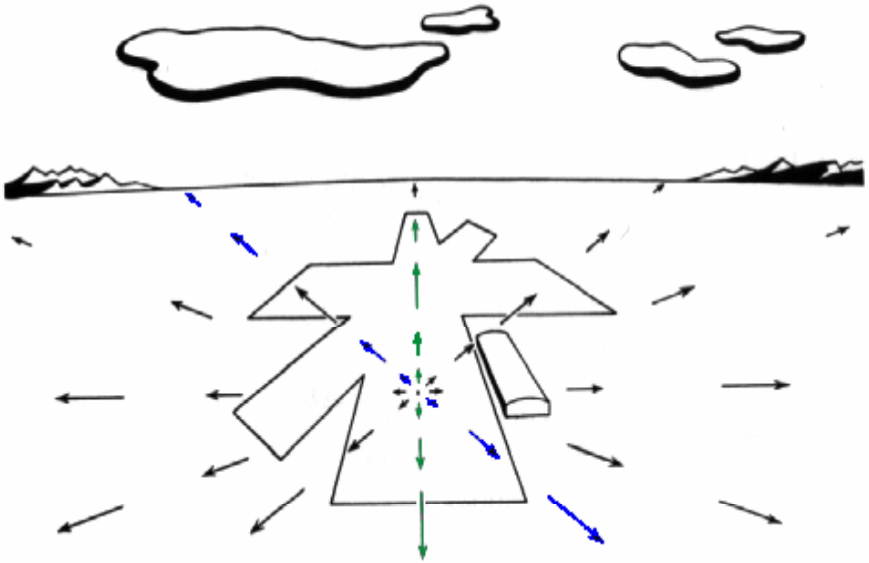
- Length of the vector is:
  - inversely proportional to the distance of the point
  - proportional to the sine between the direction in which the point lies and direction of movement of the camera



Motion Vector

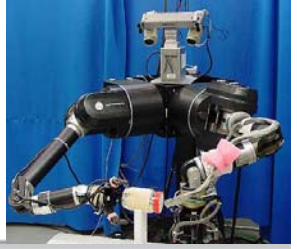


- Determination of the motion vector through image plane velocity
- Determination of the FOE (divergence of vectors = forward movement) or FOC (convergence of the vectors = backward motion)

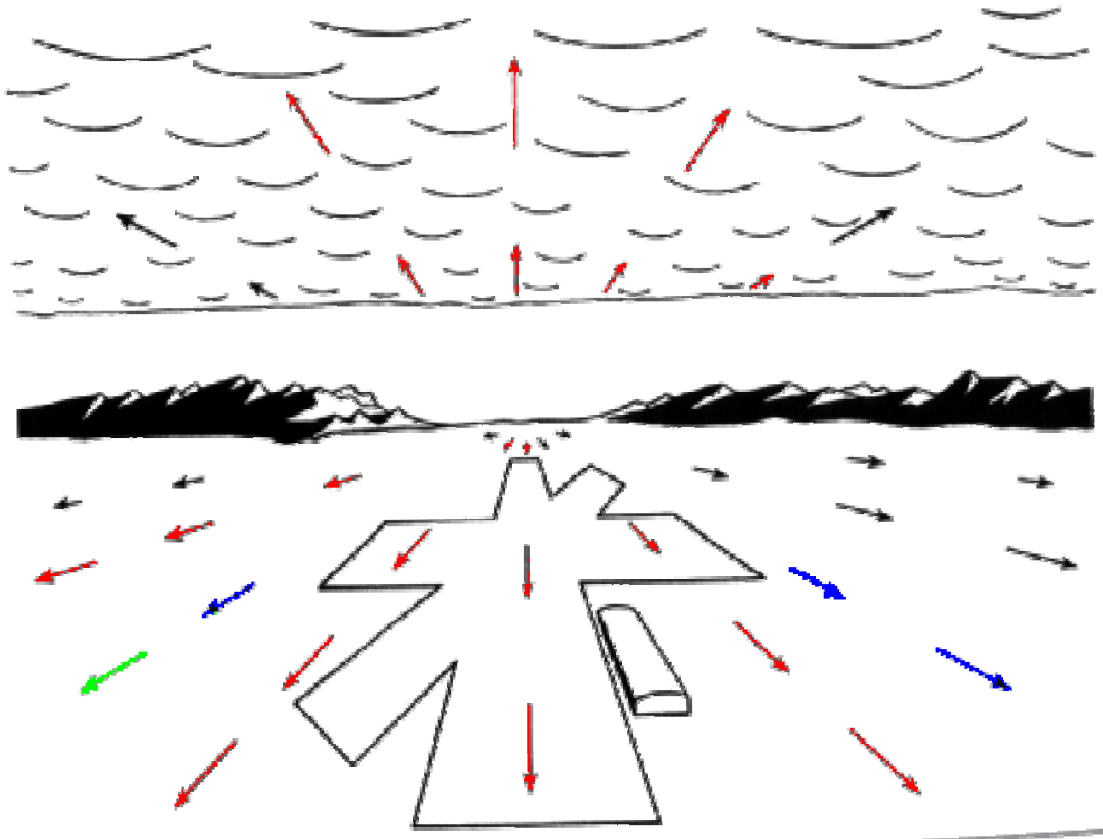


- Analogy to Stereo:
  - Baseline of the stereo images => Any projection of a scene point must move along the epipolar line
  - converge at the epipole = FOE or FOC
  - Caution! Not every point that has no vector magnitude is FOE (FOC) => infinite distance = no movement

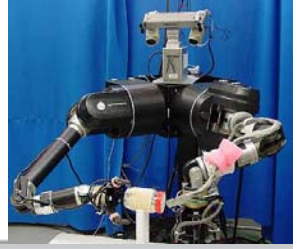
FoE and FoC



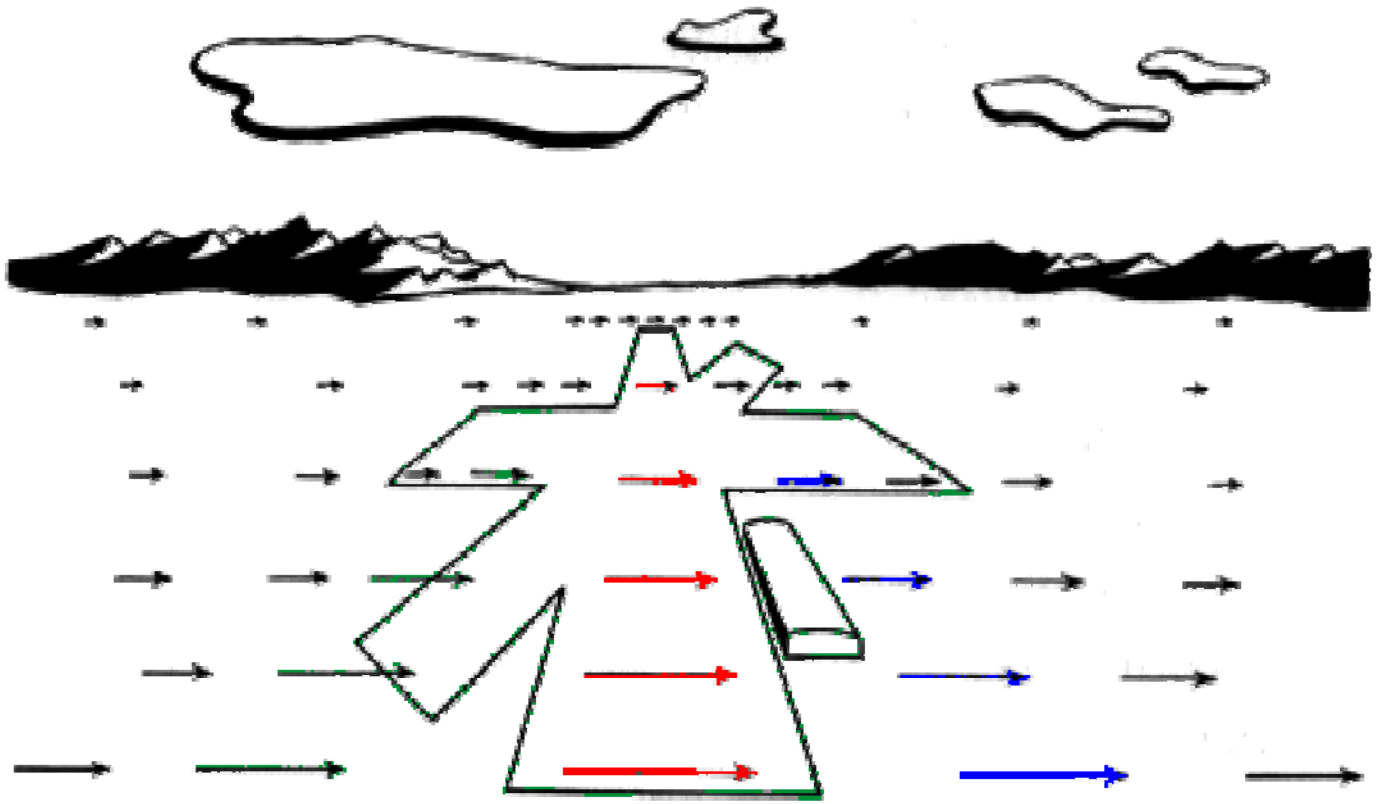
- Intersection between moving direction and image plane
- Amount of movement = 0
- Convergence (divergence) of all motion vectors.



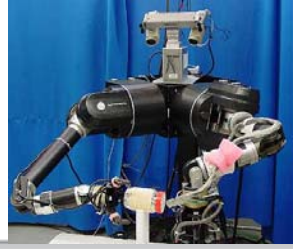
Special Case: Stereo



- FOE and FOC are at infinity

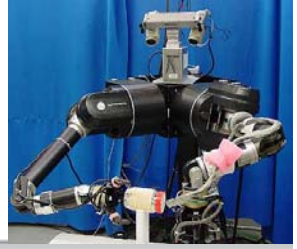


Motion Field Estimation

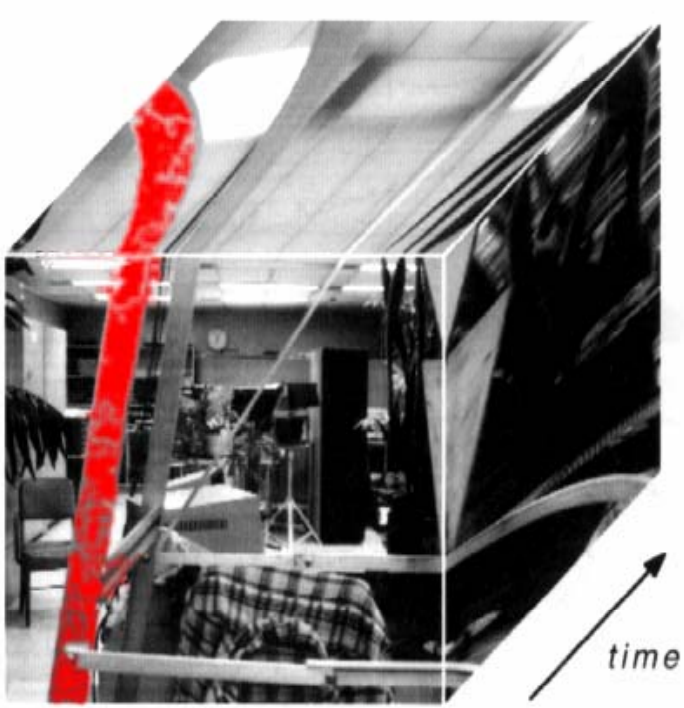


- Problem: Determination of corresponding points in two images
  - sparsely occupied vector field
  - same problem as stereo - just moving direction of the camera not known
  - epipolar line not known in the beginning
- In order to find correspondence between images:
  - high temporal sampling = low differences
  - either unchanged intensities in both images or unchanged edges in both images

Motion Field Estimation

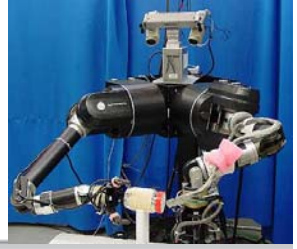


- Similar to area-based and feature-based stereo:
  - Motion: Intensity Flow or Edge Flow (Optical Flow)
  - But: In Motion epipolar lines are not known!
- All Isobrightness lines or image edges have to be tracked
  - Combination of the two assumptions: unchanged intensities and image edges

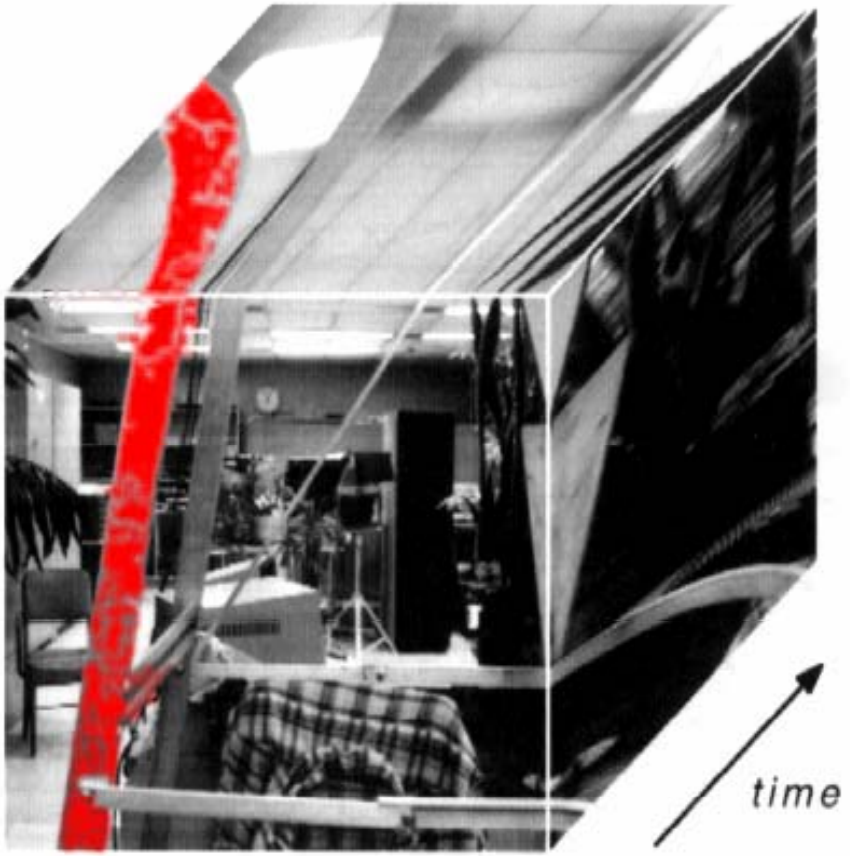


Optical Flow

Motion – Range Image Computation



- Range Image Computation possible if (prerequisites):
  - Knowledge of the direction of movement of the camera
  - Knowledge of the speed of the camera
- Algorithm: **Geometric Stereo**



Optical Flow

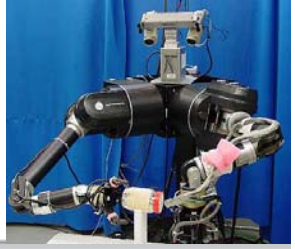
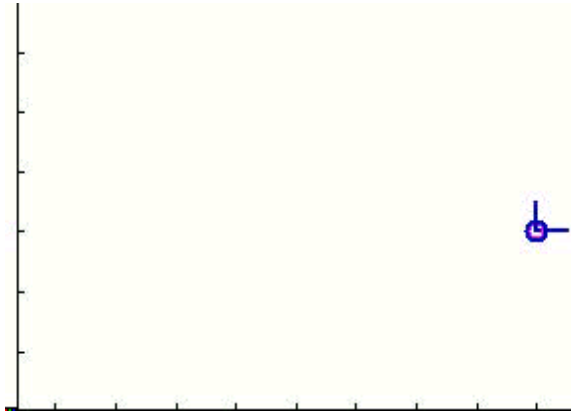


Image sequence
(single camera)

Image tracking

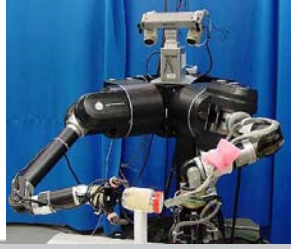
Tracked sequence

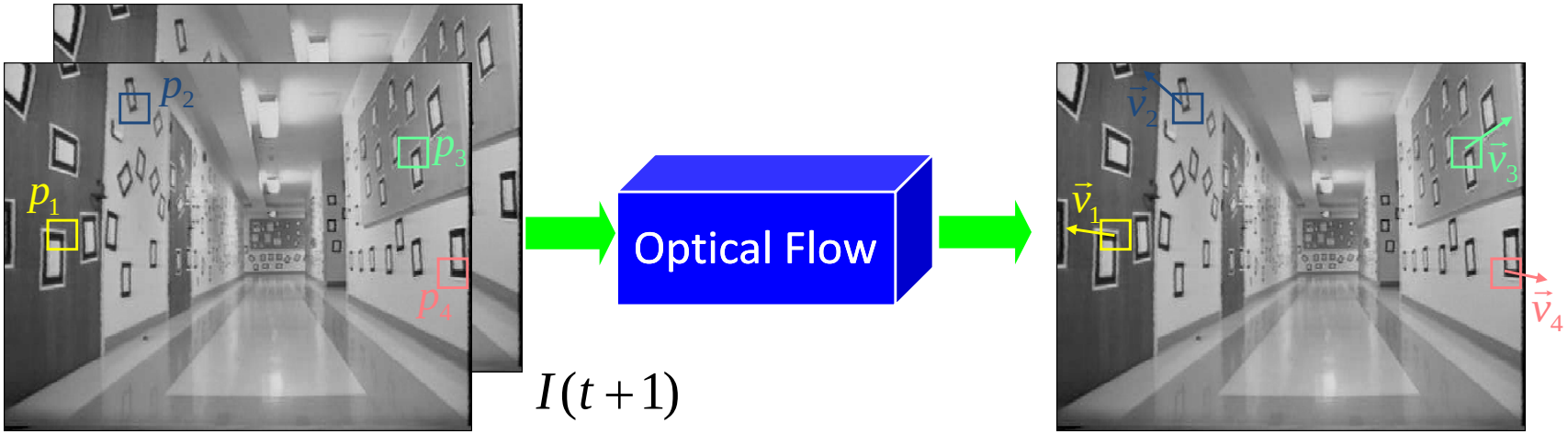
3D computation



3D structure
+
3D trajectory

What is Optical Flow?





$I(t+1)$

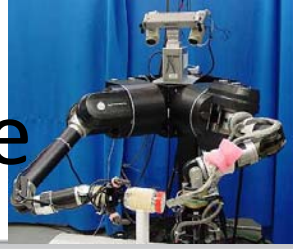
$I(t), \{p_i\}$

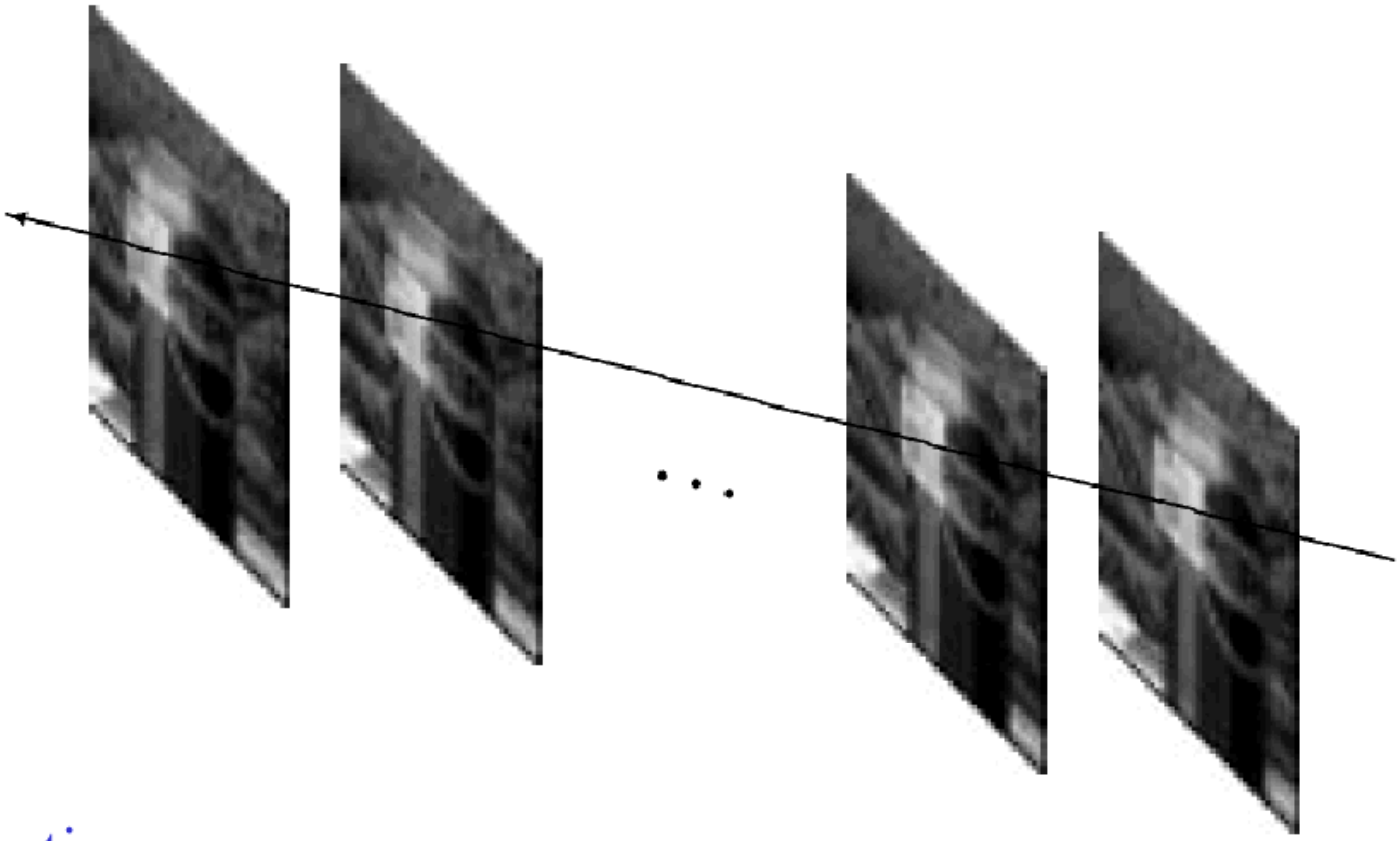
Velocity vectors $\{\vec{v}_i\}$

- Optical flow
  - is the relation of the motion field to 2D displacement of pixel patches on the image plane.
  - the 2D projection of the physical movement of points relative to the observer
- Common assumption:
  - The appearance of the image patches do not change (brightness constancy)

$$I(p_i, t) = I(p_i + \vec{v}_i, t+1)$$

Optical Flow Assumption: Temporal Persistence





Assumption:

The image motion of a surface patch changes gradually over time.

Structure from Motion Example