Mtrx 4700 : Experimental Robotics

Sensors, Measurements & Perception

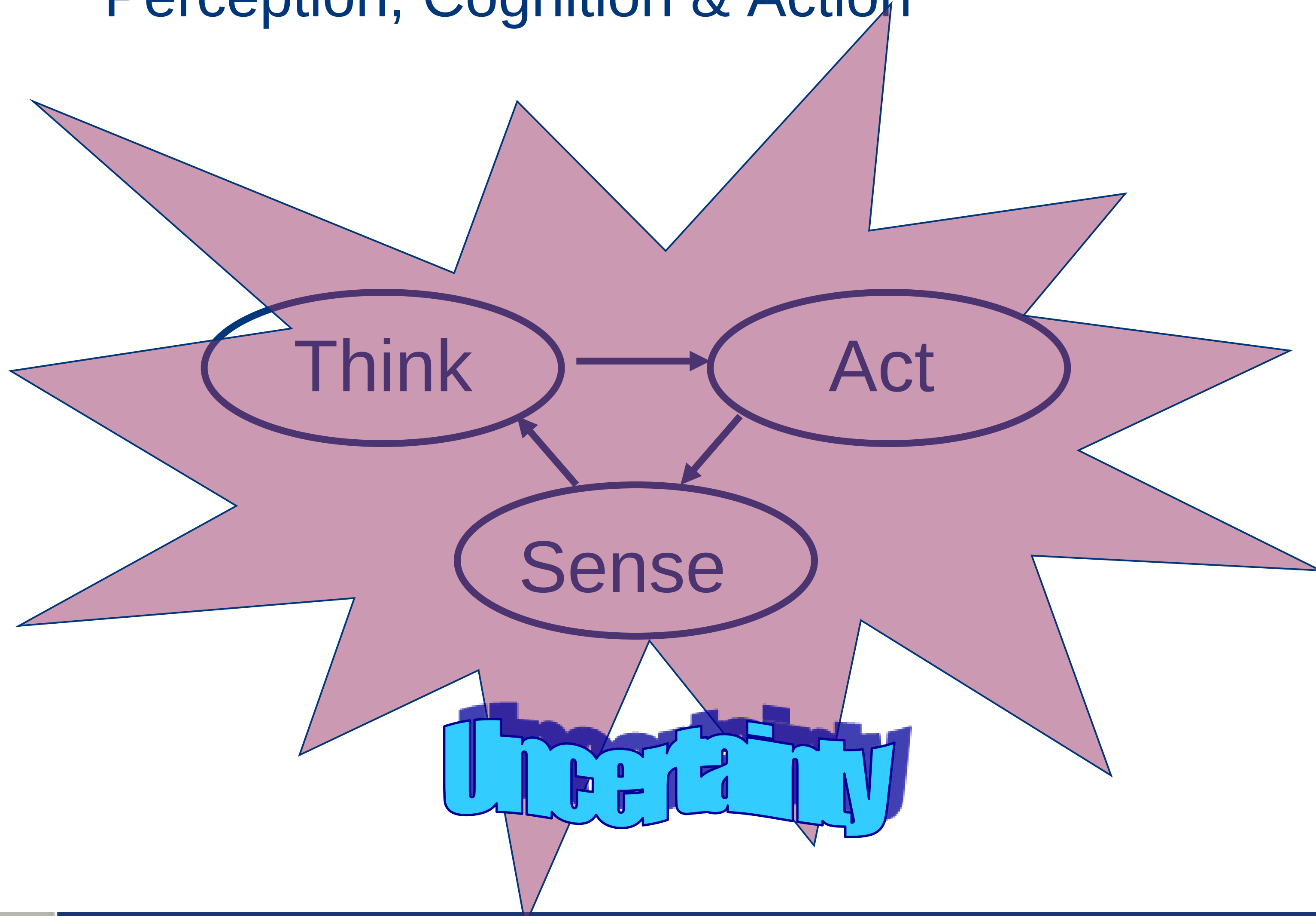
Dr. Stefan B. Williams

Course Outline

Week	Date	Content	Labs	Due Dates
1	5 Mar	Introduction, history & philosophy of robotics		
2	12 Mar	Robot kinematics & dynamics	Kinematics/Dynamics Lab	
3	19 Mar	Sensors, measurements and perception	“	
4	26 Mar	Robot vision and vision processing.	*No Tute (Good Friday)*	**Kinematics Lab**
	2 Apr	BREAK		
5	9 Apr	Localization and navigation	Sensing with lasers	
6	16 Apr	Estimation and Data Fusion	Sensing with vision	
7	23 Apr	Extra tutorial session (sensing)	Robot Navigation	**Sensing Lab**
8	30 Apr	Obstacle avoidance and path planning	Robot Navigation	
9	7 May	Extra tutorial session (nav demo)	Major project	**Navigation Lab**
10	14 May	Robotic architectures, multiple robot systems	“	
11	21 May	Robot learning	“	
12	28 May	Case Study	“	
13	4 June	Extra tutorial session (Major Project)	“	**Major Project**
14		Spare		

Robot & Agent

- Perception, Cognition & Action



Perception

- the act or faculty of apprehending by means of the senses or of the mind; cognition; understanding.

Sensors $\Rightarrow$ Measurements $\Rightarrow$ **Perception**

Perception: Low to High Levels

- Measurements from cameras, laser scanners and other perception sensors.

- Features (corner, line, texture)

- Spatial Structure
- Object Recognition
- Motion Tracking
- Activity/Action/Behavior Recognition

- Interaction & Higher level Perception

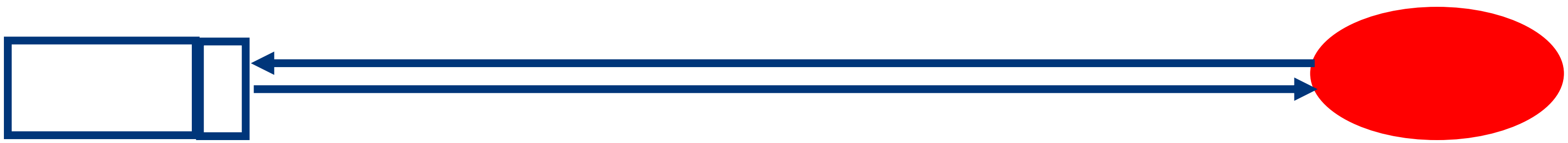
Perception Sensors

- Mechatronics 4721: Sensors and Signals

  Introduction, Signal Processing and Modulation, Radiometers, Imaging Infrared, Visible Imaging and Image Intensifiers, Time of Flight Sensors, Time of Flight Applications ,Time of Flight Imaging , Propagation Effects, Target and Clutter Characteristics, Detection of Signals in Noise, High Range-Resolution Techniques, Doppler Measurement, Millimetre Wave Radiometers, Radio Tags and Transponders, Range Estimation and Tracking, Angle Tracking, Tracking Moving Targets in 3D, Phased Array Principles, Synthetic Aperture Methods, 3D Imaging
- What we focus on:
  - Laser scanners (this week)
  - Cameras (next week)

Laser based Range Measurement

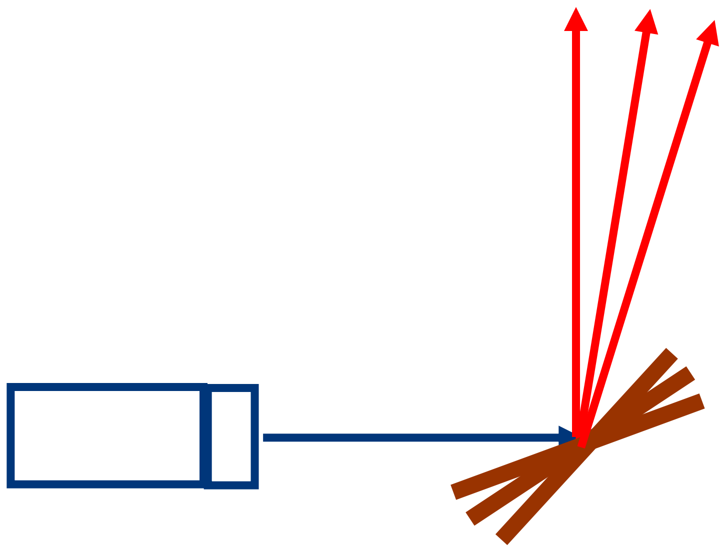
- Time of Flight (TOF)



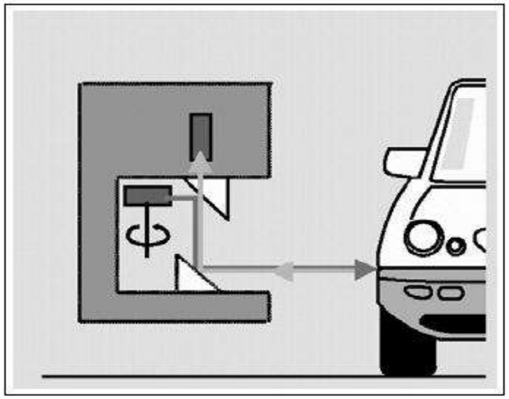
$$D = \frac{C \cdot t}{2}$$

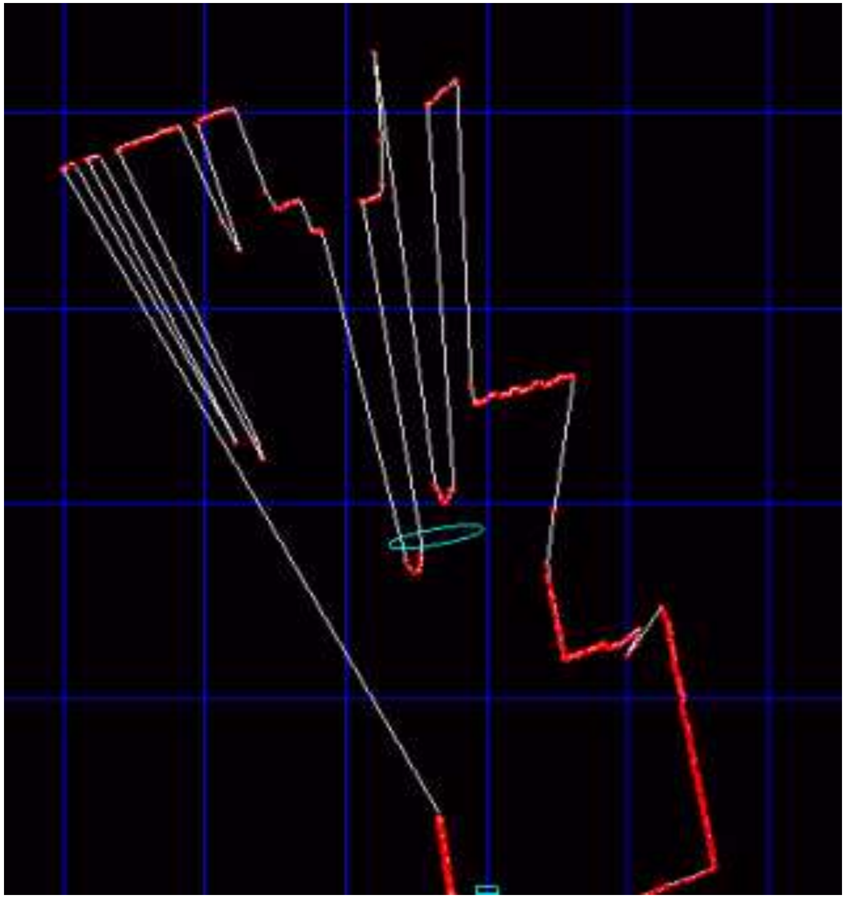
Get a line or surface using one laser measurement device

- Scanning
- 2D and 3D



2D Laser Scanners

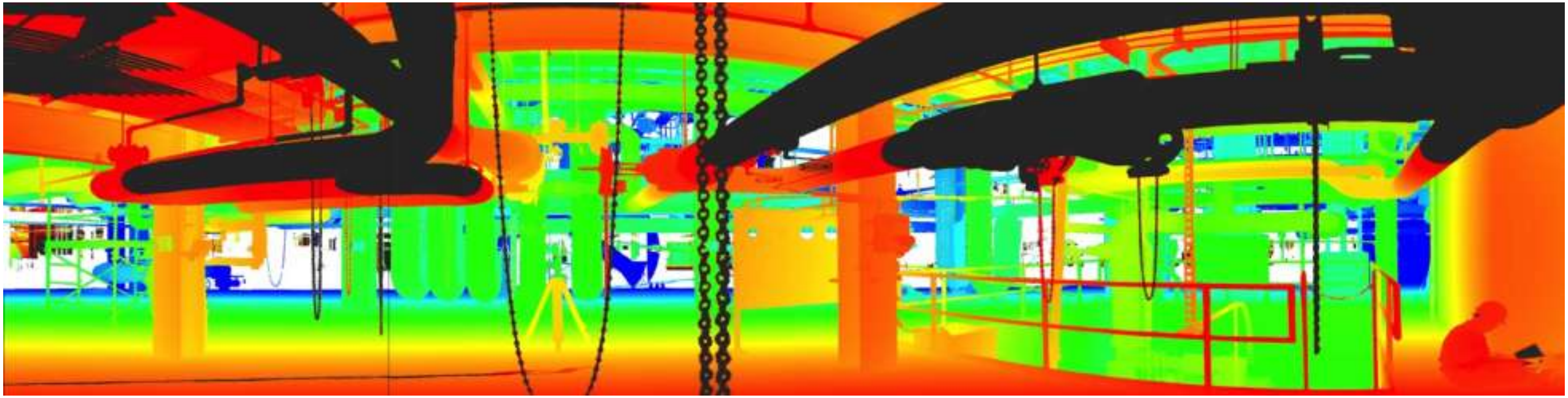




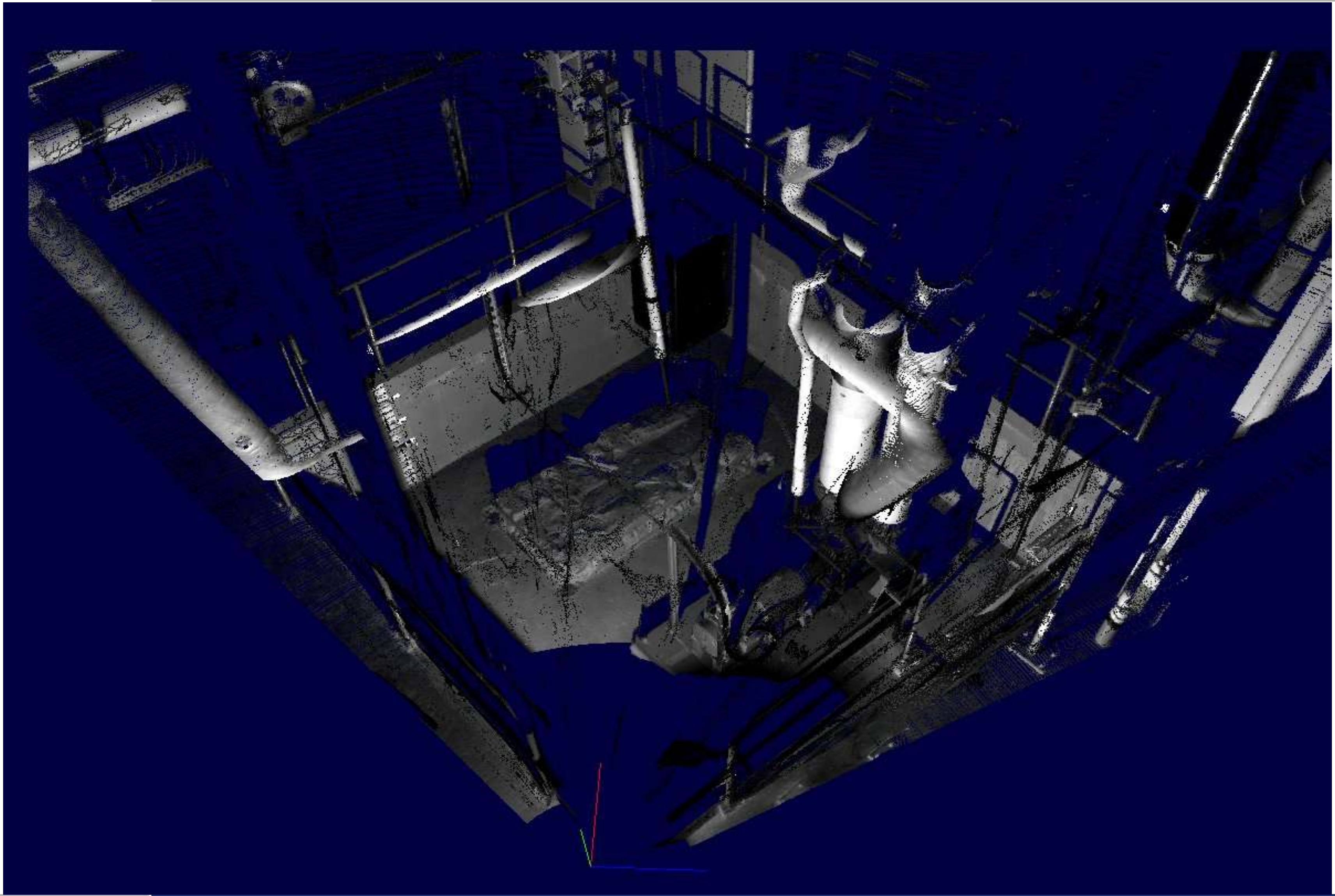
Z+F Inc.

Reflectance

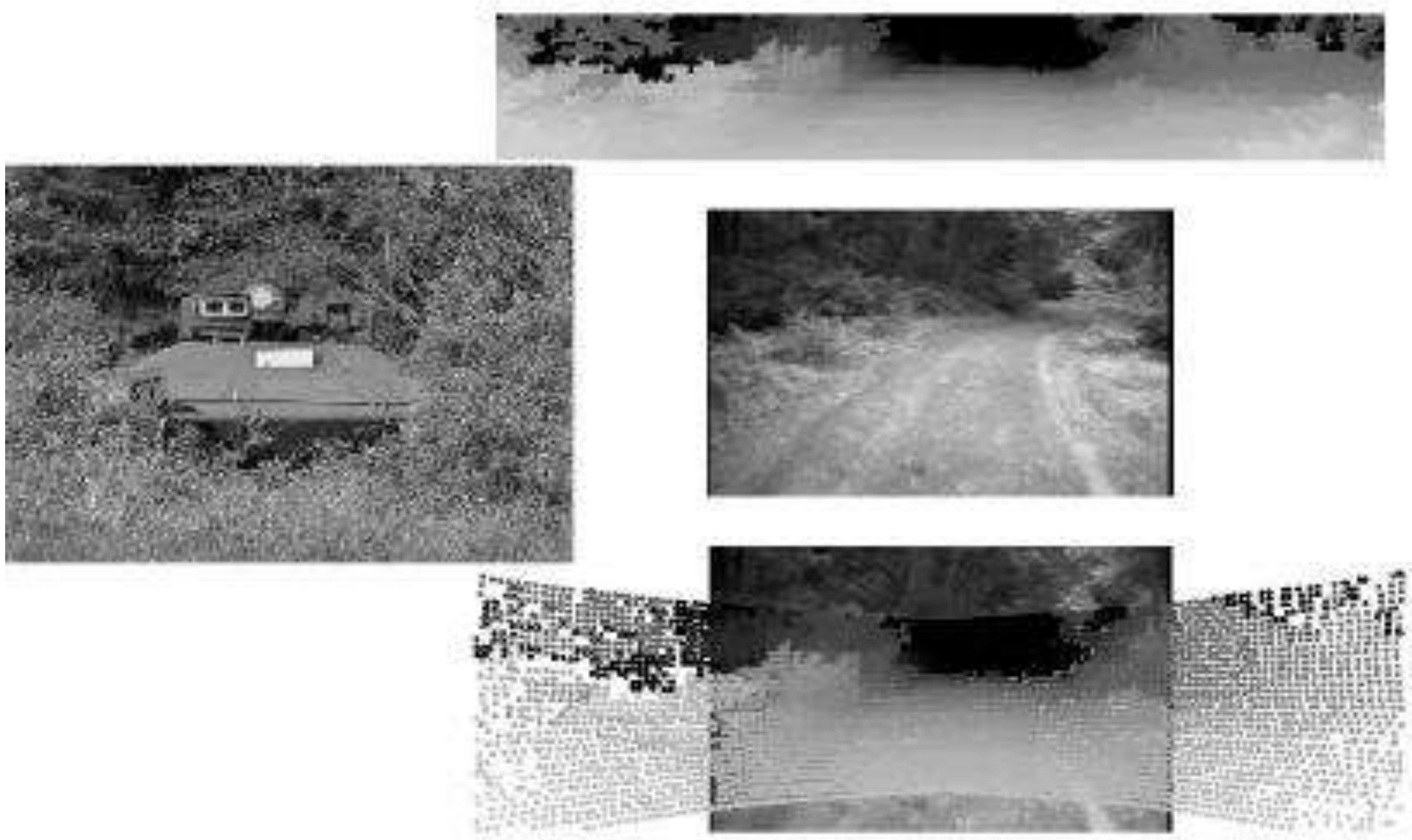
Range



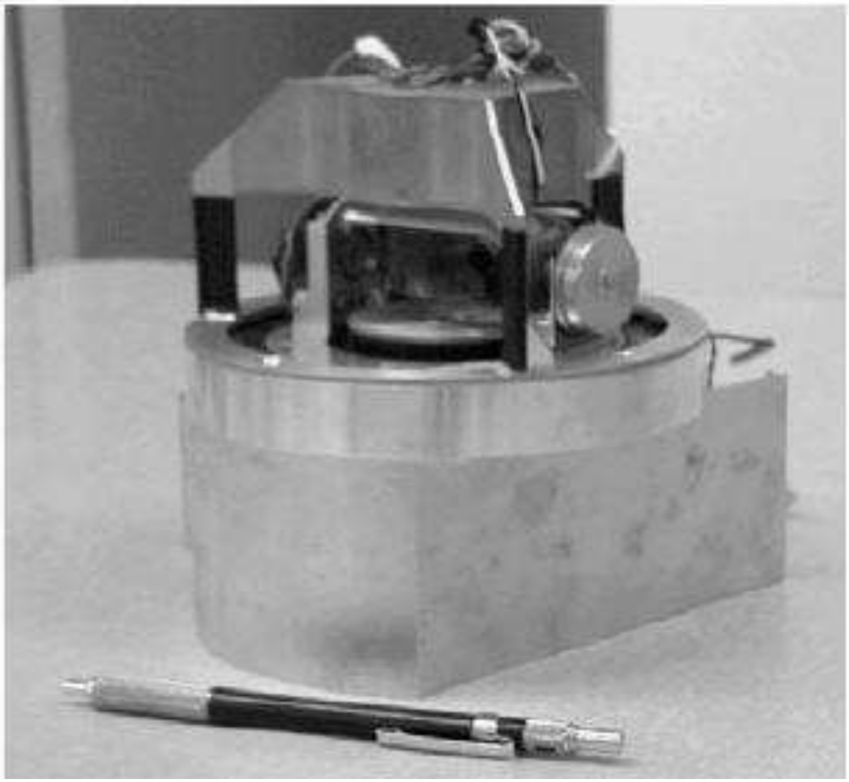
3D-View

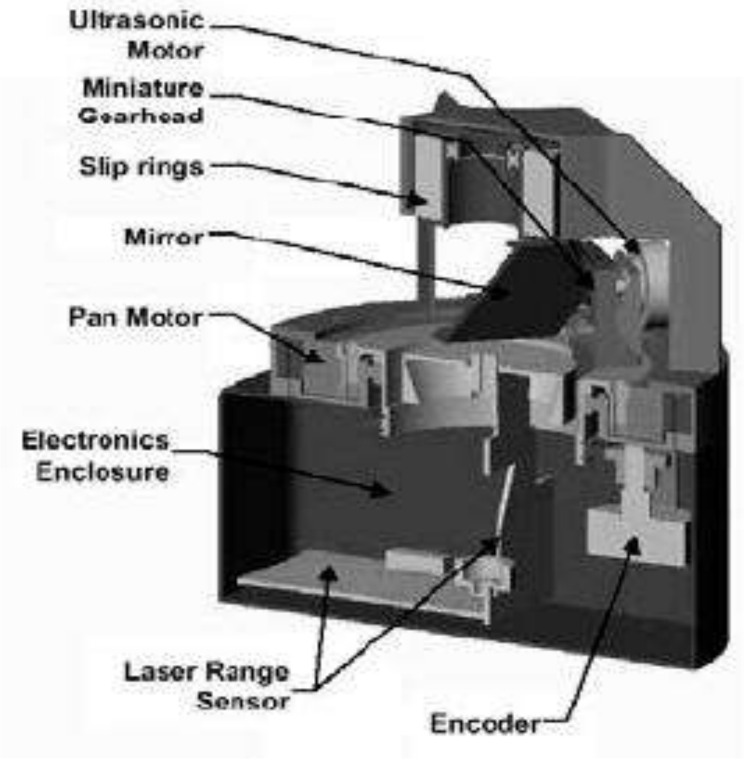


Schwartz electro-optics [NIST]

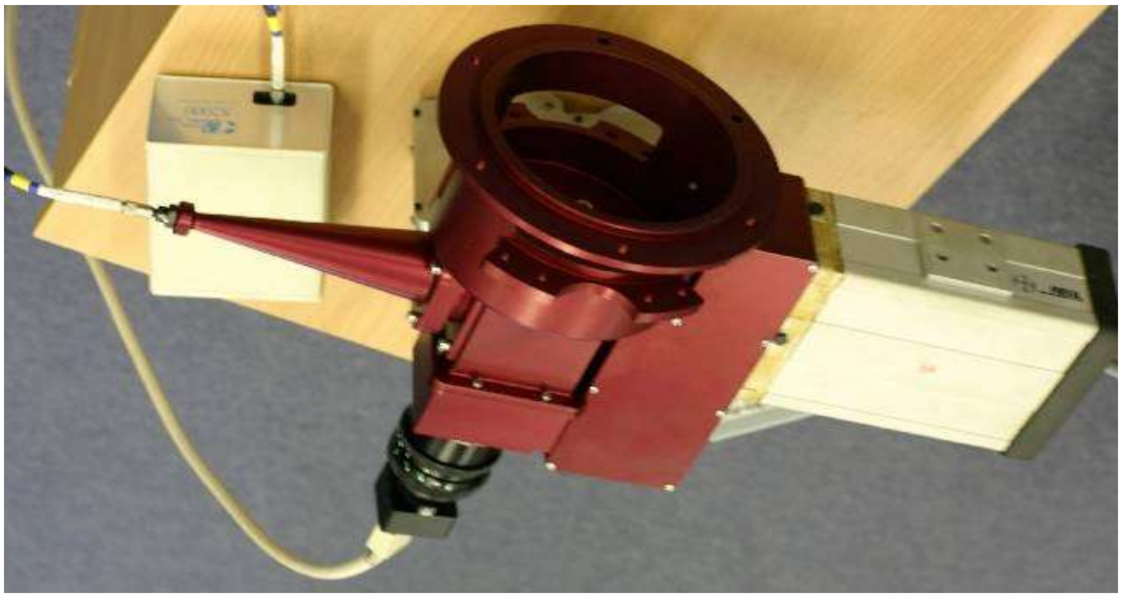


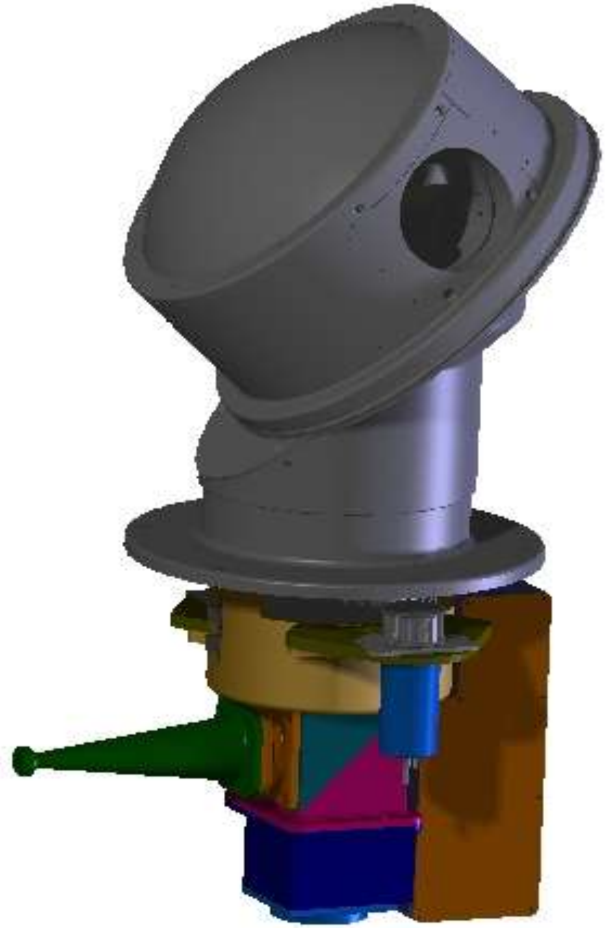
JPL Small Laser Scanner





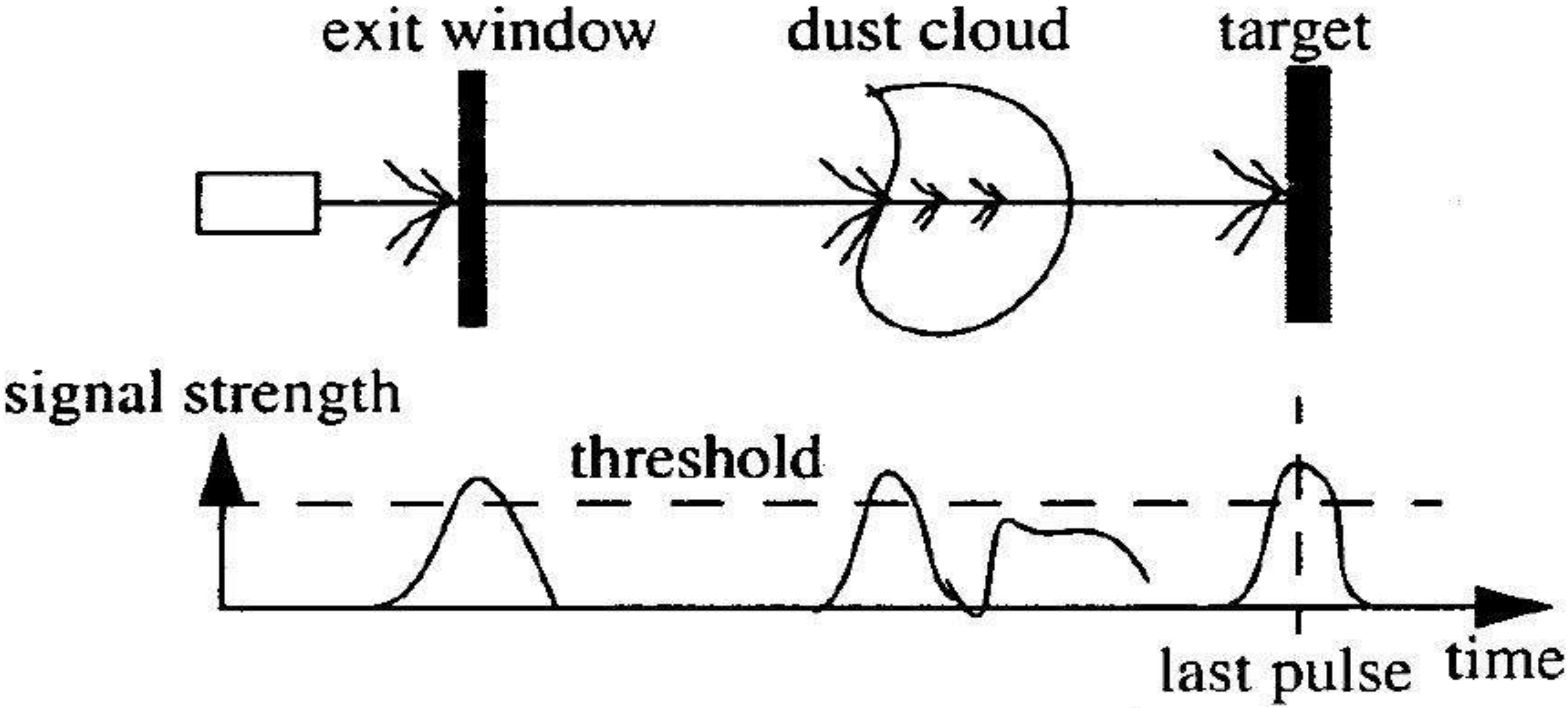
ACFR (Mark Bishop)





Hostile Areas: Fog, Dust or Smoke

- "Last pulse measuring" techniques



Other ways to get range estimates

- Big Issue with Scanners: SCANNING

- Stereo Cameras
- Structured Light with Camera
- And…

Eliminate Scanning

- 3DVSystem
- Kodak

Range Image Processing

In Detail (for localization & mapping)

- Line Extraction/Estimation
- Scan/Surface/Range Image Matching

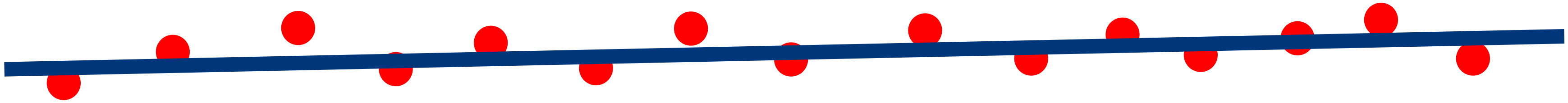
Mention Briefly

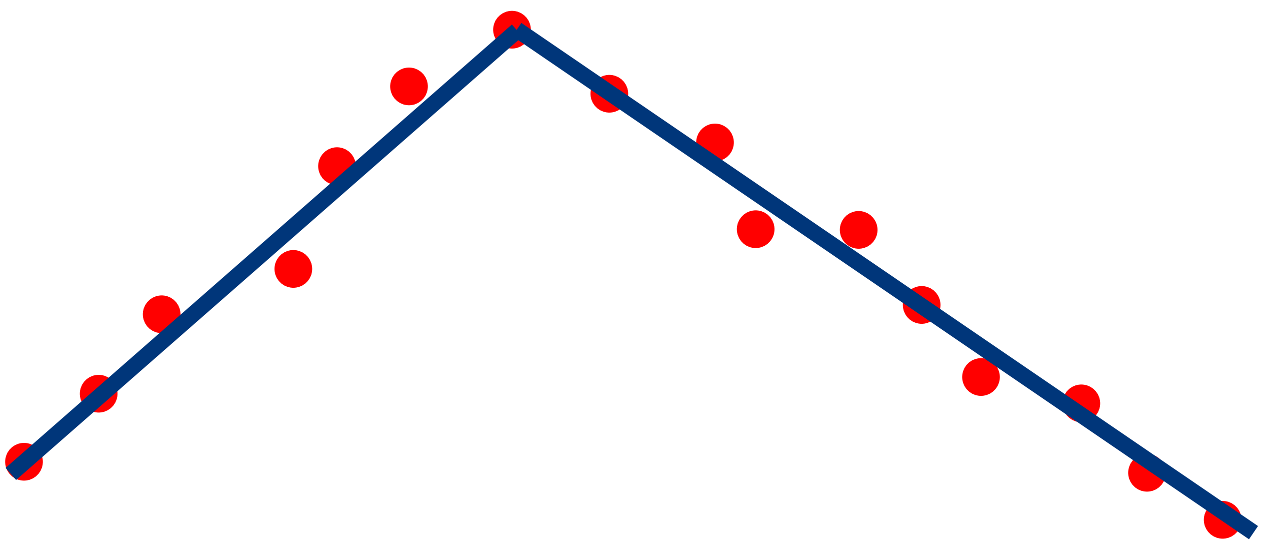
- Recognition
- Non-rigid surface matching
- Advanced topics

Line Extraction/Estimation

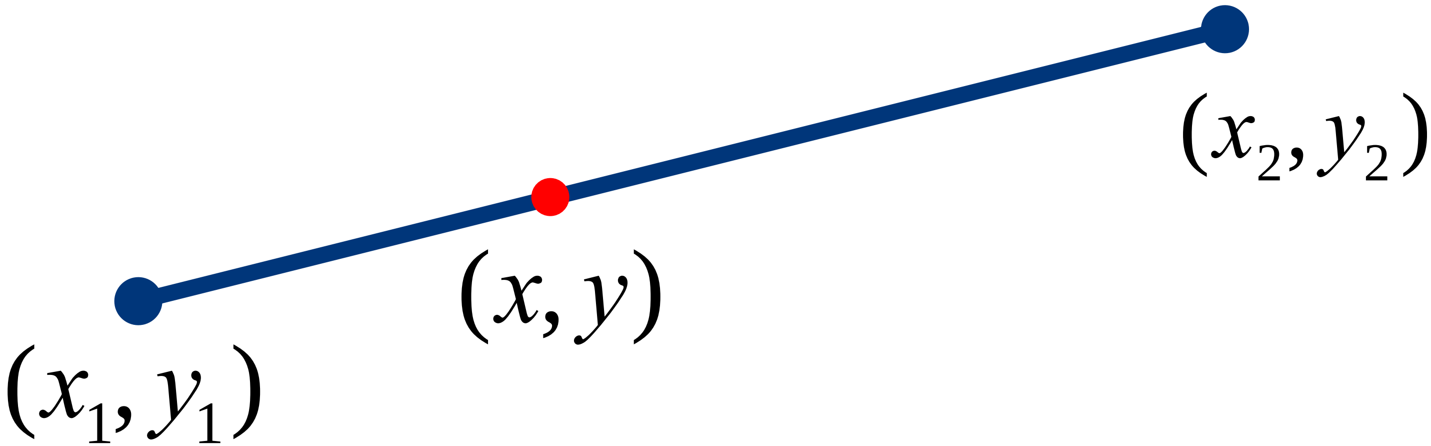
- Lines are a predominant feature in human-made (engineered) environments.

Line Estimation and Segmentation





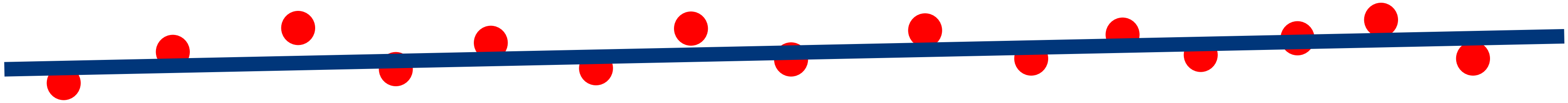
Line formula



$$\frac{y - y_1}{x - x_1} = \frac{y_2 - y_1}{x_2 - x_1}$$

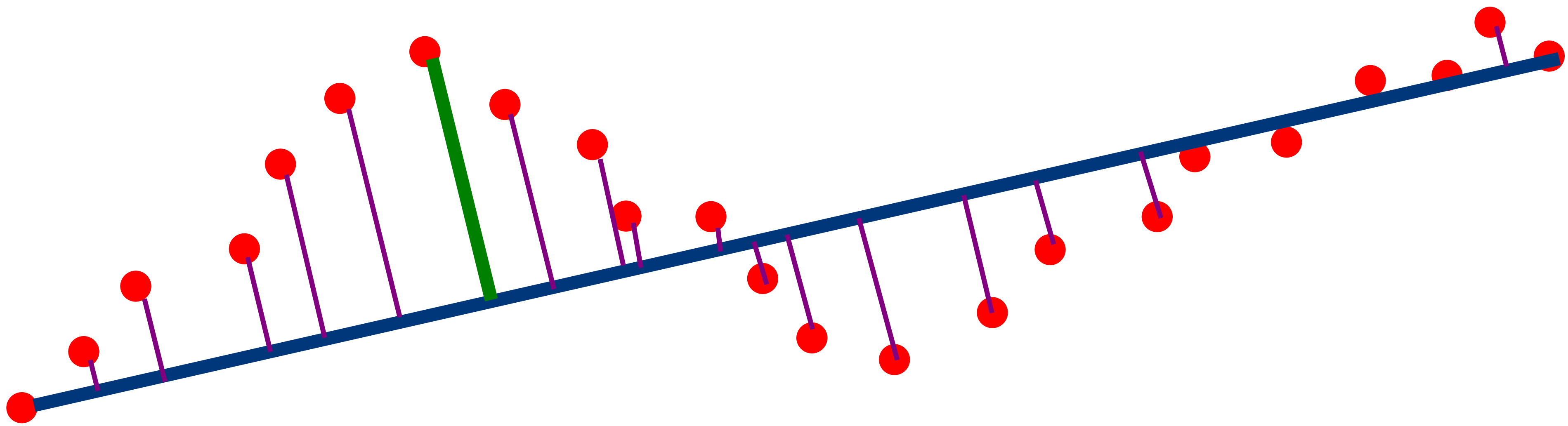
$$\boxed{y = ax + b}$$

Line Estimation

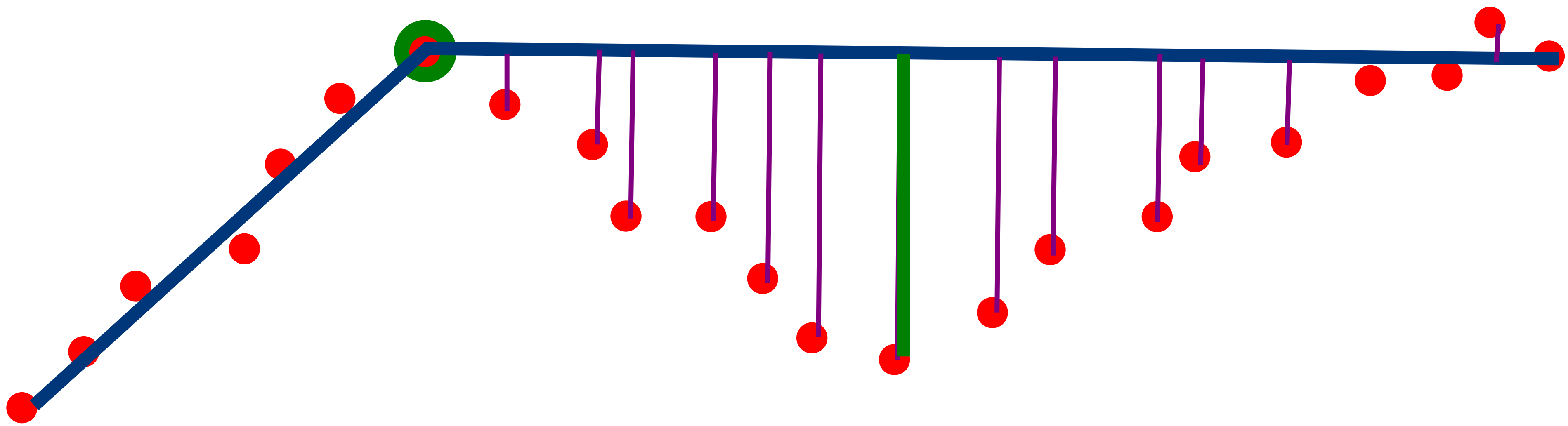


- Least square minimization
  - Line Equation: $y - ax - b = 0$
  - Error in fit: $\sum_i (y_i - ax_i - b)^2$
  - Solution: $\begin{pmatrix} \overline{xy} \\ \overline{y} \end{pmatrix} = \begin{pmatrix} \overline{x^2} & \overline{x} \\ \overline{x} & 1 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$

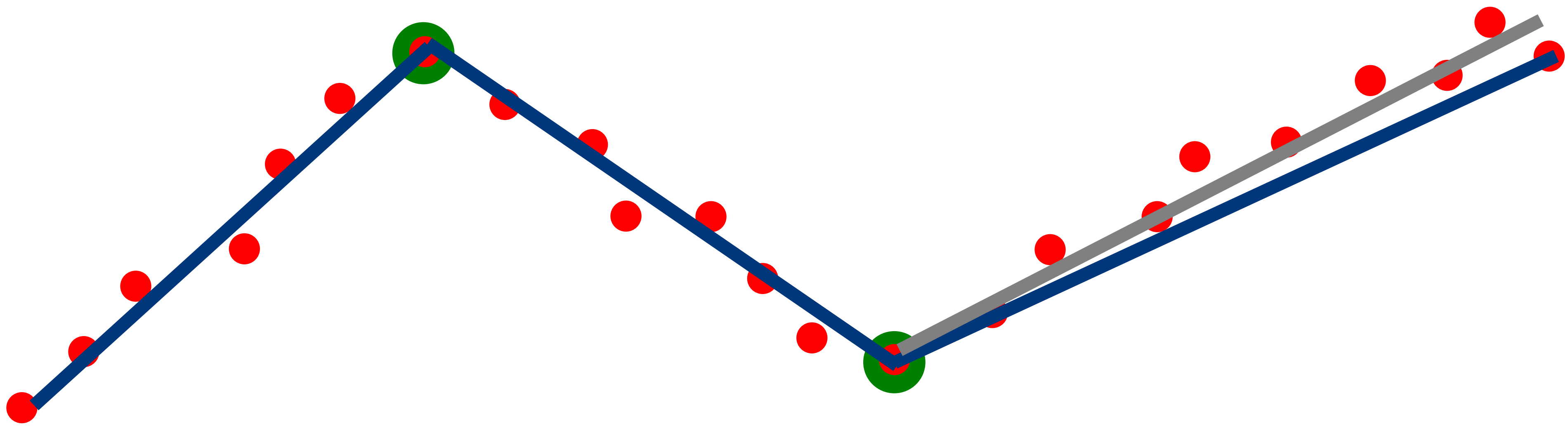
Line Splitting/Segmentation



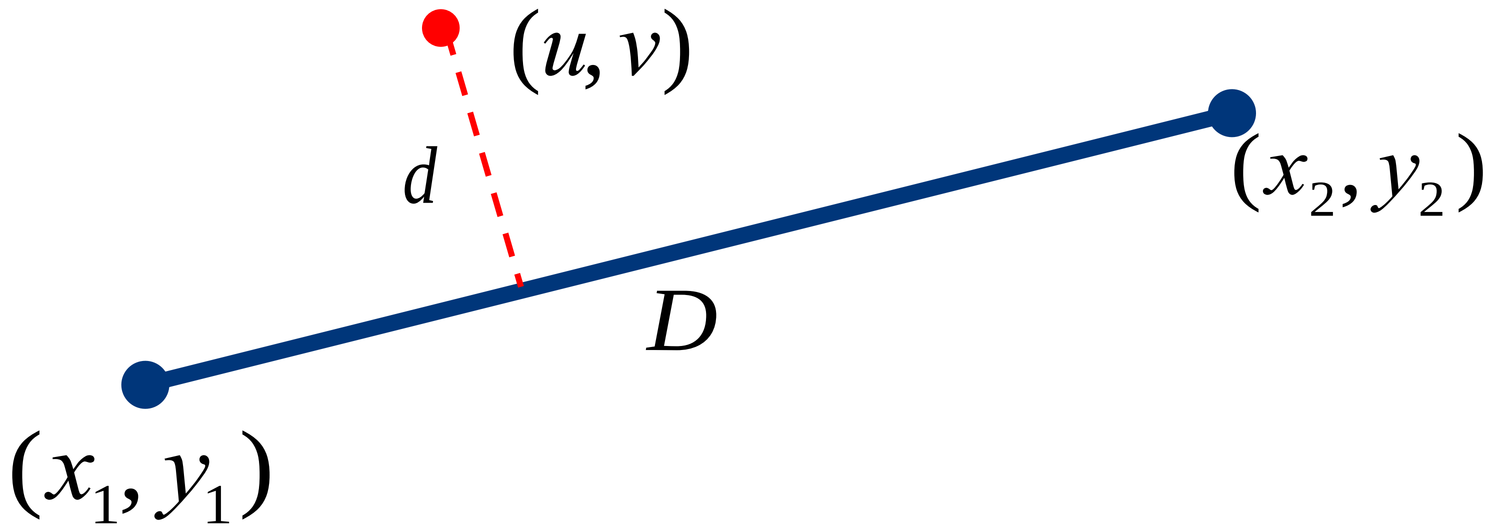
Line Splitting/Segmentation



Line Splitting/Segmentation



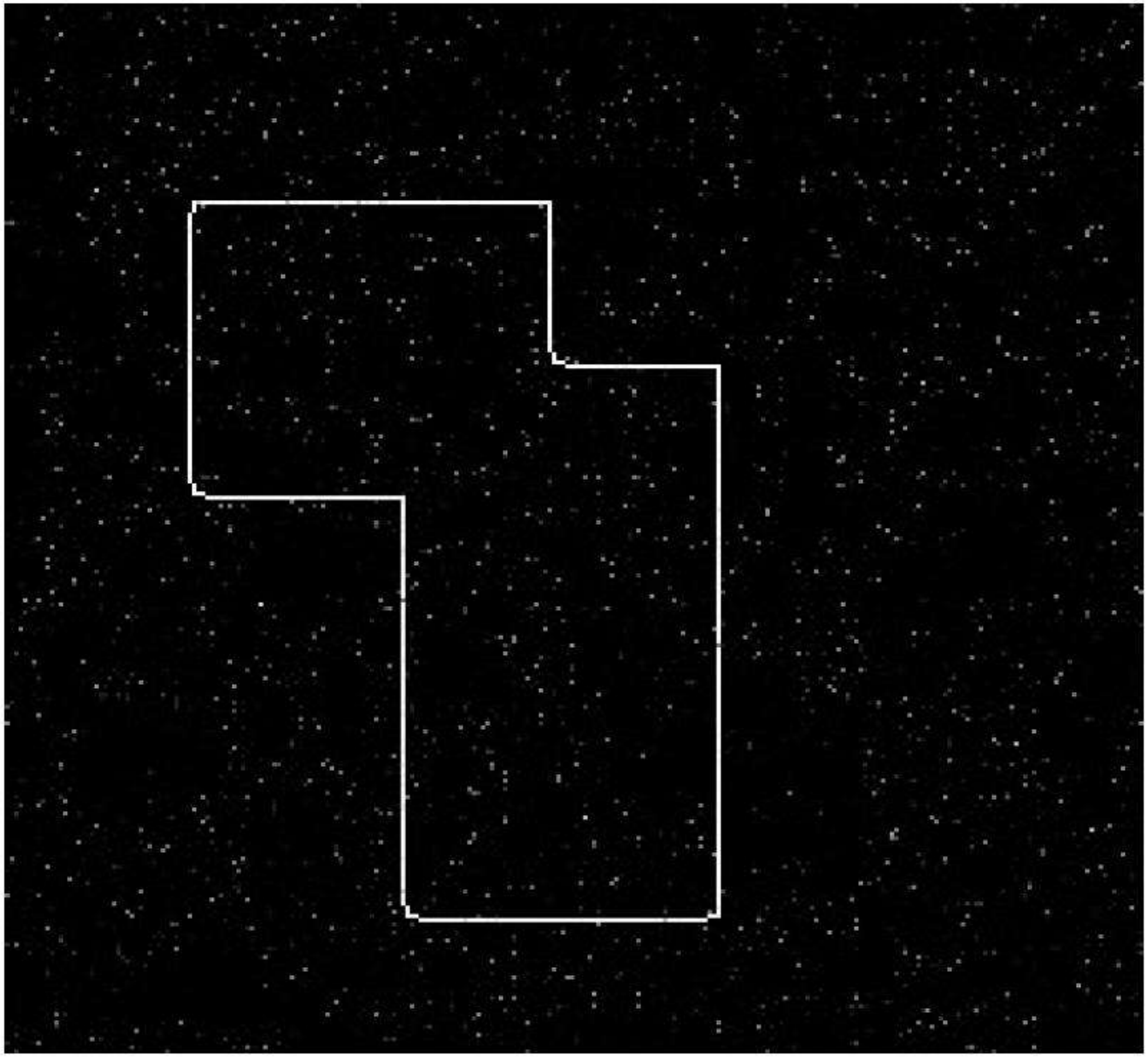
The perpendicular distance of a point from a line segment



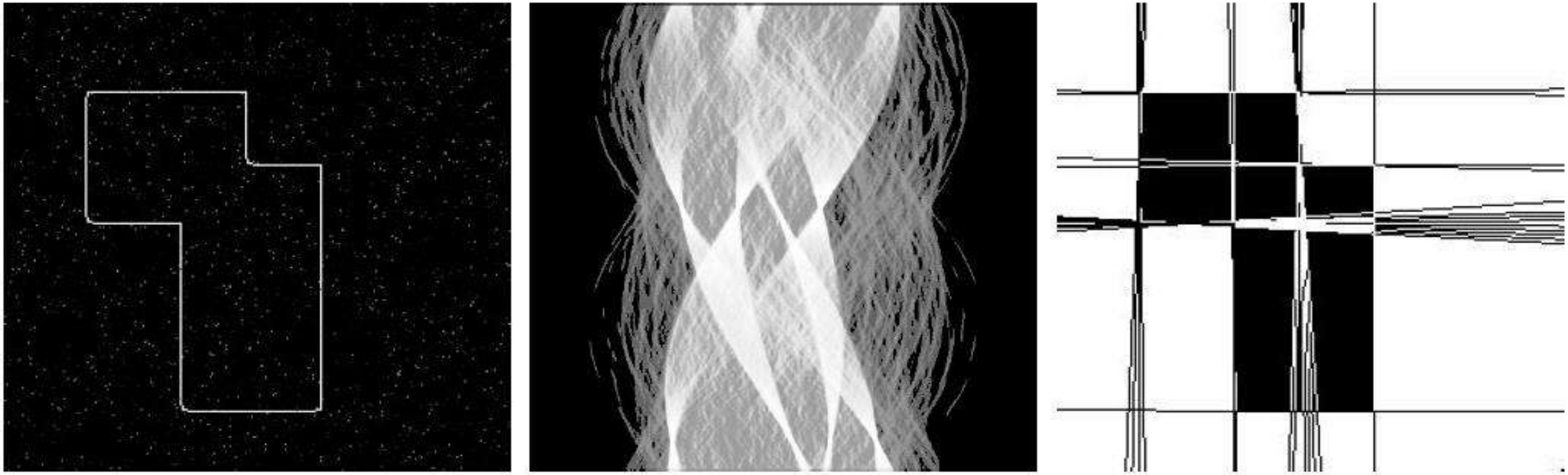
$$r = u(y_1 - y_2) + v(x_2 - x_1) + y_2 x_1 - y_1 x_2$$

$$d = \frac{r}{D}$$

The problem: Noisy Data



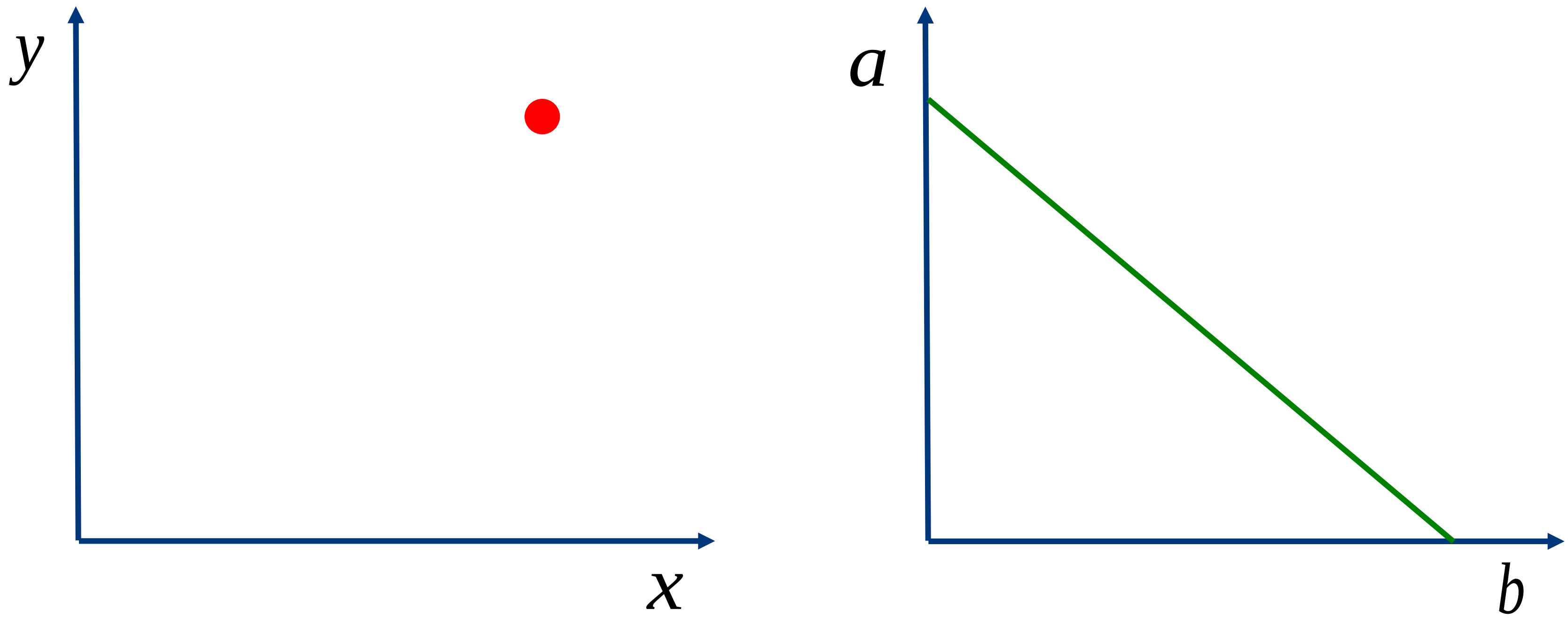
The Hough Transform



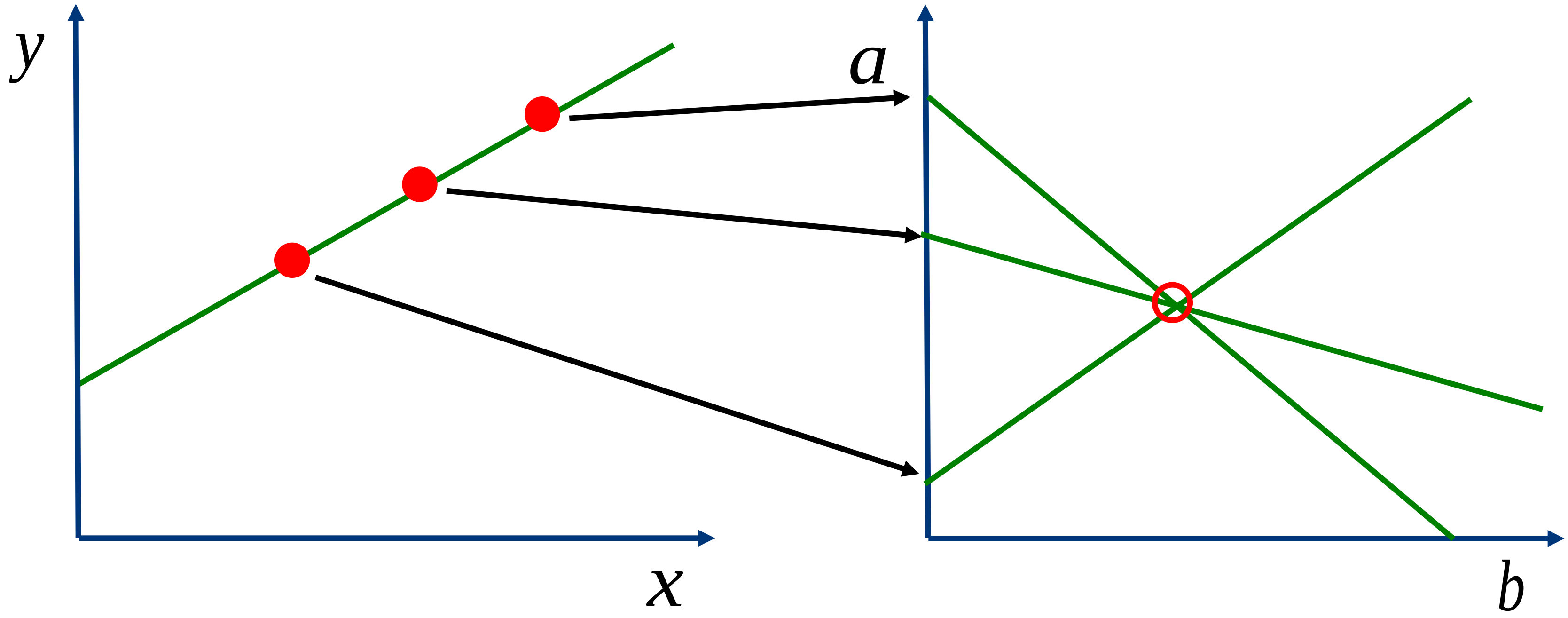
- Use a voting mechanism
- One of the most popular ones: the Hough transform.
- Can be used for lines and other shapes.

Voting Space

$$y = ax + b \qquad\qquad b = y - ax$$



Voting Space

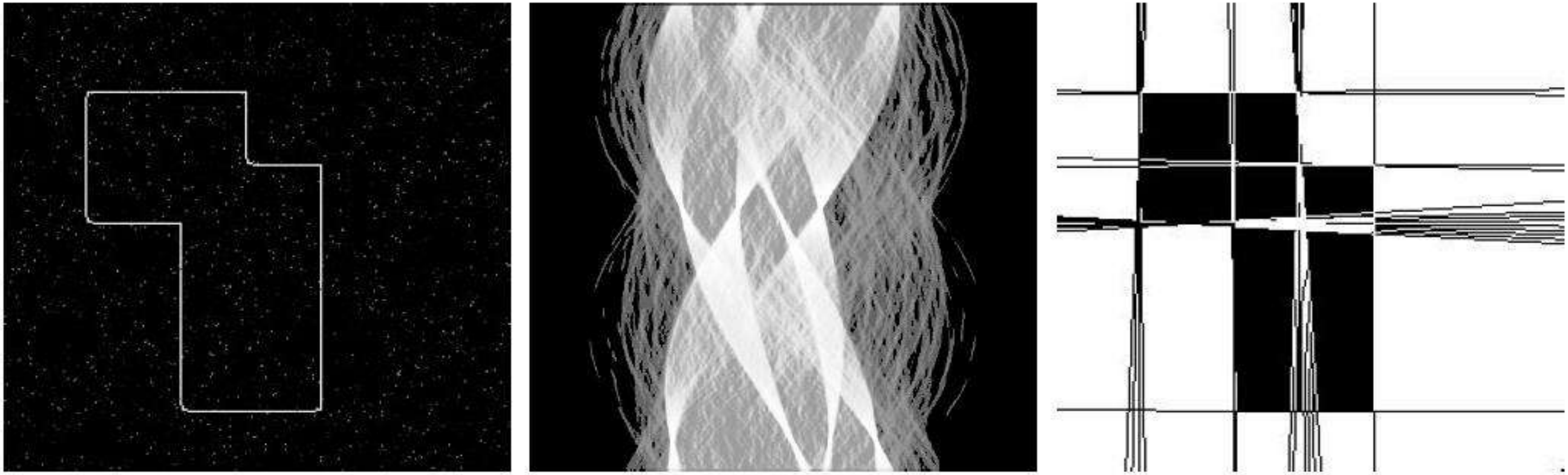


- In practice, the polar form of the line is used.

$$\rho = x \cos\theta + y \sin\theta$$

- to avoid problems with lines that are nearly vertical.

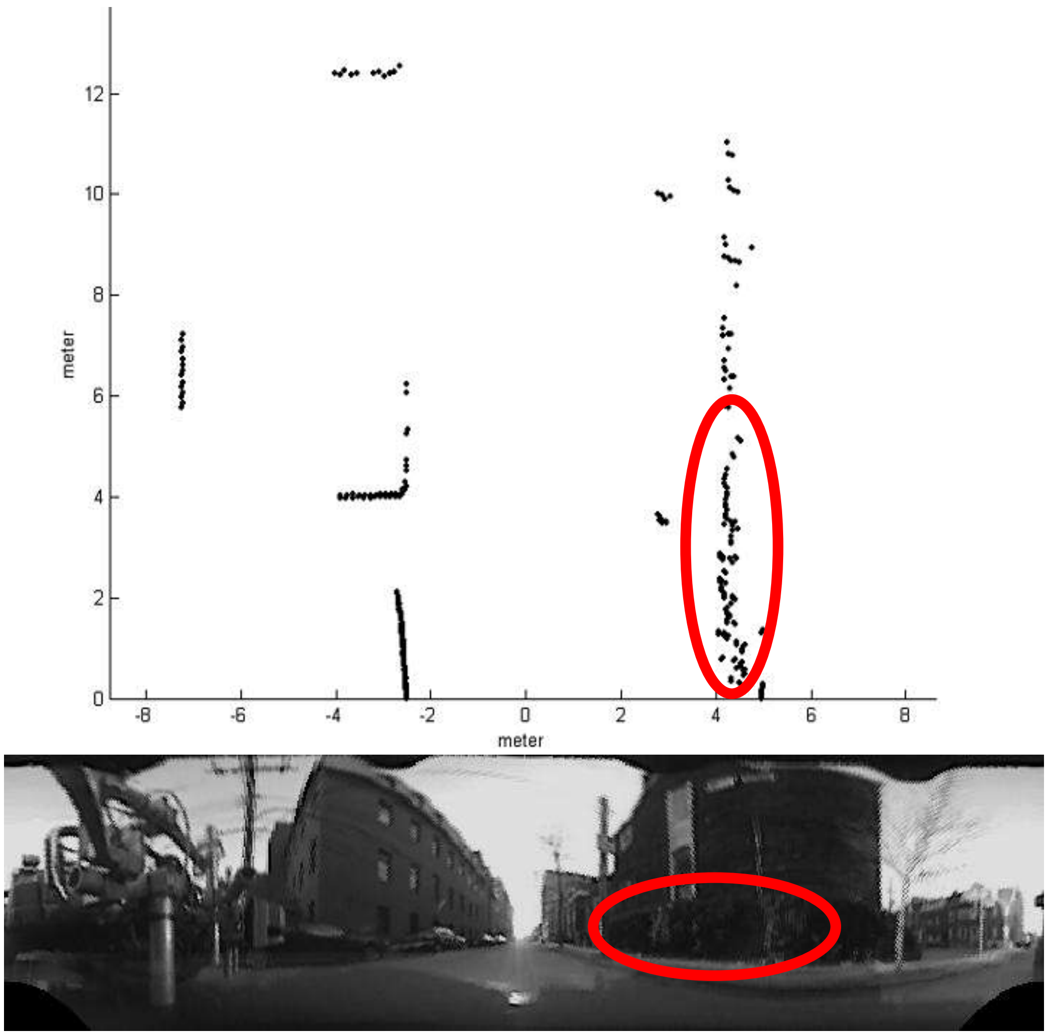
An example

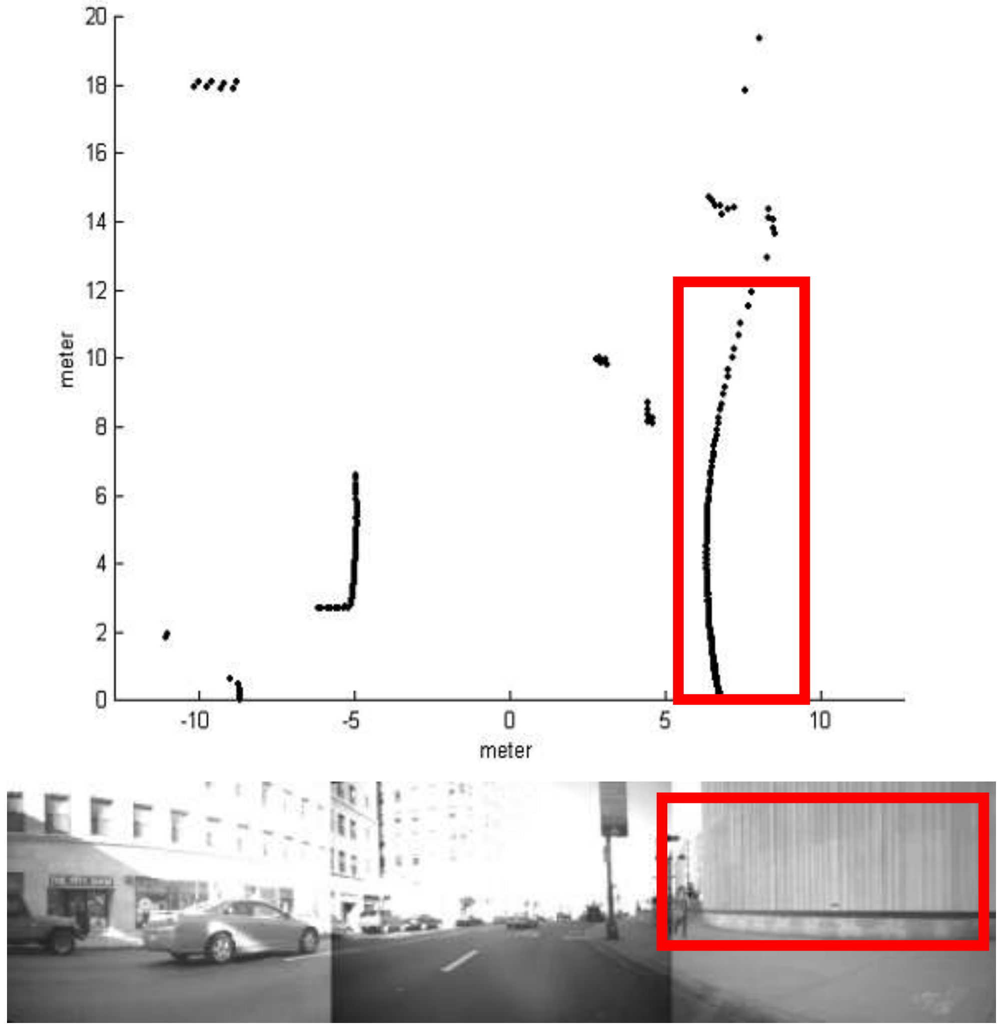


Hough Transform Algorithm

1. Quantize the parameter space appropriately.
2. Assume that each cell in the parameter space is an accumulator. Initialize all cells to zero.
3. For each point (x,y) in the (visual & range) image space, increment by 1 each of the accumulators that satisfy the equation.
4. Maxima in the accumulator array correspond to the parameters of model instances.

Lines may not be good as features



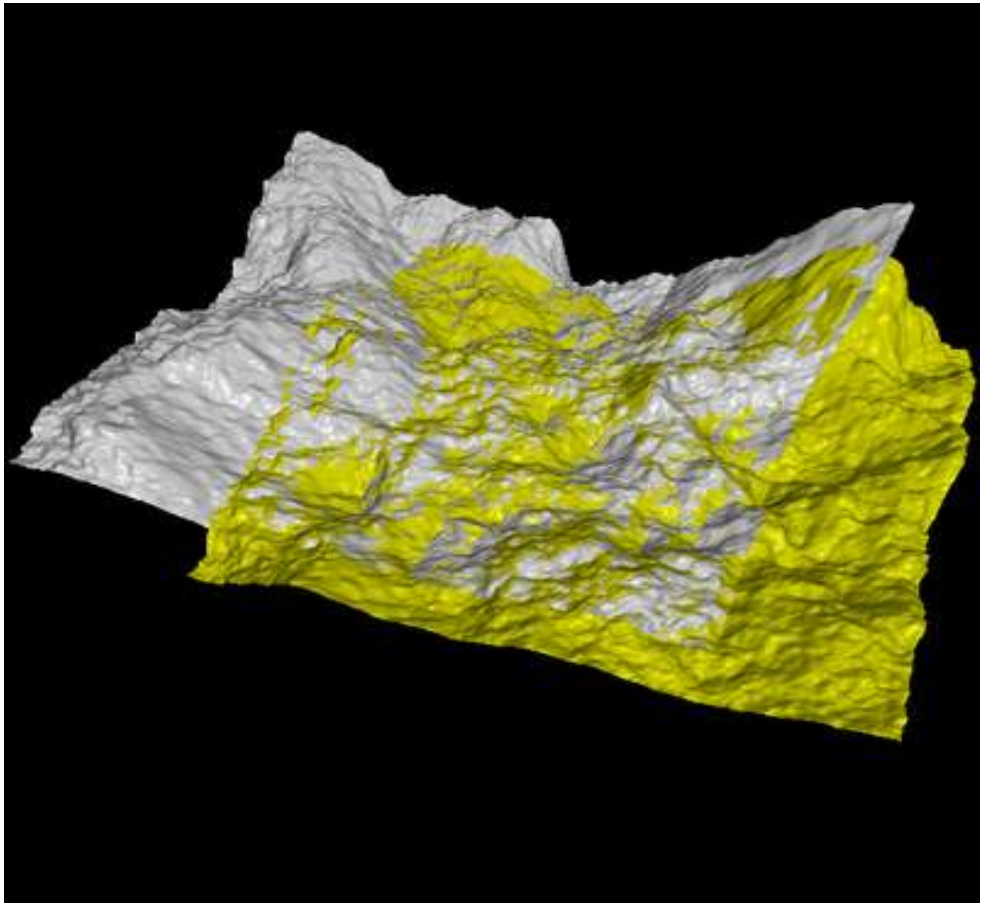


Surface Registration/Scan Matching

- Align two partially-overlapping point sets given initial guess of relative transform
- point set = mesh =surface = shape

$$p(\mathbf{B} \mid T', \mathbf{A})$$

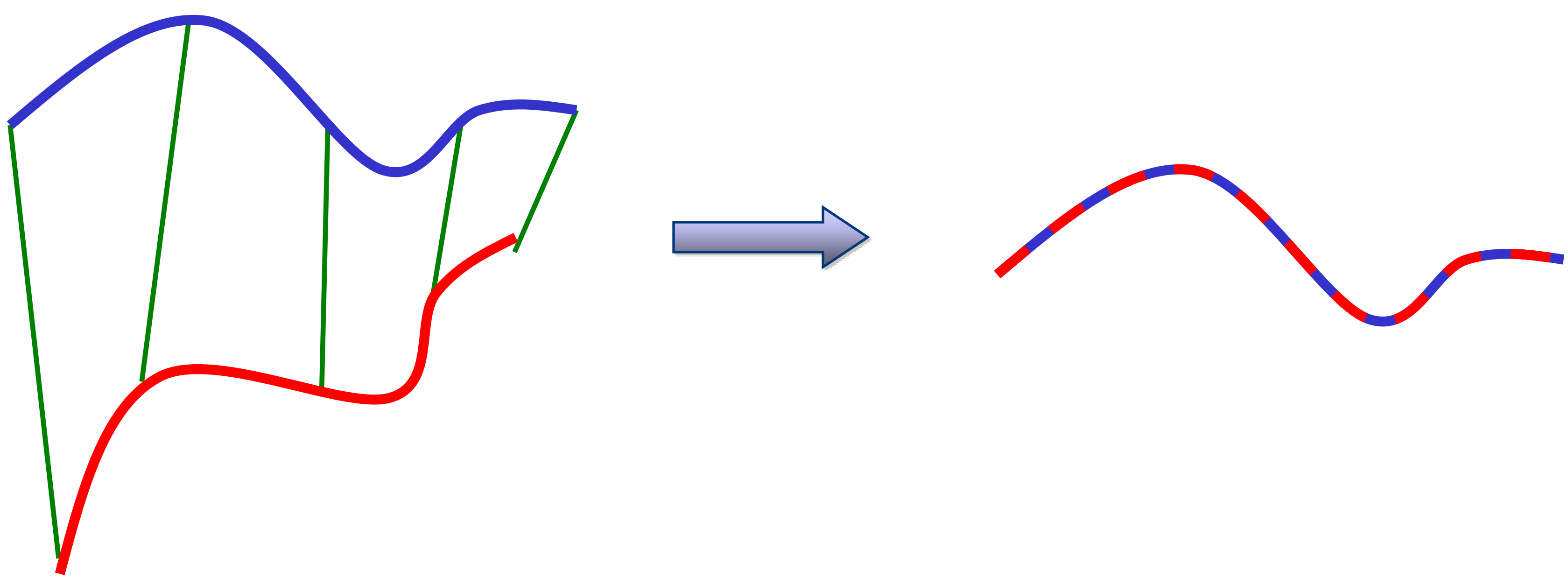
$$p(z_k \mid x_k, M)$$



Video from Szymon Rusinkiewicz's 3DIM 2001 talk

2D/3D Shape Matching

- If correct **correspondences** are known, it is possible to find correct relative transformation (rotation + translation).



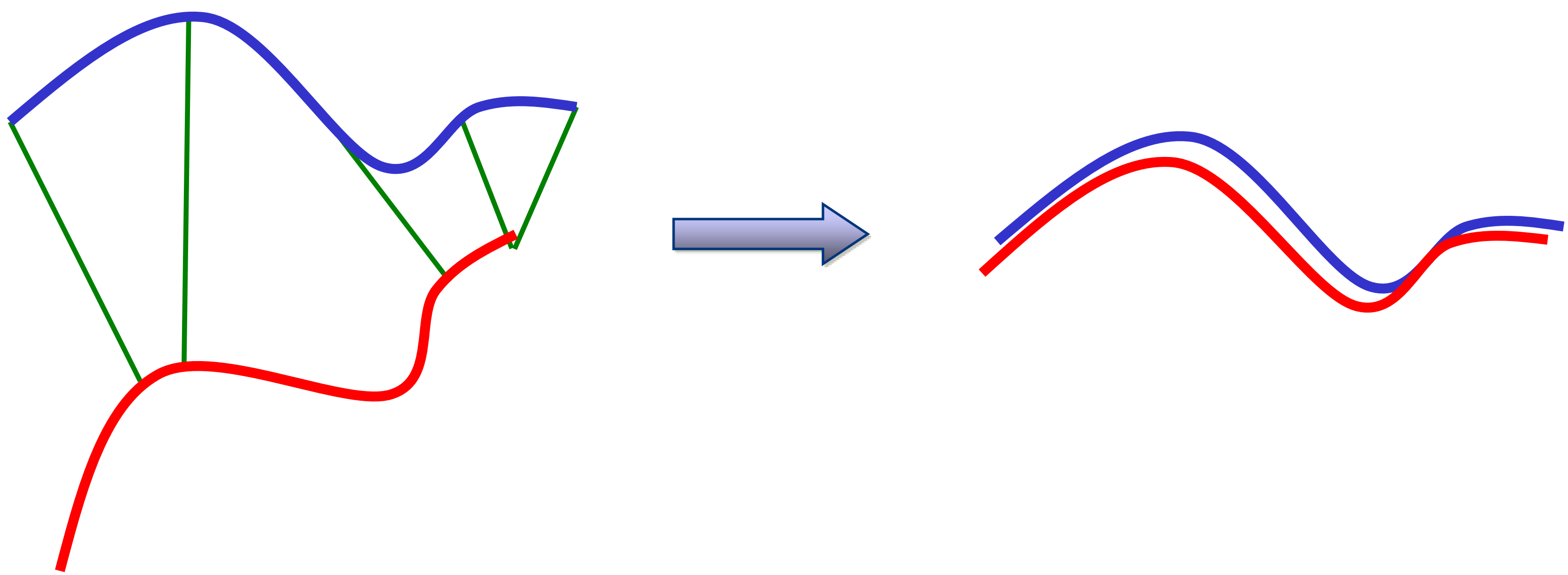
How to find **Correspondences?**

- Surface Matching is a **Data Association** problem.

  - User input
  - Feature matching
  - Surface signatures
  - Iterated Closest Point (ICP)

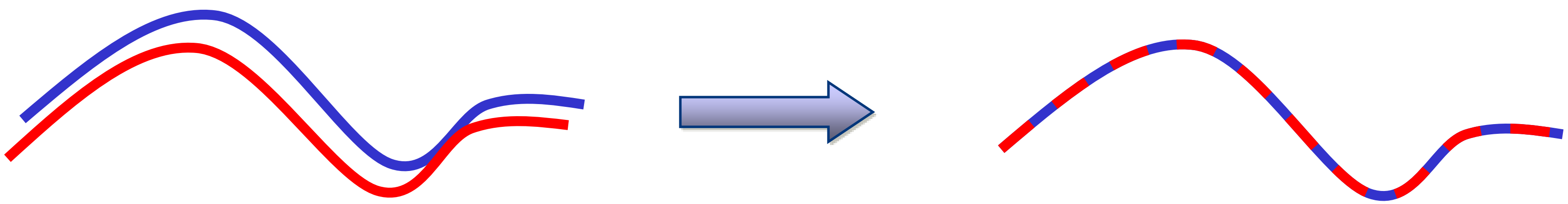
Iterated Closest Point (ICP)

- A heuristic way to solve **Data Association**
- Assume closest points correspond to each other, compute the best transformation.

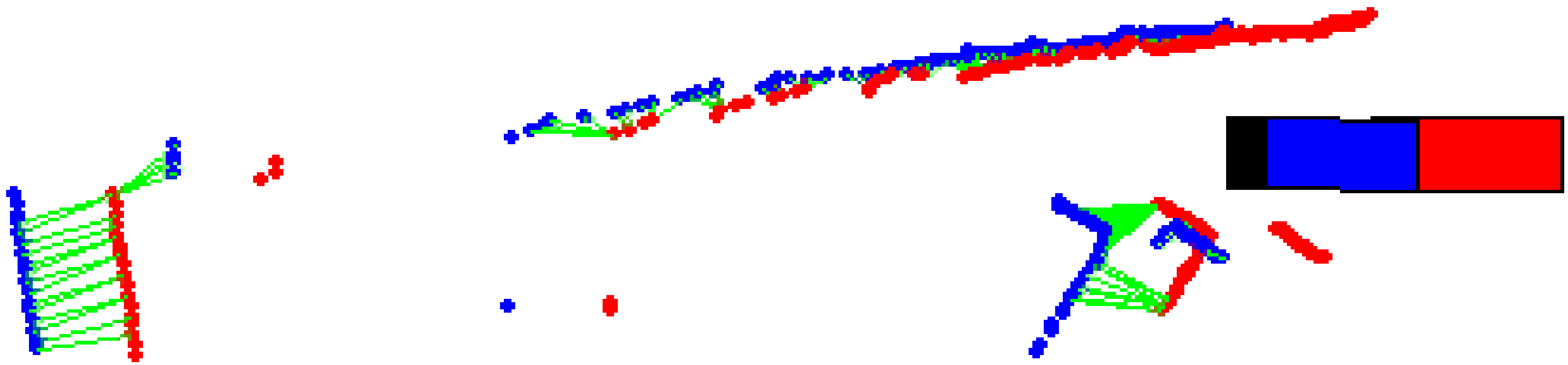


Iterated Closest Point (ICP)

- … and iterate to find alignment
  [Besl & McKay 92]
- Converges if starting position “close enough“



Robot Localization using ICP



The ICP algorithm of Best and Mckay [1992]

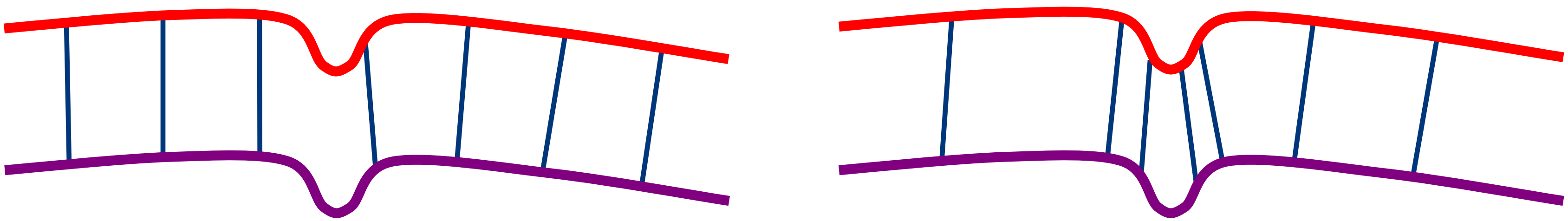
```
Function ICP(Model, Scene);
begin
E' ← +∞;
(Rot, Trans) ← Initialize-Registration(Scene, Model);
repeat
   E ← E';
   Registered-Scene ← Apply-Registration(Scene, Rot, Trans);
   Pairs ← Return-Closest-Pairs(Registered-Scene, Model);
   (Rot, Trans, E') ← Update-Registration(Scene, Model, Pairs, Rot, Trans);
   until |E' − E| < τ;
return (Rot, Trans);
end.
```

ICP Variants [Rusinkiewicz 01]

- Procedures:
  - Selecting source points (from one or both point sets)
  - Matching to points in the other point set
  - Weighting the correspondences
  - Rejecting certain (outlier) point pairs
  - Assigning an error metric to the current transform
  - Minimizing the error metric

Stage 1: Selecting

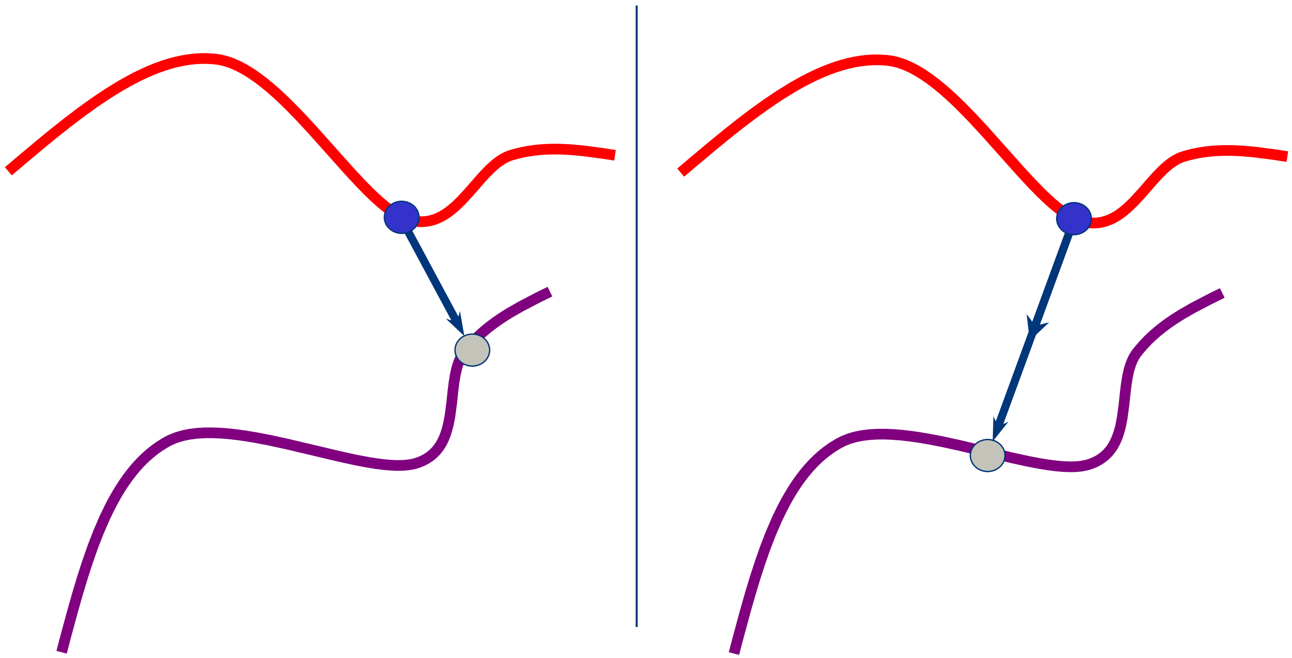
- Use all Points
- Uniform subsampling
- Random sampling
- Normal surface sampling



For outdoor applications, the data may not be dense enough.
SICK: 0.25, 0.5 1 degree resolution.

Stage 2: Matching

- Closest point
- Normal shooting
- Closest compatible point



Stage 2: Matching

- Matching strategy has greatest effect on convergence and speed
- Finding closest point is the most expensive stage of the ICP algorithm
- Speed Up: Structure for Organizing Data

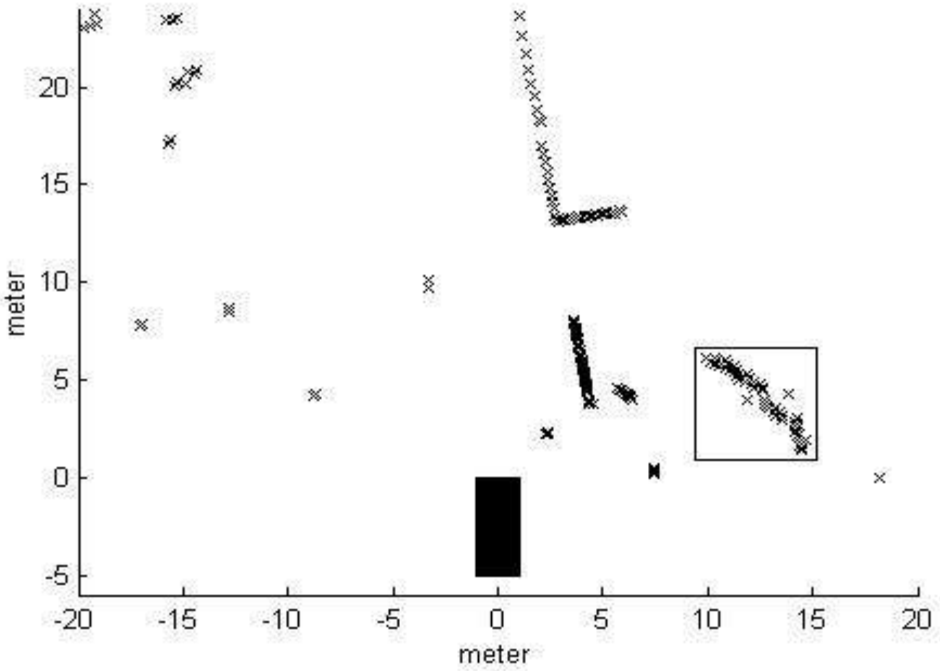
Good Refs:

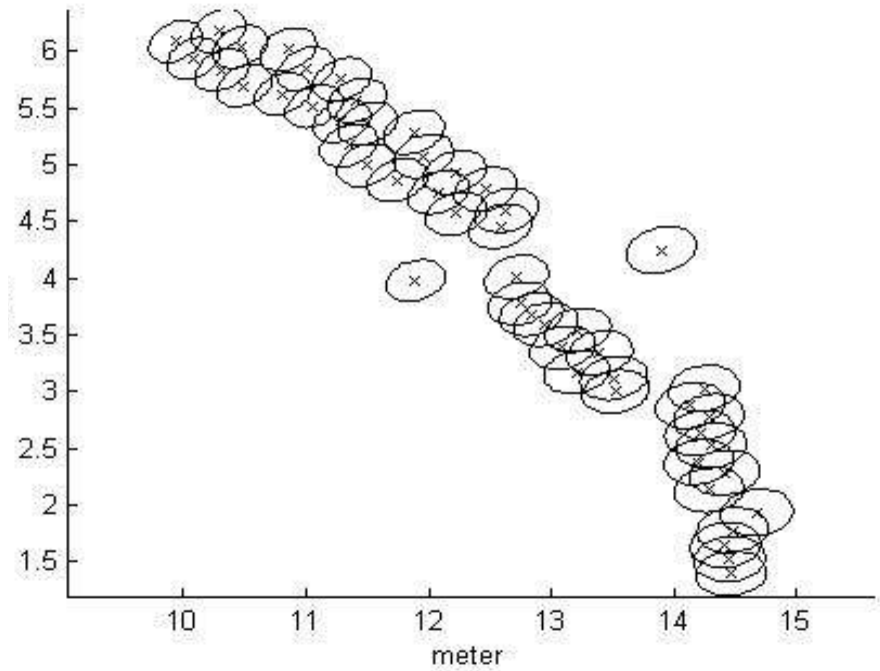
S. A. Nene and S. K. Nayar. Closet Point Search in High Dimensions. *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, San Francisco, June 1996.

T. Liu, A. Moore, A.Gray and K Yang. An Investigation of Practical Approximate Nearest Neighbor Algorithms, 2004.

Stage 3: Weighting

- Weighting can achieve the same effect with selecting.
- But weighting is more…





Stage 4: Rejecting

- Distance between corresponding points
- Robust methods
- (SLAM in Dynamic Environments)
- (SLAM with DATMO)

Stage 5: Error Metric & Stage 6: Minimizing this metric

- Point-to-point distance

$$E = \sum_{i=1}^{n} \| \oplus(T', b^i) - a^i \|^2$$

$$\hat{T}_\theta = \arctan \frac{\Sigma_{b_x a_y} - \Sigma_{b_y a_x}}{\Sigma_{b_x a_x} + \Sigma_{b_y a_y}}$$

$$\hat{T}_x = \bar{a}_x - (\bar{b}_x \cos \hat{T}_\theta - \bar{b}_y \sin \hat{T}_\theta)$$

$$\hat{T}_y = \bar{b}_y - (\bar{a}_x \sin \hat{T}_\theta + \bar{a}_y \cos \hat{T}_\theta)$$

$$\bar{a}_x = \frac{1}{n}\sum_{i=1}^{n} a_x^i \quad , \quad \bar{a}_y = \frac{1}{n}\sum_{i=1}^{n} a_y^i \quad , \quad \bar{b}_x = \frac{1}{n}\sum_{i=1}^{n} b_x^i \quad , \quad \bar{b}_y = \frac{1}{n}\sum_{i=1}^{n} b_y^i$$

$$\Sigma_{b_x a_x} = \sum_{i=1}^{n} (b_x^i - \bar{b}_x)(a_x^i - \bar{a}_x) \quad , \quad \Sigma_{b_y a_y} = \sum_{i=1}^{n} (b_y^i - \bar{b}_y)(a_y^i - \bar{a}_y)$$

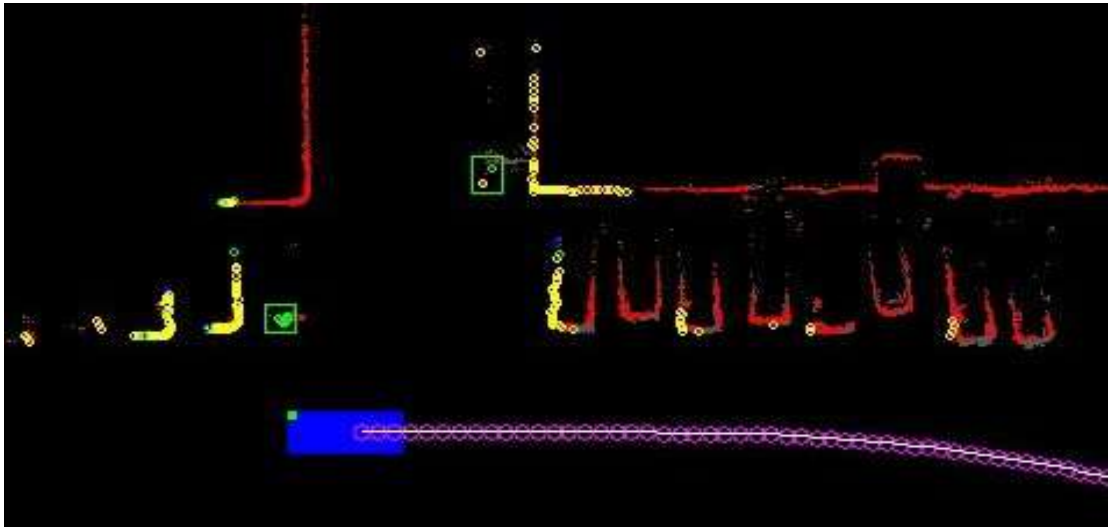
$$\Sigma_{b_x a_y} = \sum_{i=1}^{n} (b_x^i - \bar{b}_x)(a_y^i - \bar{a}_y) \quad , \quad \Sigma_{b_y a_x} = \sum_{i=1}^{n} (b_y^i - \bar{b}_y)(a_x^i - \bar{a}_x)$$

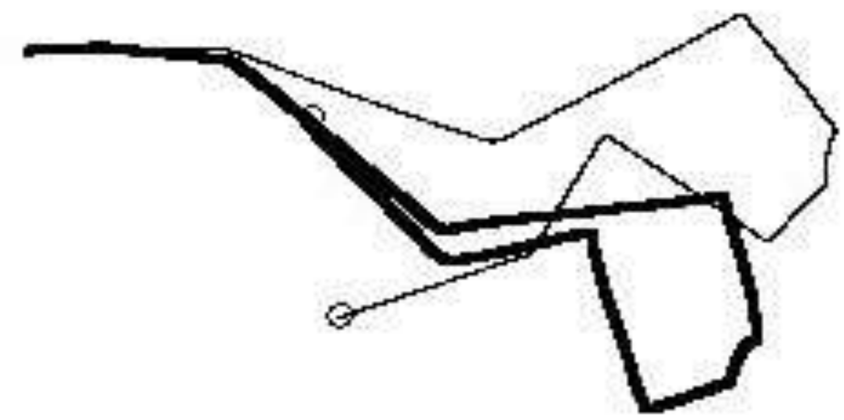
See Further reading [3] for the derivation

ICP Issues

- From the point of view of Computer Science:
  - Speed
  - Stability
  - Tolerance of Noise and/or Outliers
  - Convergence
- From the point of view of Robotics:
  - Measurement Noise
  - Sparse Data
  - Featureless Data
  - Uncertainty Estimation

ICP based SLAM [Wang & Thorpe 02]

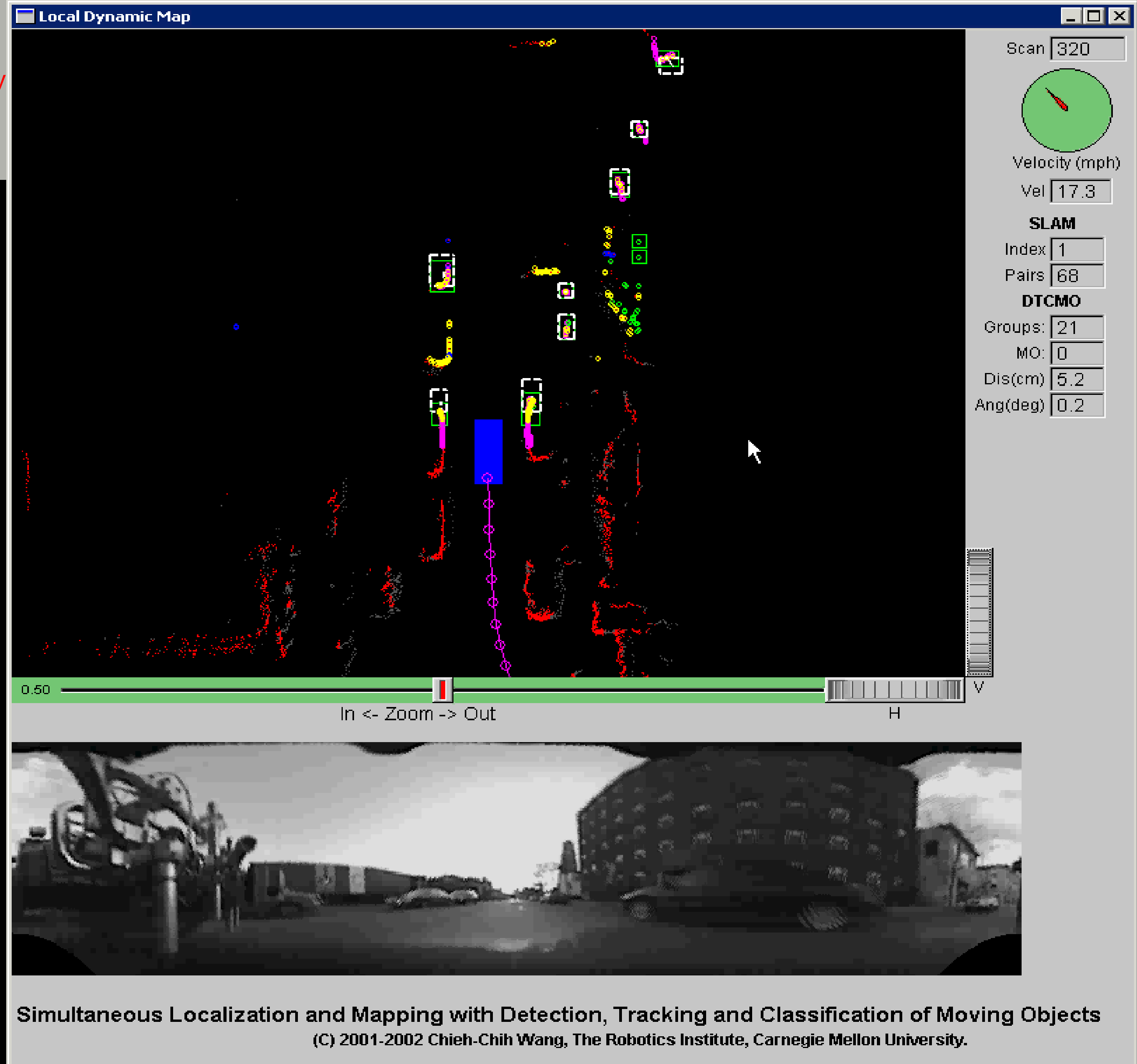


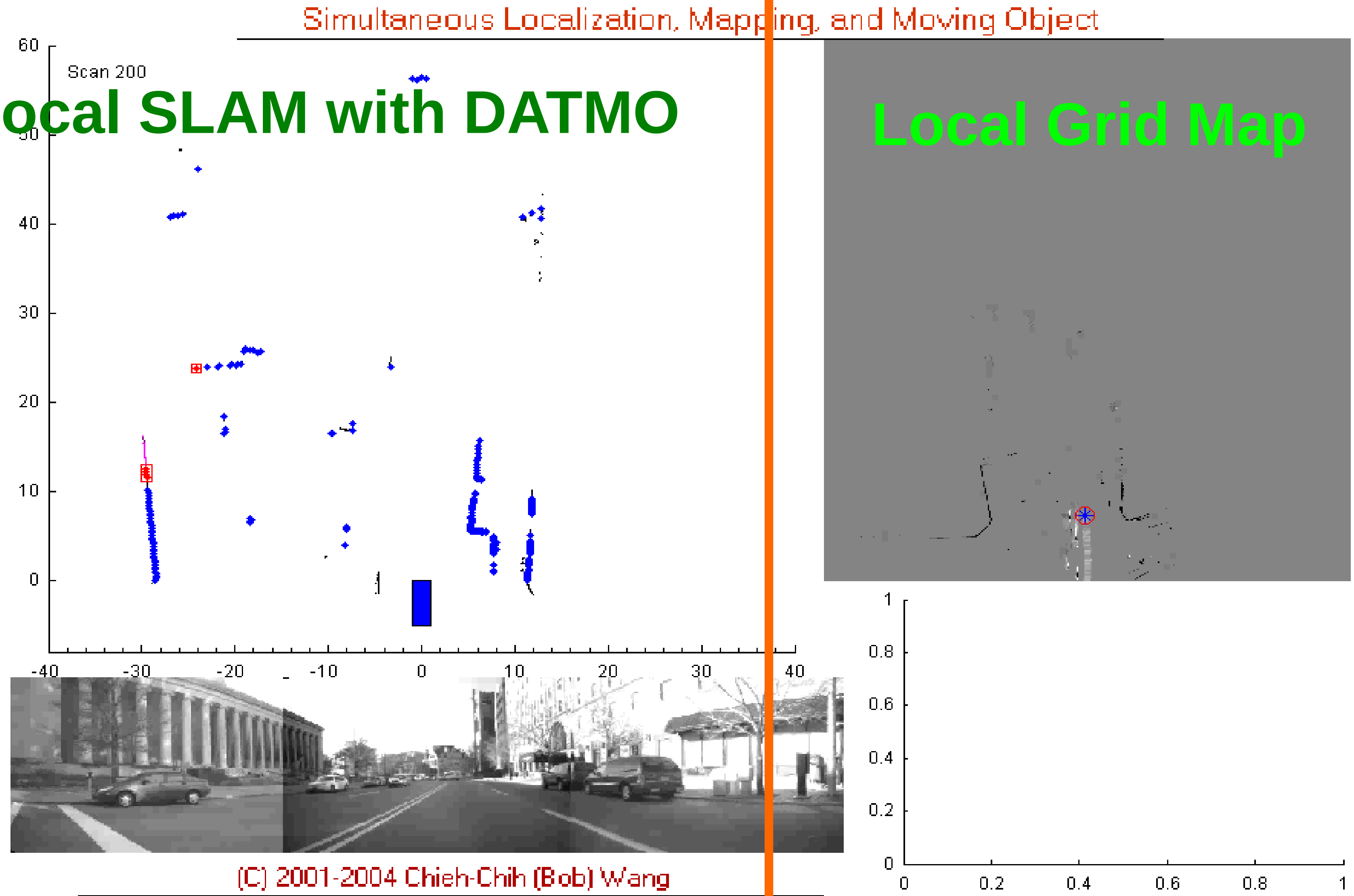


Map:
Red→Stationary
Gray→Moving

Current Scan:
Yellow→Stationary
Blue→Unidentified
Green→Moving

Tracking:
Green Box→MO
White Box → Future Location
Magenta→ data associated with MO





Local SLAM with DATMO

Local Grid Map

Visual Image

Global SLAM

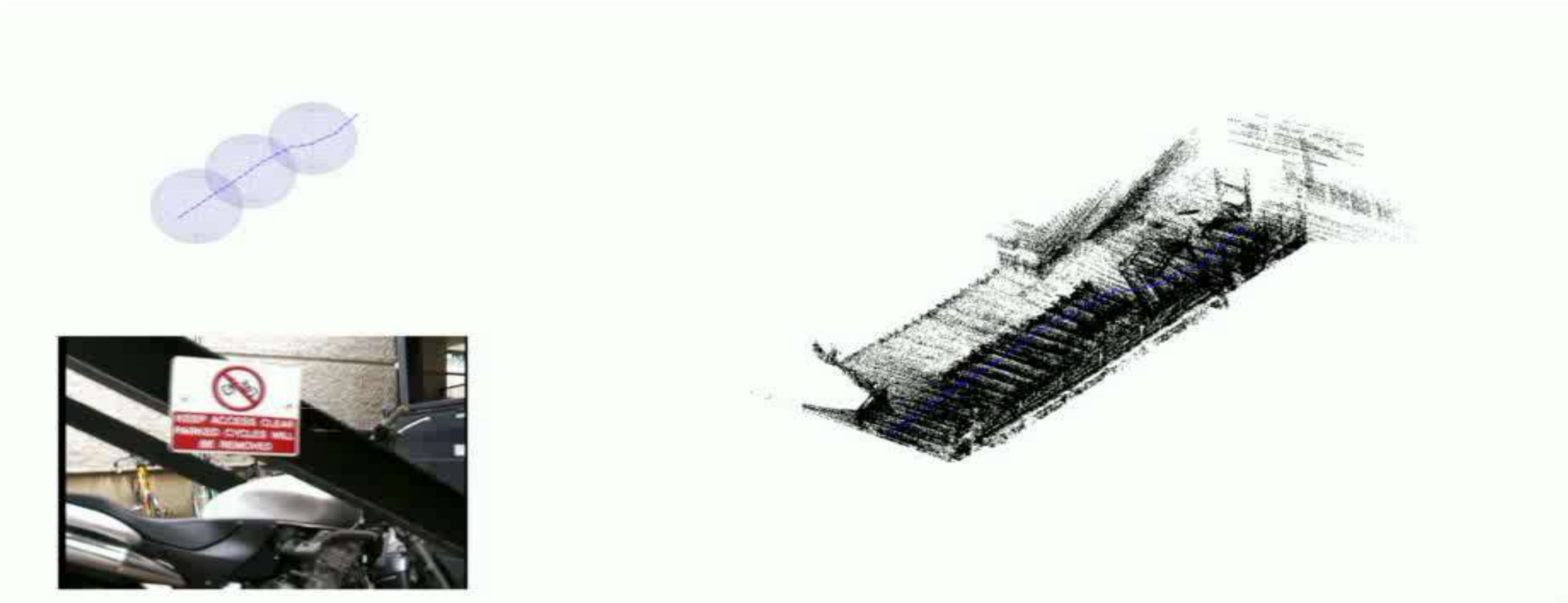
Loop Closing

Hierarchical Free-Form Object based SLAM [Wang & Thorpe 2004]

Ground Vehicle SLAM

3D Laser Mapping (Video courtesy of P Newman)

Ground Vehicle SLAM



Visual Saliency Loop Closure (Video courtesy of P Newman)

Major Projects & Advanced Topics

- Integration and Simplification (Mapping)
- Multiple Surface Registration (SLAM)
- Non-rigid (Deformable) Surface Matching
- Laser-based Car Tracking
- Object Recognition in Urban Areas
- 3D Object Classification and Recognition
- And more…

Further Reading

1. Siegwart & Nourbakhsh, *Introduction to Autonomous Mobile Robots*
   - Chapter 4: Perception
2. Jain, Kasturi & Schunck, *Machine Vision*
   - Chapter 6: Contours
3. Forsyth & Ponce, *Computer Vision - A Modern Approach*
   - Chapter 21: Range Data