Advanced Sonar Sensing for Robot Mapping and Localisation

by

Lindsay Kleeman
Associate Professor
Intelligent Robotics Research Centre
Monash University, Australia

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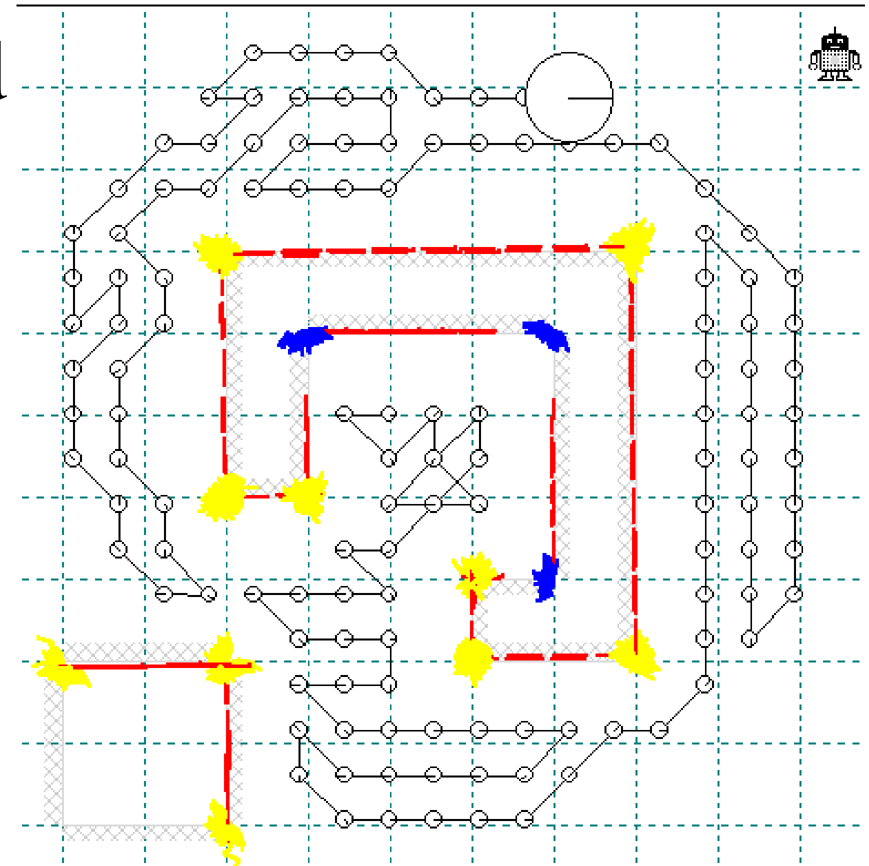
Introduction - Mobile Robot Applications

- Courier - offices, hospitals, factories
- Area coverage - cleaning, hazardous chemical/nuclear decontamination, painting
- Security and surveillance
- Disability Aids

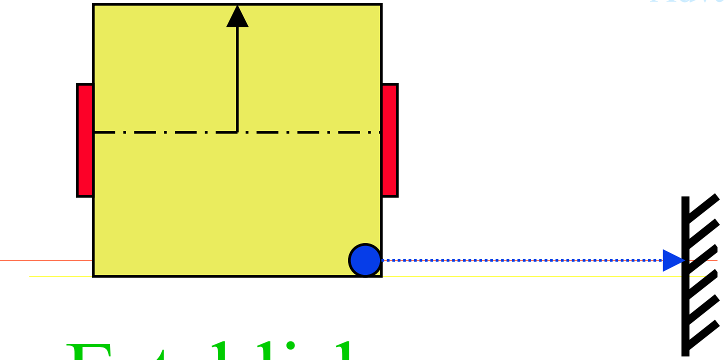
Introduction - Mobility Tasks

- Localisation (position and orientation)
- Path planning
- Obstacle avoidance
- Map building and maintenance

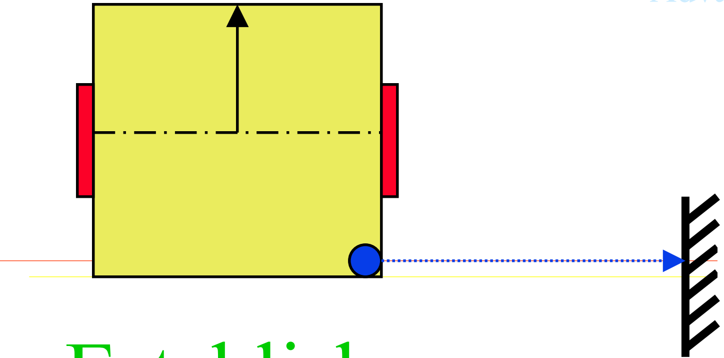


Introduction

- Why is sonar classification important?
  - Allows prediction of feature measurements from new positions.
  - Localisation w.r.t. features.
  - Assists association of measurements with map features.



Establish new plane feature



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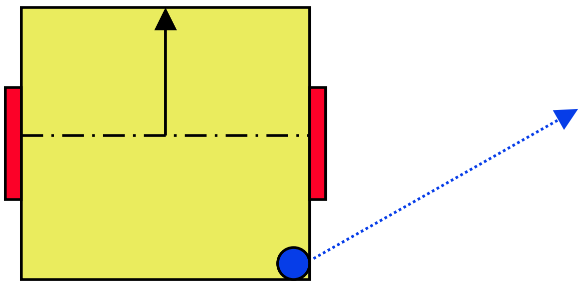
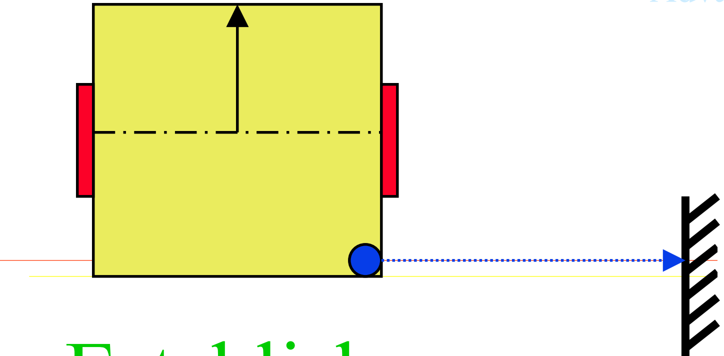


Associate new measurement to plane feature



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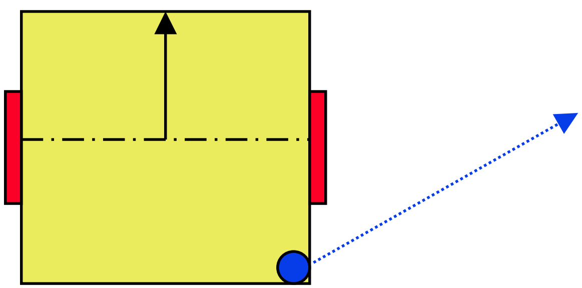

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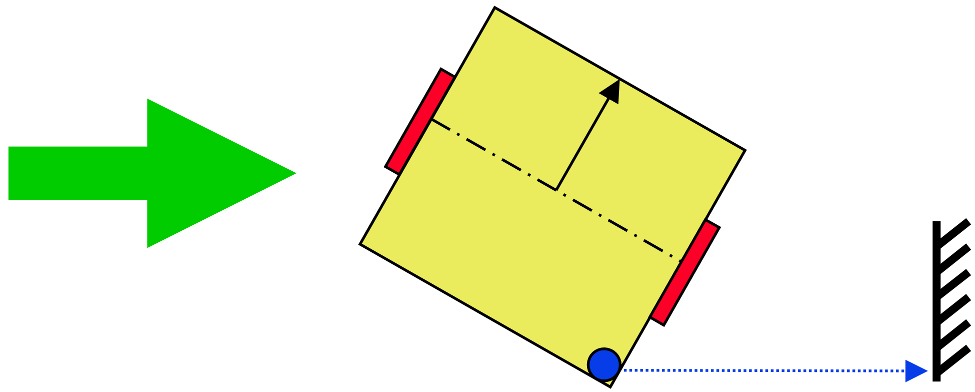
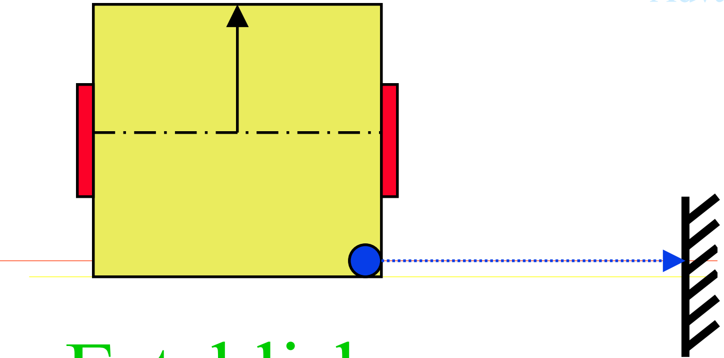


Constrains robot position and orientation



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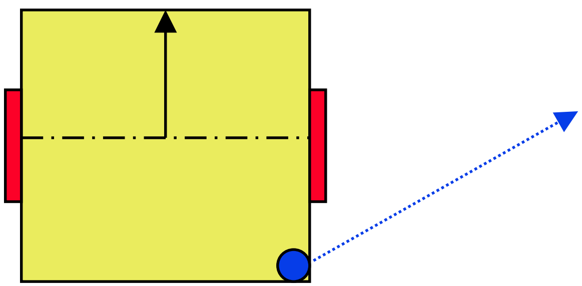

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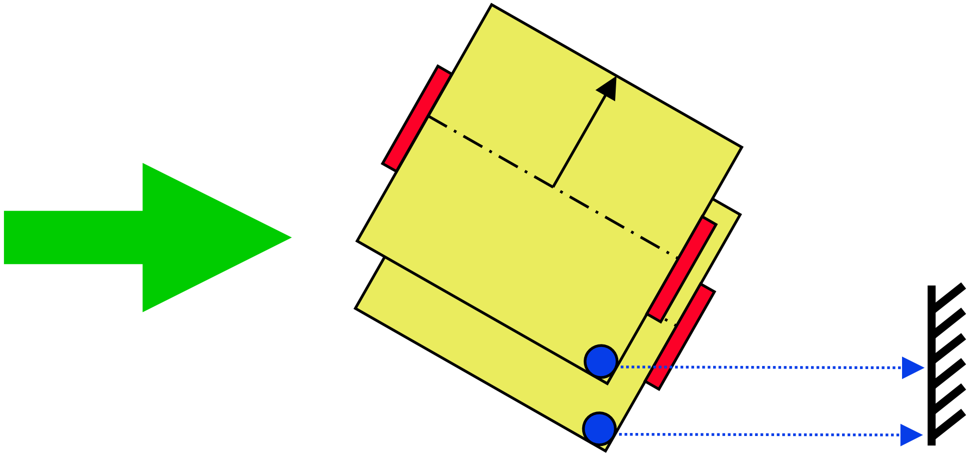

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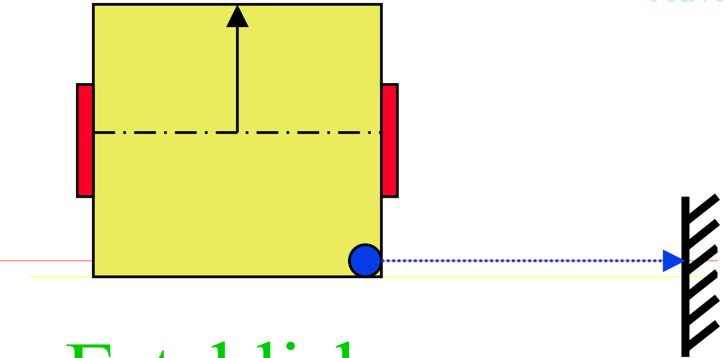

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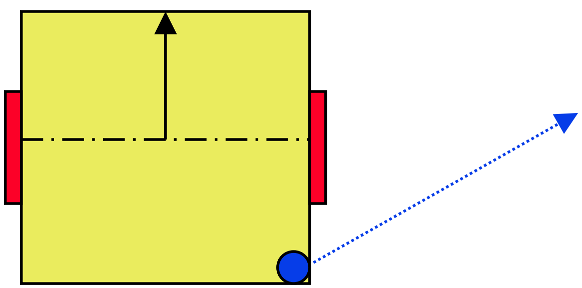

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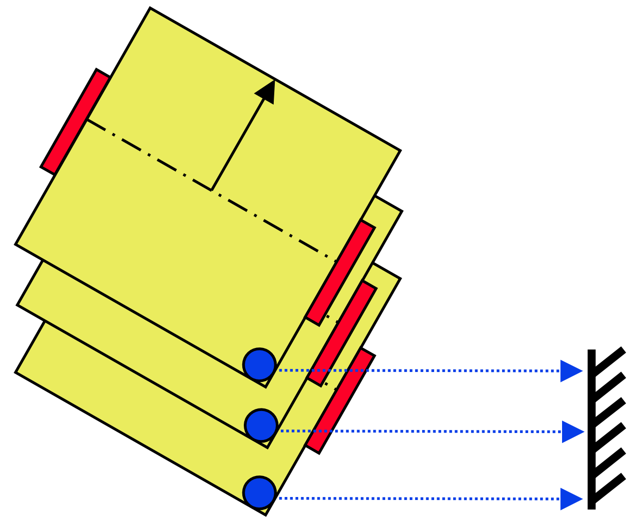

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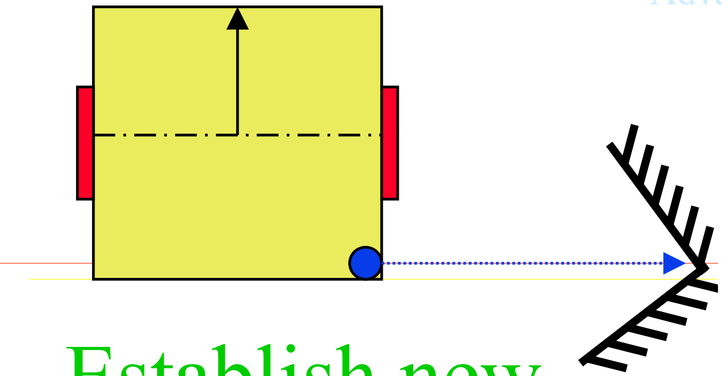
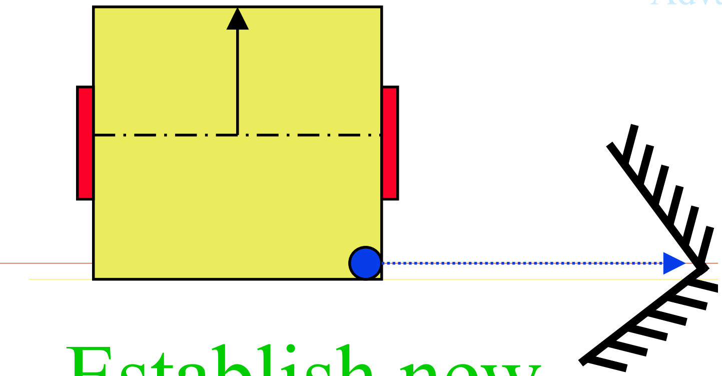
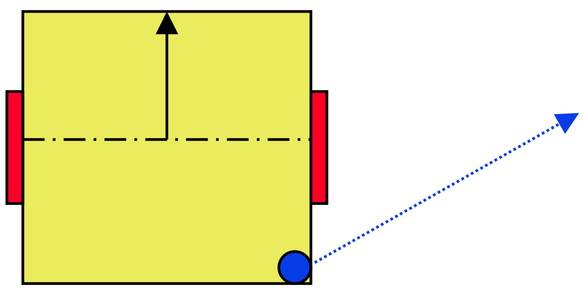


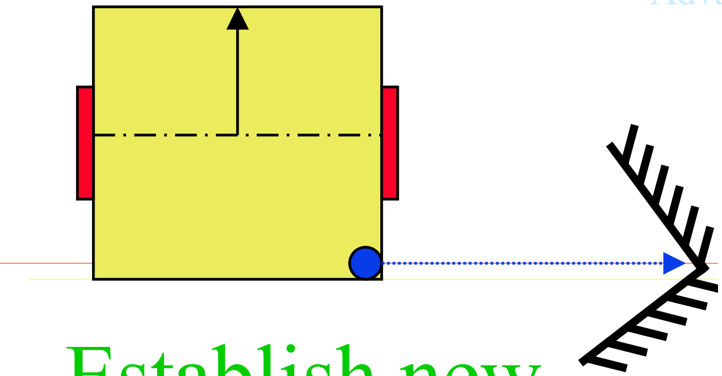
Establish new corner feature



Establish new corner feature



Associate new measurement to corner feature



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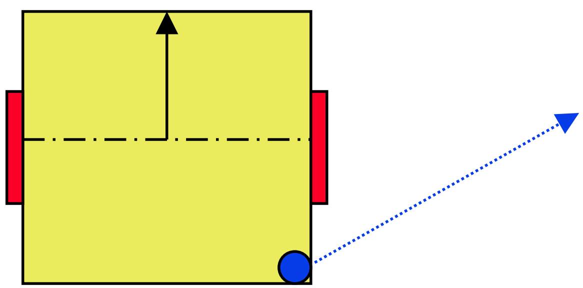
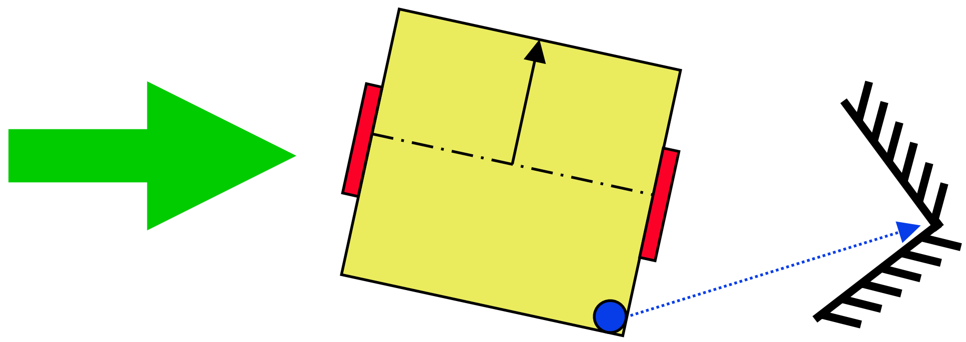
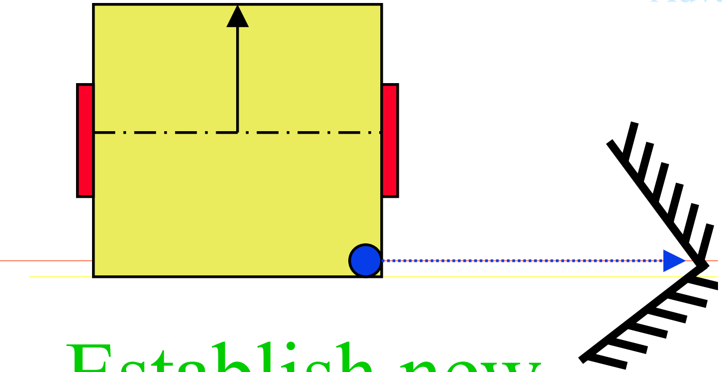


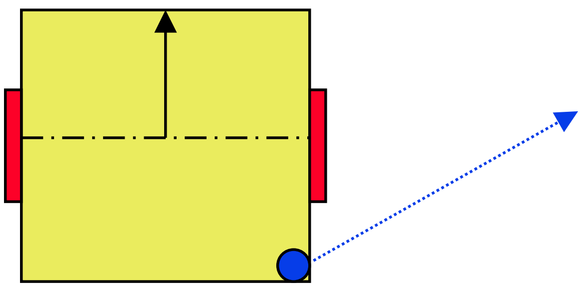


Associate new measurement to corner feature

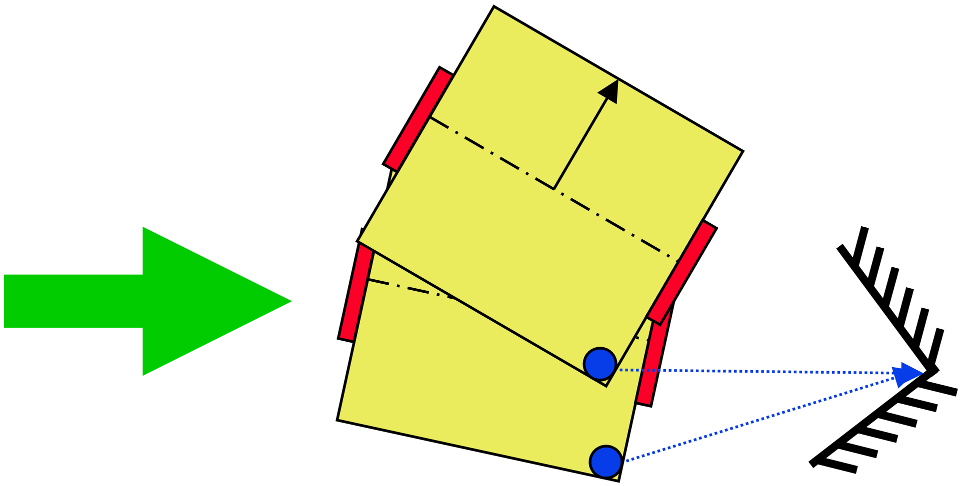
Constrains robot position and orientation



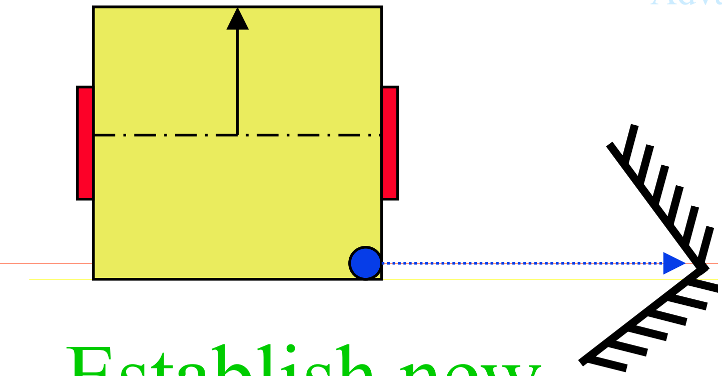
Establish new
corner feature



Associate new
measurement to
corner feature



Constrains robot
position and
orientation



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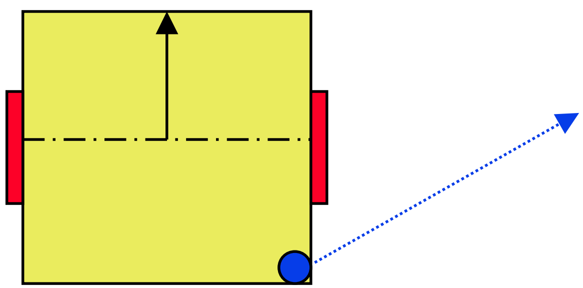
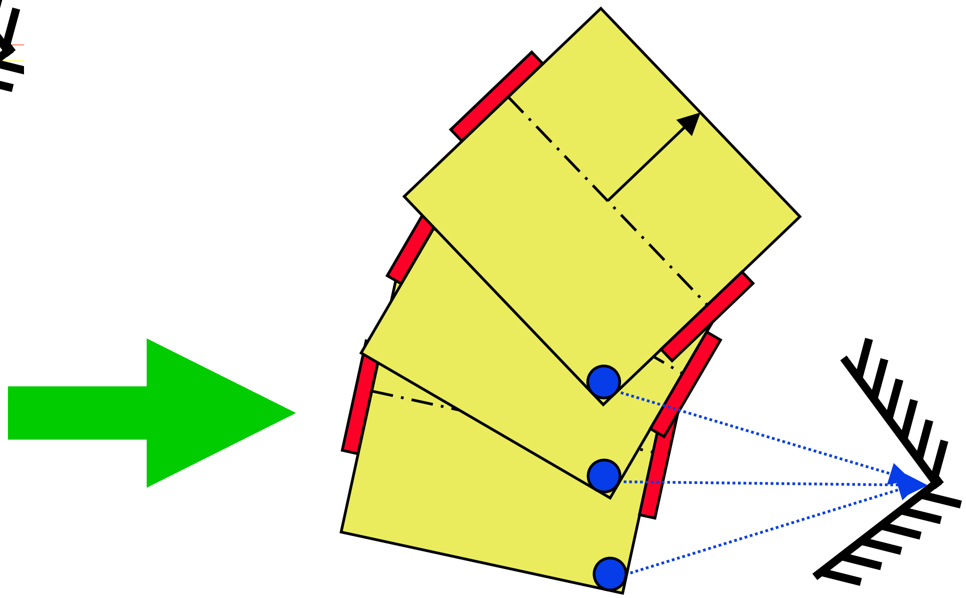


Associate new measurement to corner feature



Constrains robot position and orientation

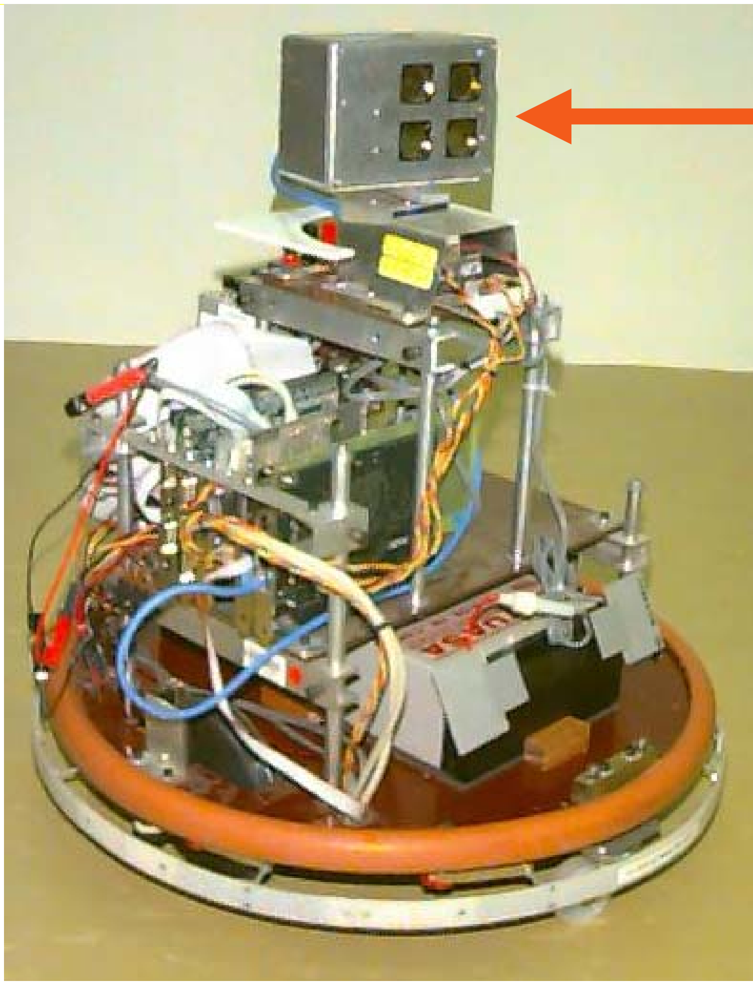
Introduction

- Early sonar classifies with a stationary robot:
  - Kleeman & Kuc 1995, "Mobile robot sonar for target localisation and classification" IJRR.
  - Peremans, Audenaert & Campenhout 1993, "A high resolution sensor based on tri-aural perception" IEEE R&A
- Other classifier needs several different positions
  - Feder, Leonard & Smith 1999, "Adaptive mobile robot navigation and mapping", IJRR.
- On-the-fly single measurement classification:
  - L. Kleeman, "On-the-fly classifying sonar with accurate range and bearing estimation" IEEE/RSJ International Conference on Intelligent Robots and Systems, 2002, Lausanne, Switzerland, pp.178-183.

Introduction
- Sonar and natural selection

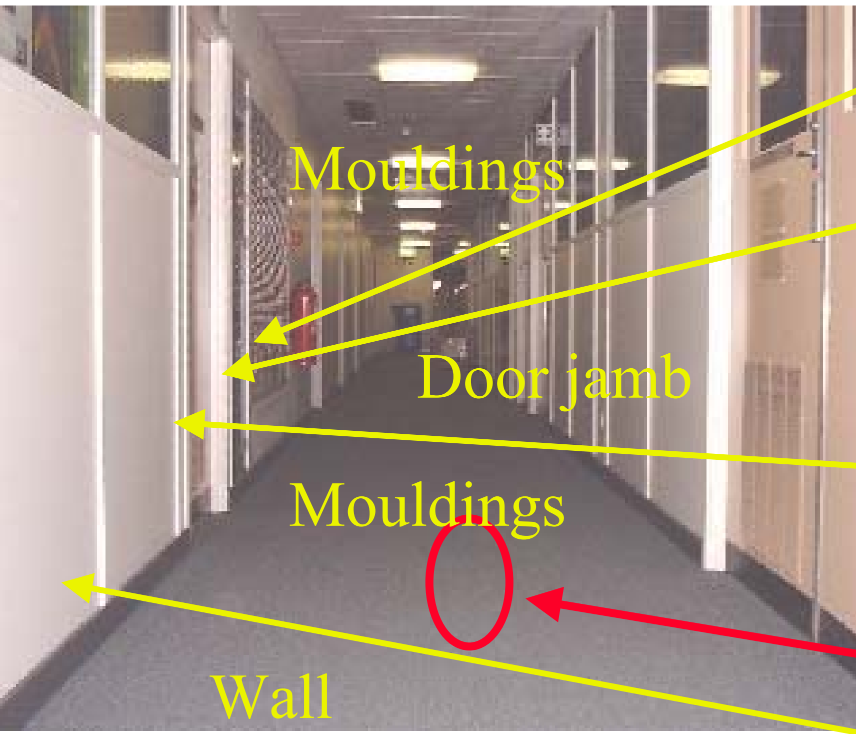
- Sonar useful for *naturally* selecting navigation beacons from the environment

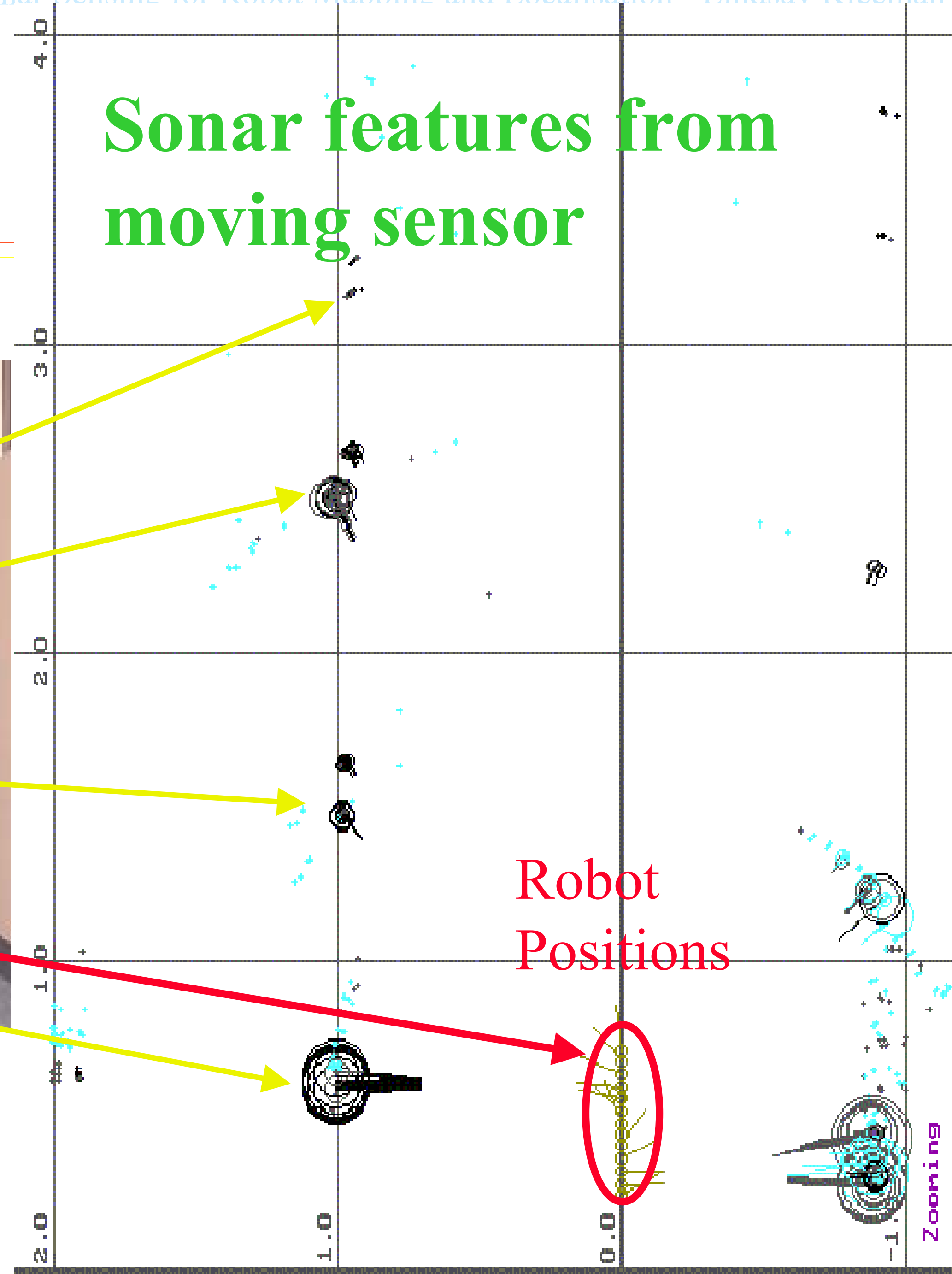
DSP Sonar System on Werrimbi



sonar

Sonar Features

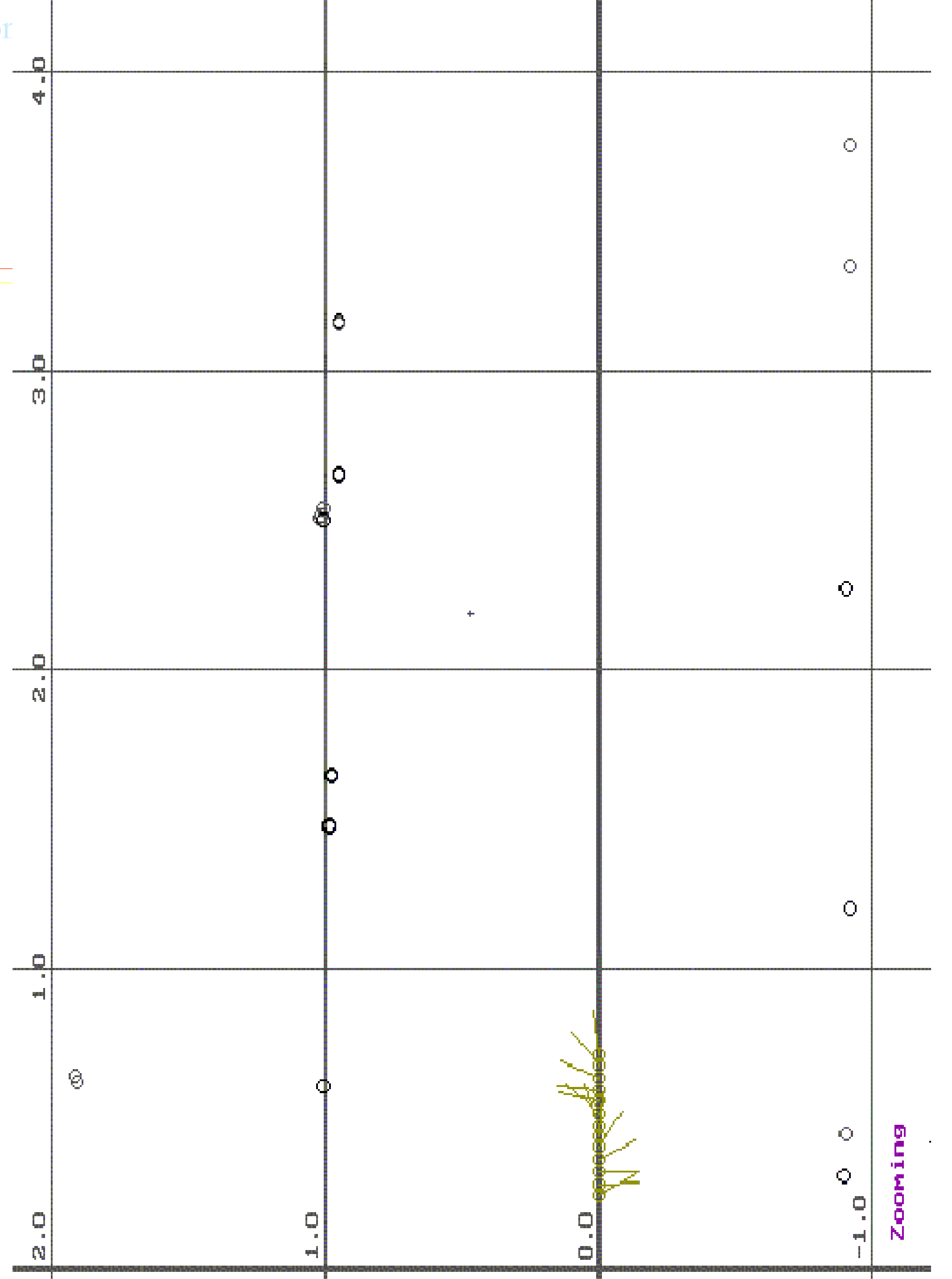




Fused Targets

Raw target data in close proximity is fused based on a weighted average.

Weights are determined by amplitude and correlation values.



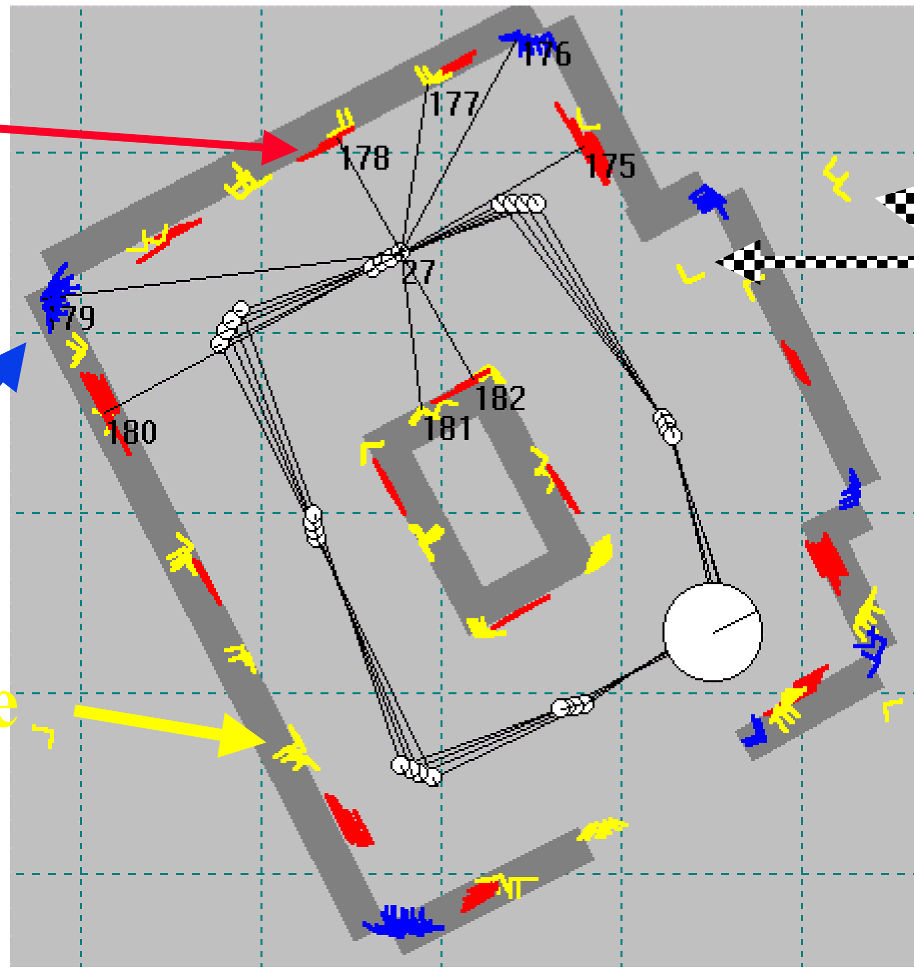
Natural sonar features

Plane feature

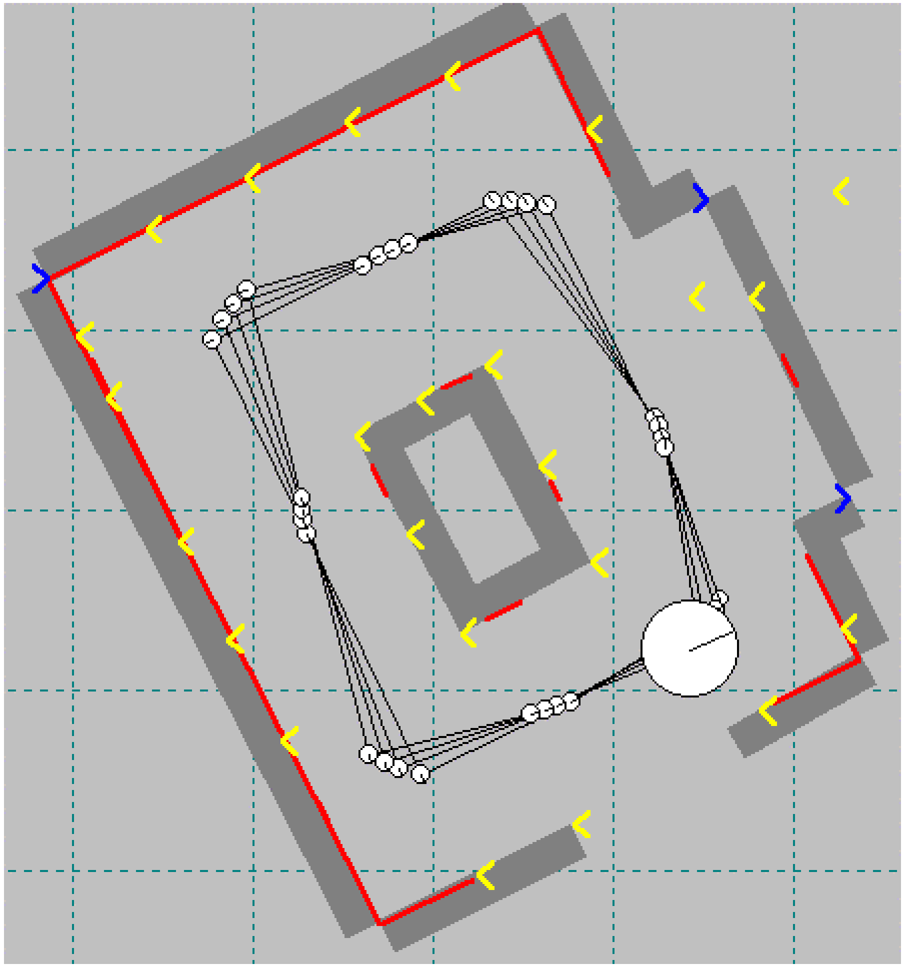
Corner feature

Edge feature

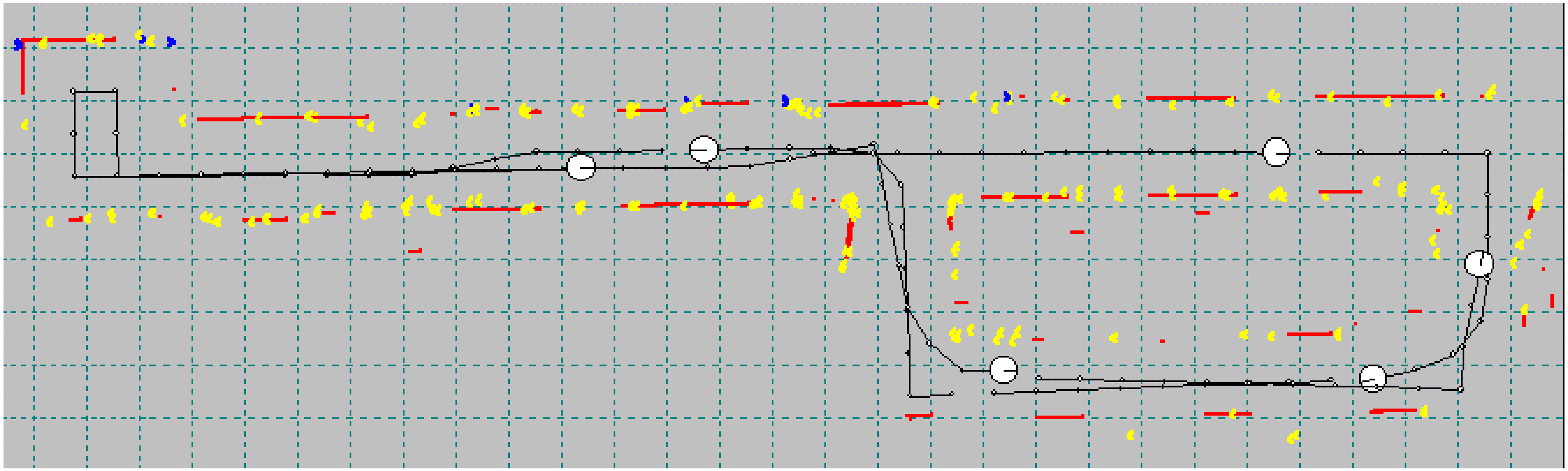
Phantom features



Simultaneous Mapping and Localisation (SLAM) Kalman Filter:



Sonar SLAM with loops – move and stop measurements



K S Chong and L. Kleeman, "Feature-based mapping in real, large scale environments using an ultrasonic array", International Journal Robotics Research, Vol 18, No. 1, 1999, pp. 3-19.

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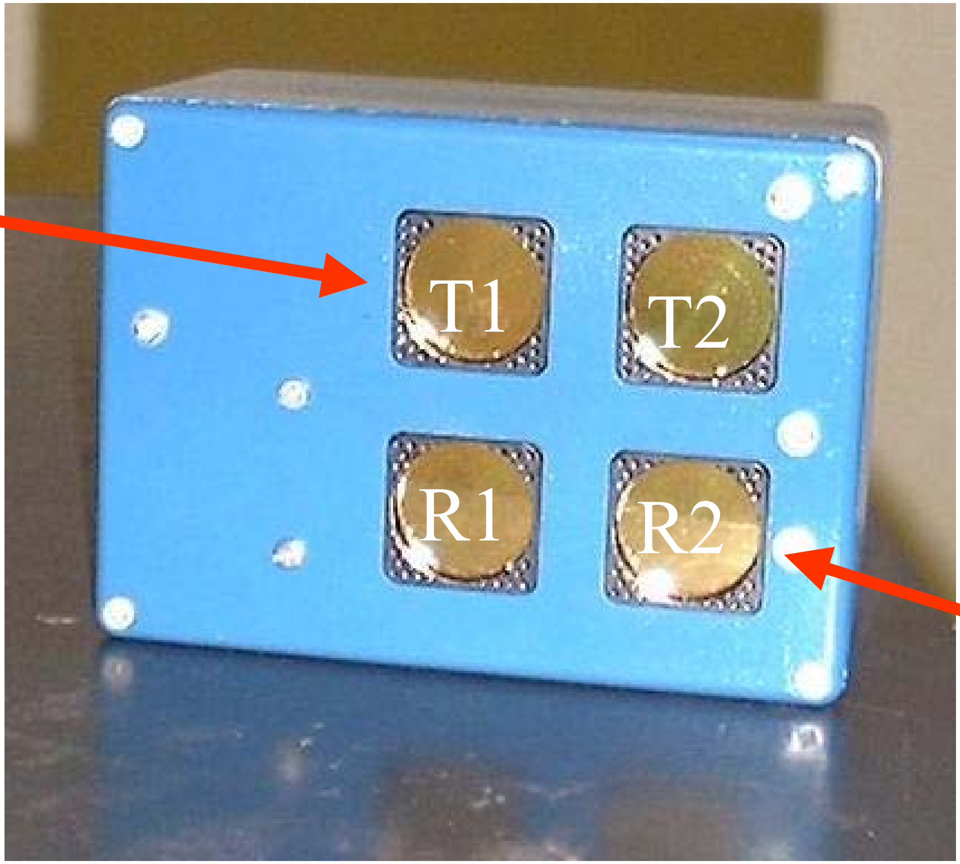
DSP Sonar Sensor

transmitters T1, T2



receivers R1, R2.

Capabilities

- Echoes are obtained from targets types *planes, corners* and *edges*.
  - These are common natural landmarks.
- Use two receivers and triangulate to determine the bearing to a target.
- Use two transmitters to determine the type of a target.

Specification

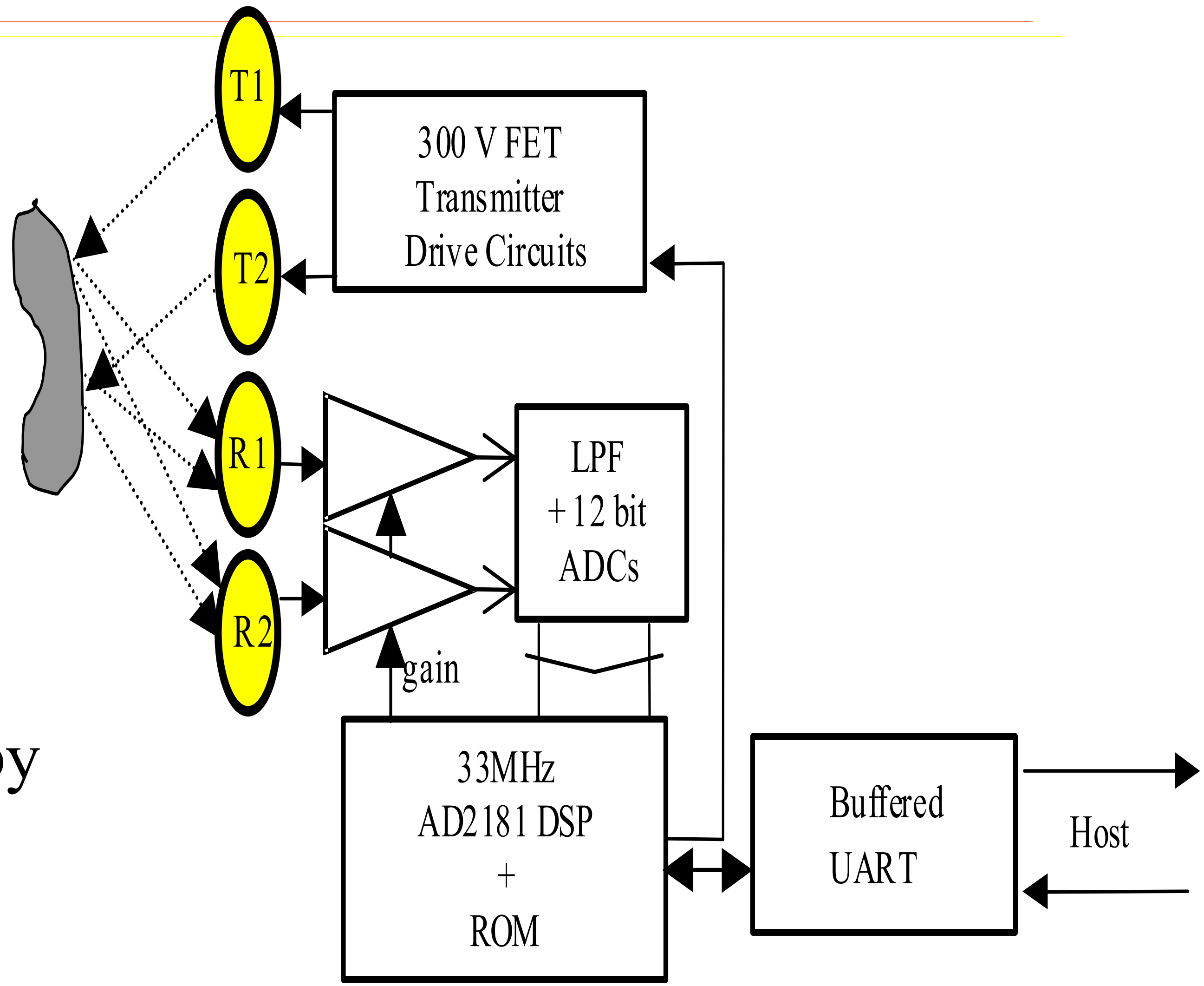
- Sonar sensing can accurately measure range and angle to specular targets
- The sonar sensor developed is accurate to 0.1 degrees, 0.2 mm to 5 metres at ~ 30 Hz.
  - subject to speed of sound calibration.
  - Estimated cost: ~$500

Hardware Description

1MHz sampling on 2 channels

All in one box reduces noise levels

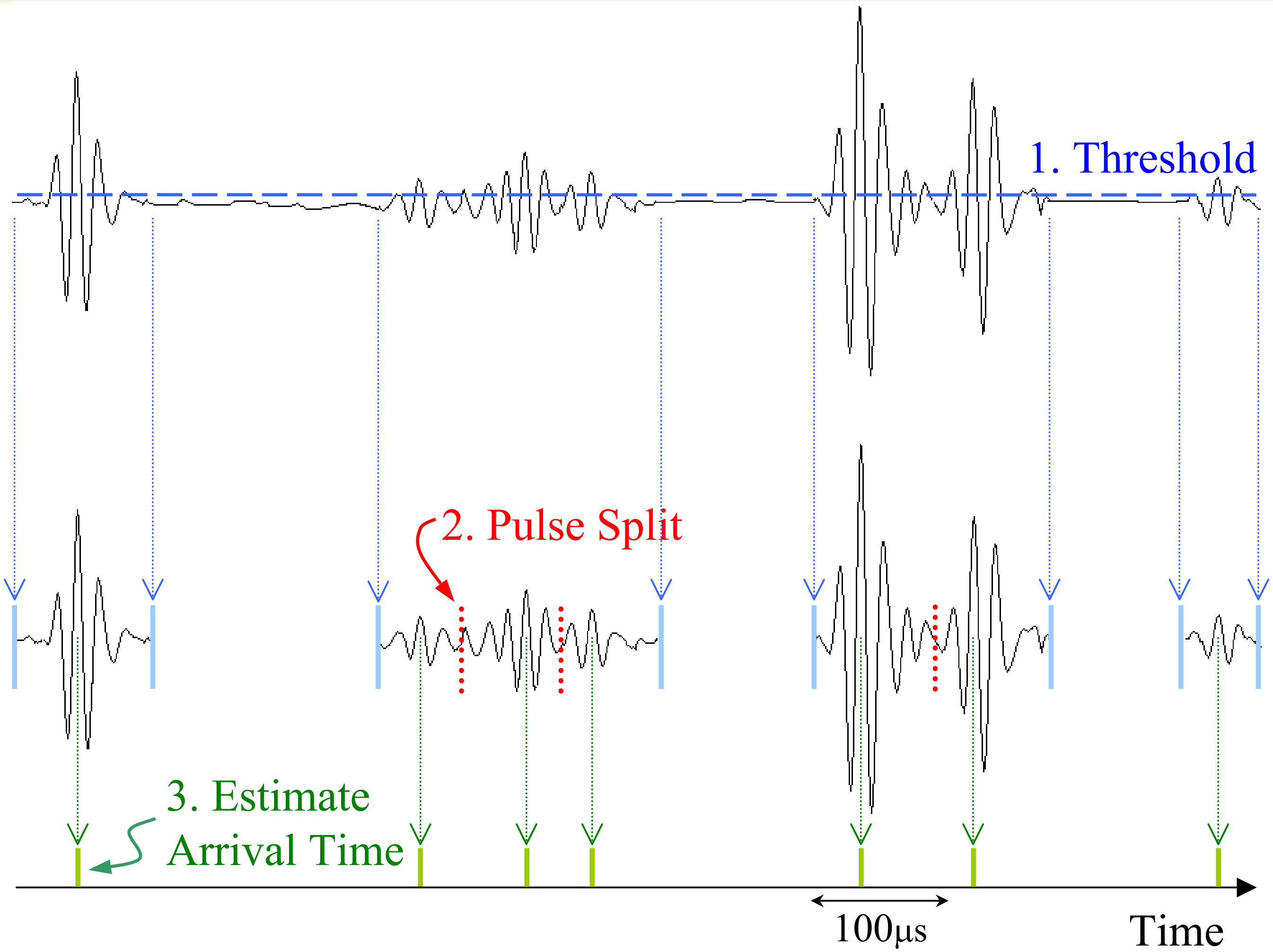
Fast processing by DSP



Signal Processing

- Thresholding
- Pulse extraction
- Pulse splitting
- Template matching
- *Double pulse recognition -later*
- Data Association
- Triangulation & Classification

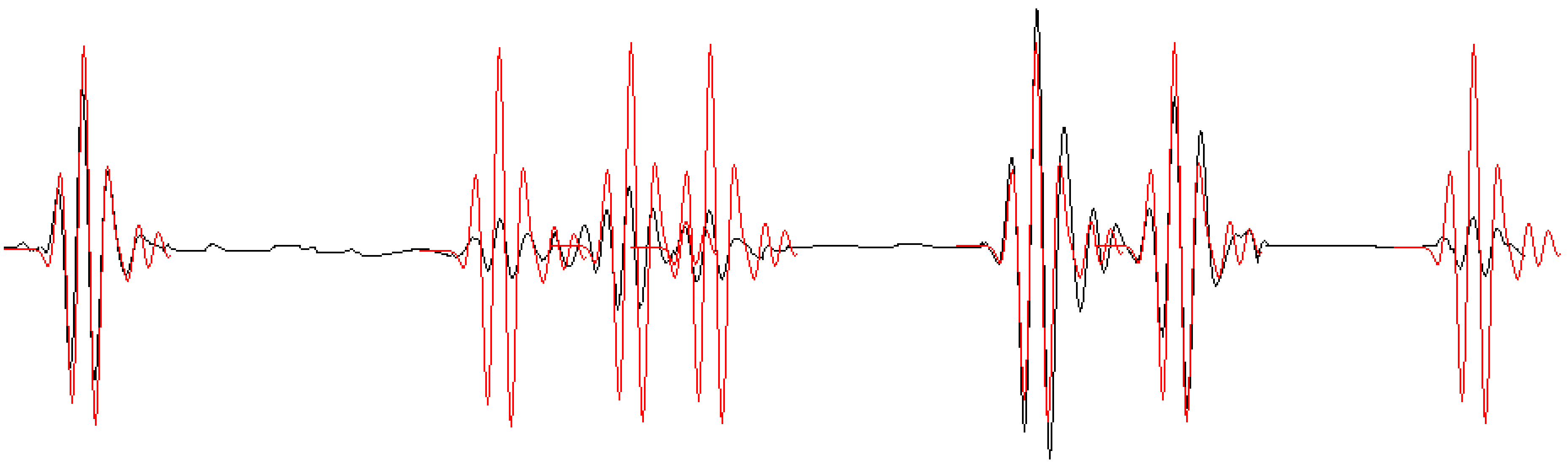
First Stages of DSP Processing



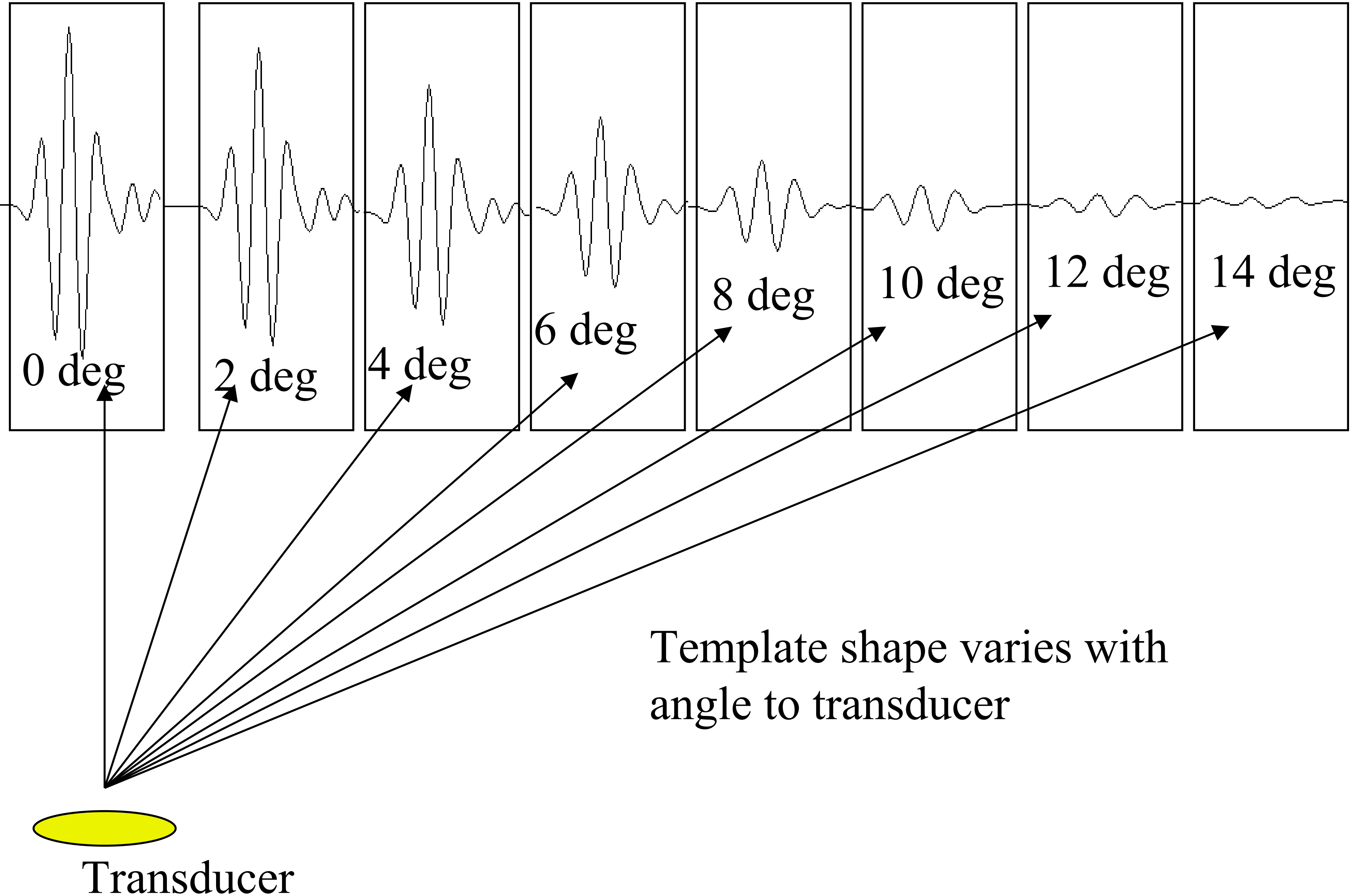
Template Matching

- Templates are pre-computed echo pulse shapes used in the arrival time estimation.
- Shape depends on arrival angle and range.
- This dependency has been accurately modelled - see *[Kleeman&Kuc IJRR 1995]*
- Thus the template set can be generated from a measured echo at normal incidence at 1 m.

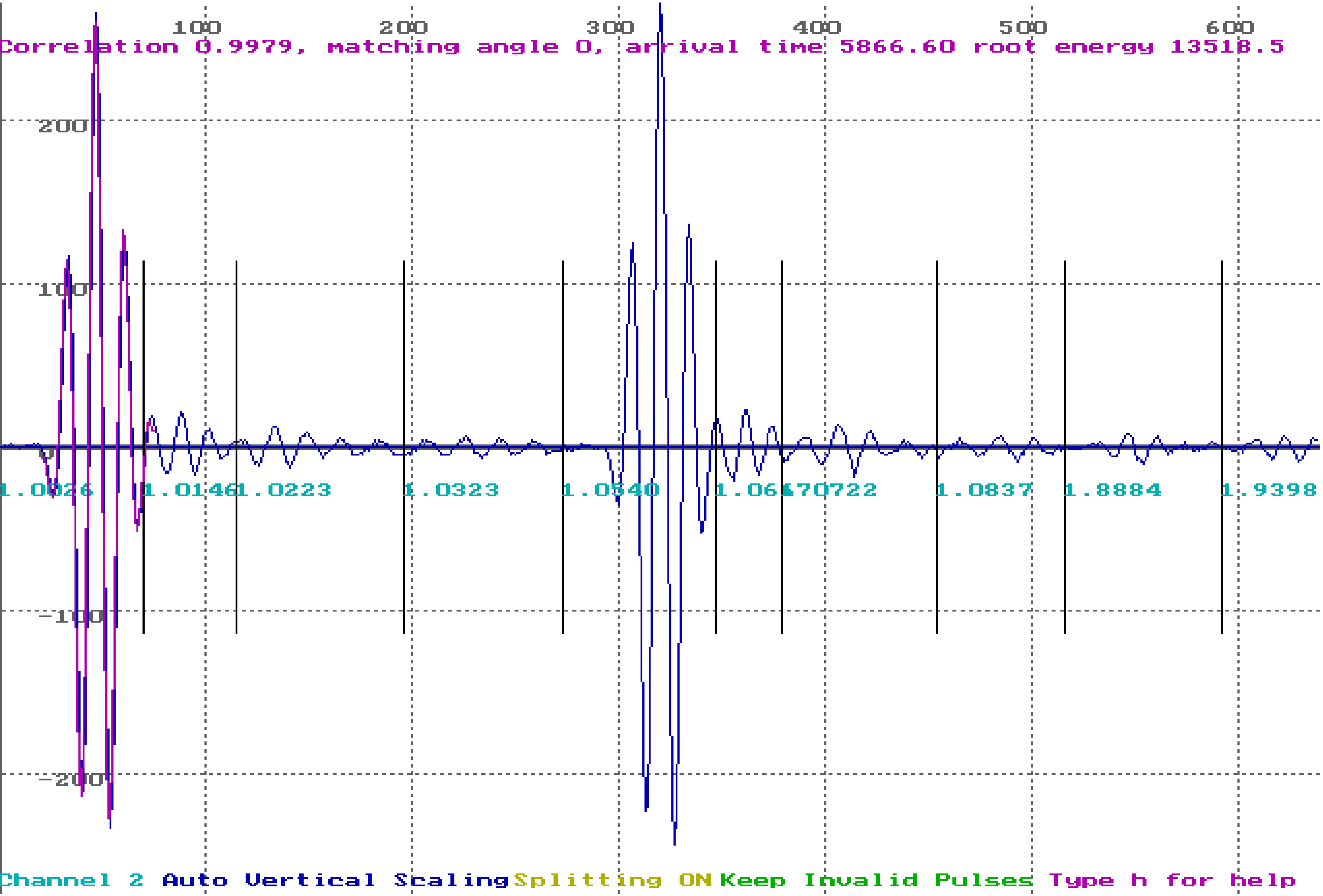
Template Matching



Templates shifted to best match the pulses using correlation of the template with the pulse.
Shape (not amplitude) are matched by a correlation.



Template shape varies with angle to transducer


100
200
300
400
500
600
Correlation 0.9979, matching angle 0, arrival time 5866.60 root energy 13518.5
200
100
0
-100
-200
1.0026
1.0146
1.0223
1.0323
1.0540
1.0647
0722
1.0837
1.8884
1.9398
Channel 2 Auto Vertical Scaling Splitting ON Keep Invalid Pulses Type h for help

Receiver Data Association

- Left and right receiver arrival times are associated based on:
  - arrival times consistent with small receiver spacing
  - amplitudes matched
  - correlation coefficients > 95%

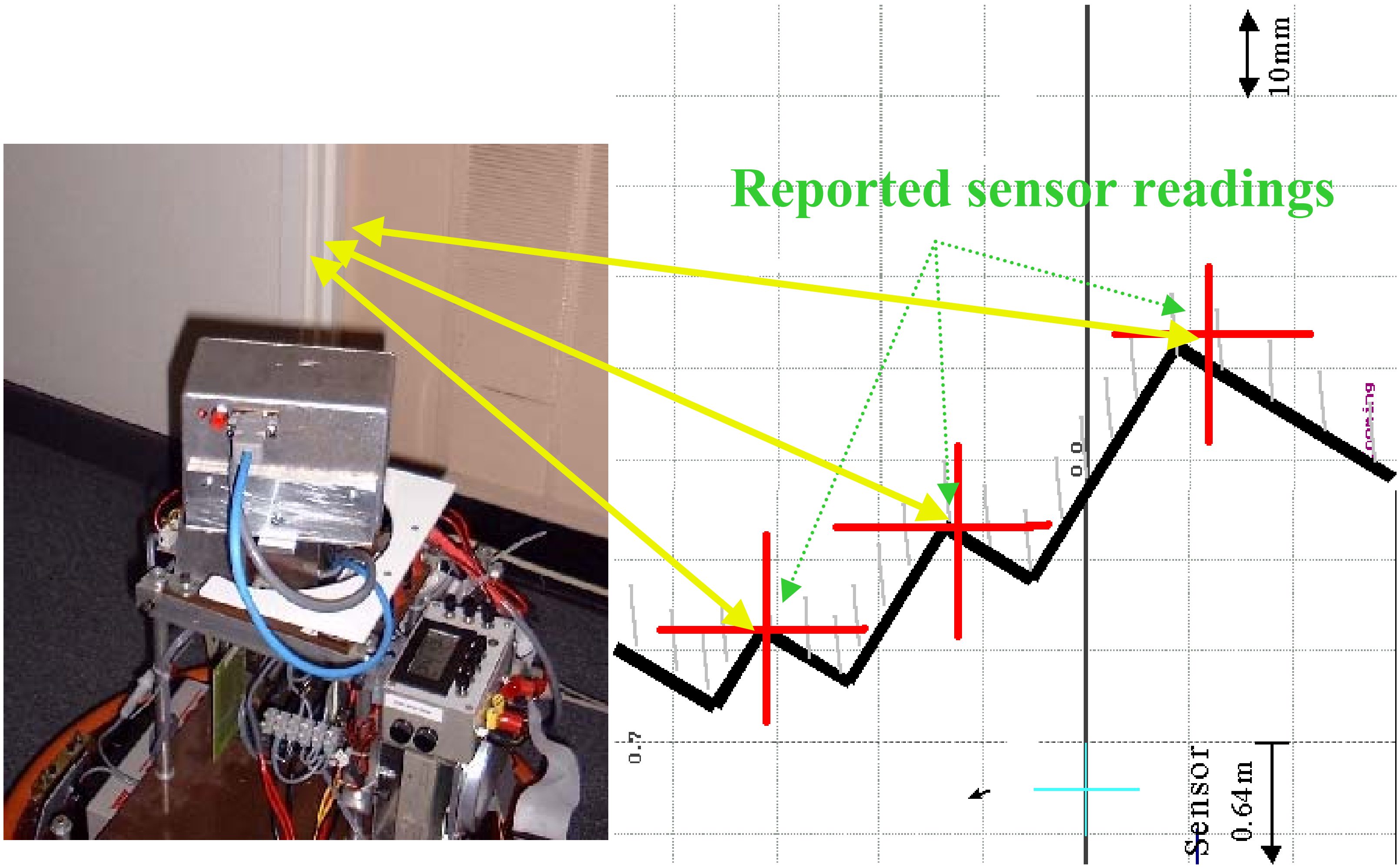
More Processing ...

- ***Triangulation*** – compute the bearing to each target.
- ***Classification*** - discussed later
- ***Double Pulse Recognition*** – rejects interference by recognising the sensor's 'voice' - *later*....

Clutter

- The echoes from closely spaced targets interfere with each other.
- To distinguish two targets, they must be at least 10 mm apart

Clutter - Door jamb experiment



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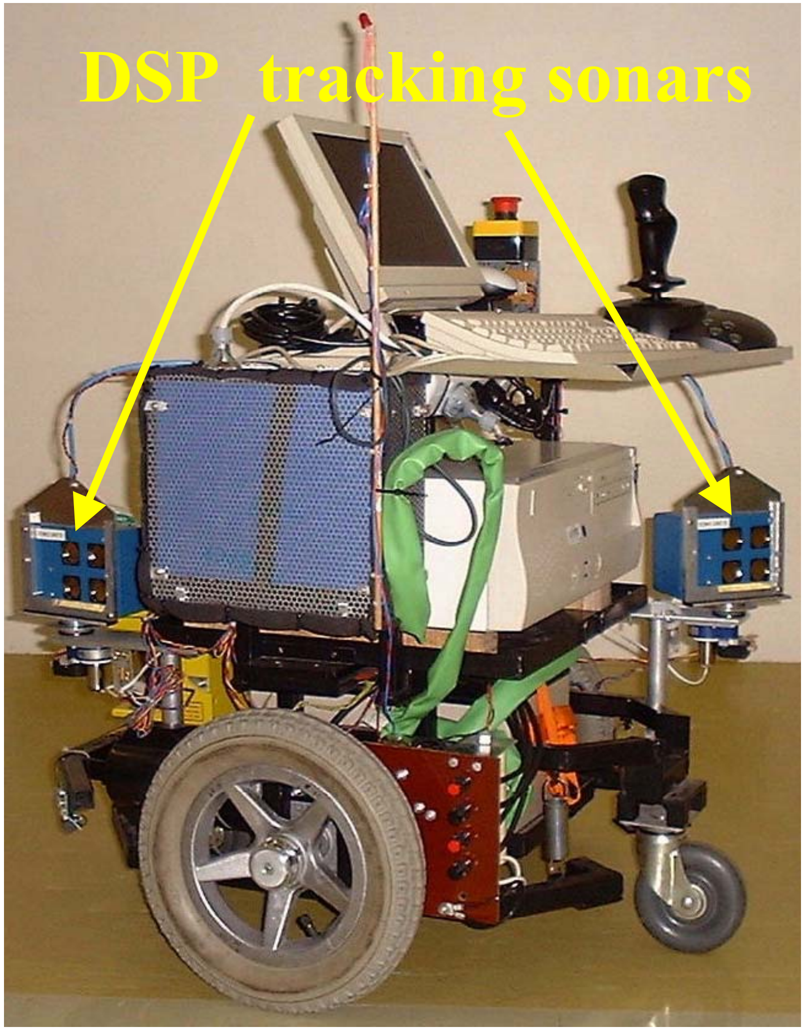
Sonars "on the Move"

Mobile robot travels at speeds up to 1 metre/sec.

Panning sonars can track a target using sonar sensed angle feedback.

Sonar also can windscreen wipe.



Target Tracking - Moving Target

Target Tracking - Moving Robot

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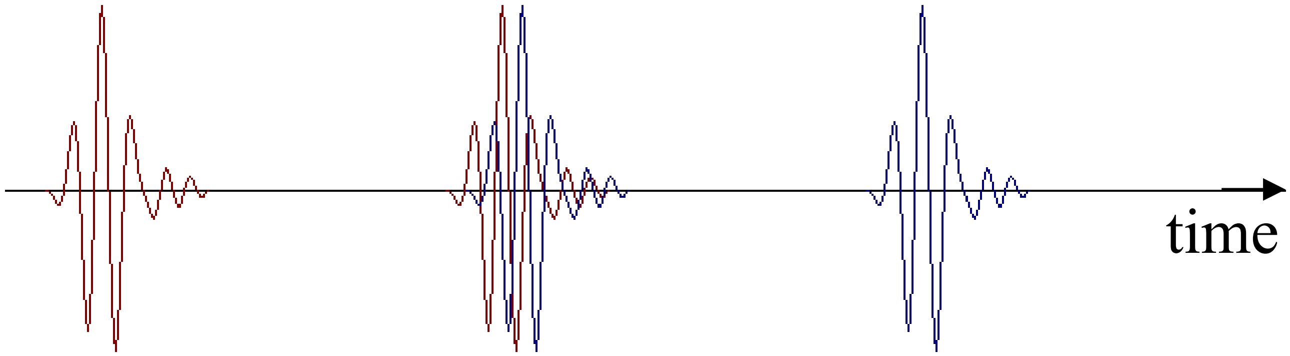
Interference

- From another sensor
  - crosstalk
- From the environment (multiple targets)
  - echoes from a nearby target and a more distant target can overlap and obscure each other



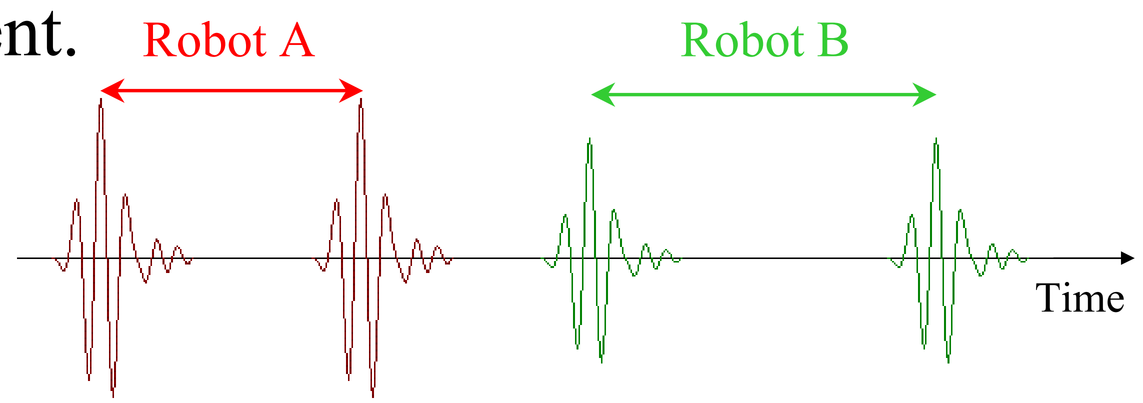
Double Pulse Coding

- In crowded caves, bats' sonar still works because each bat recognises its own voice.
- To prevent cross-talk, we give each robot a unique 'voice' using a fast and reliable technique called *double pulse coding*.
  [Kleeman IROS 1999 awarded Best Paper]

Double Pulse Coding

- When Robot A makes a reading, it transmits two sonar pulses separated by a specific interval.

- When receiving results, pairs of echoes with the same interval are accepted – but echoes from Robot B will be discarded, because the interval is different.

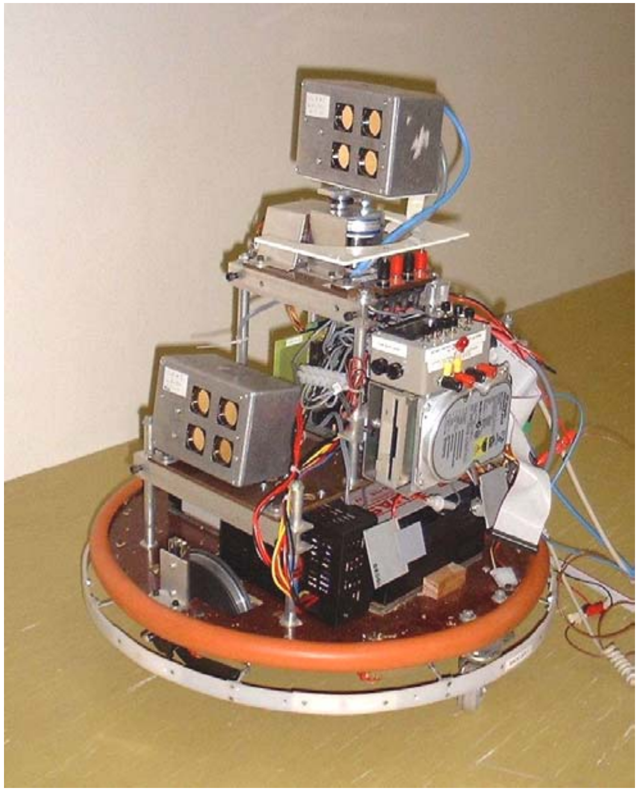


Double Pulse Coding

- *Preset* separation:
  - disastrous if two sensors use the same
  - blindness to certain targets
- Random separation: [Heale & Kleeman ACRA2000]
  - simple, automatic
  - problems do not persist

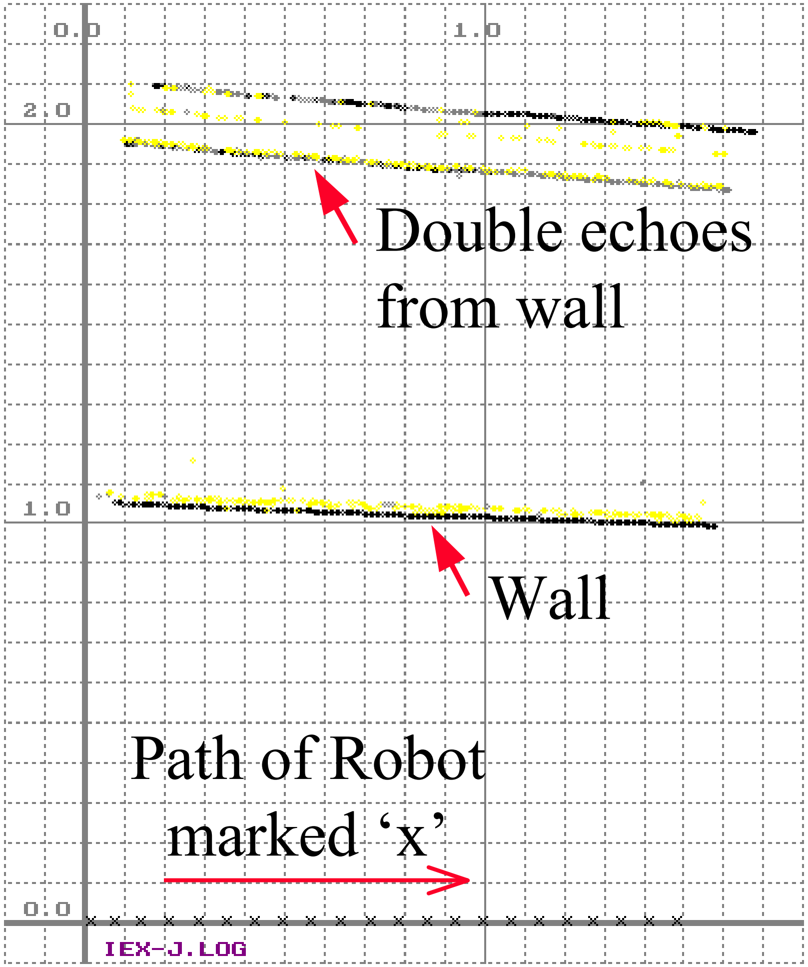
Interference Experiments

- Mapping a wall
  - 1 m range, moving parallel
  - 2000+ measurements taken
- **Aim:** to show robustness of double pulse coding



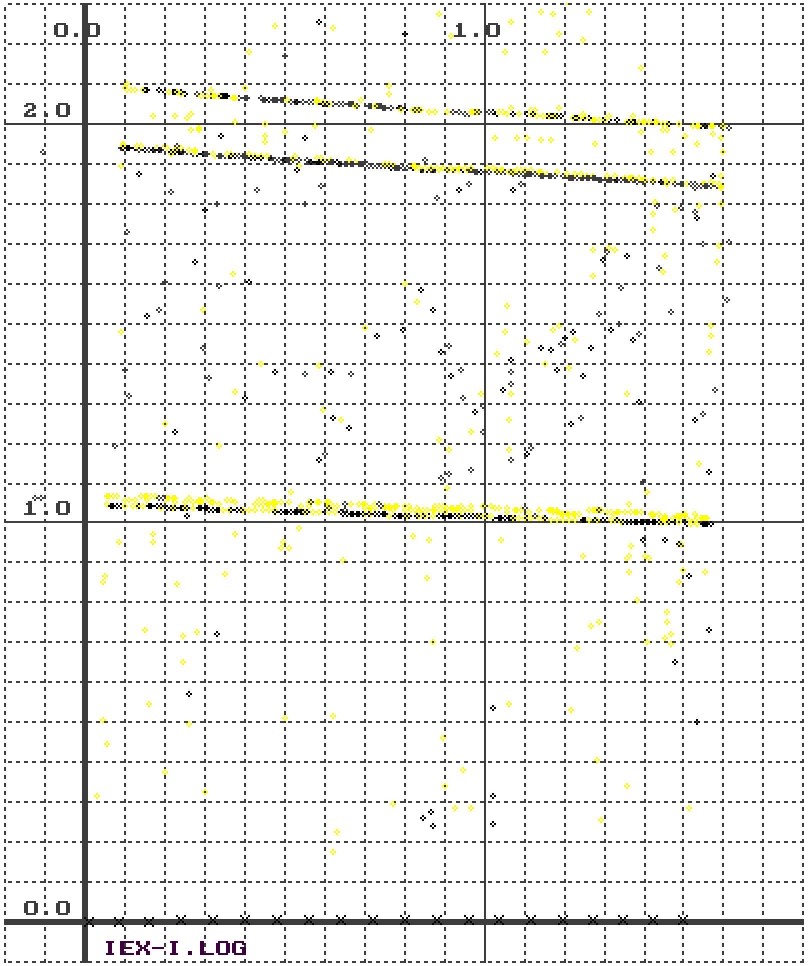
Interference from another sensor

- Double/Double with different separations
- no errors



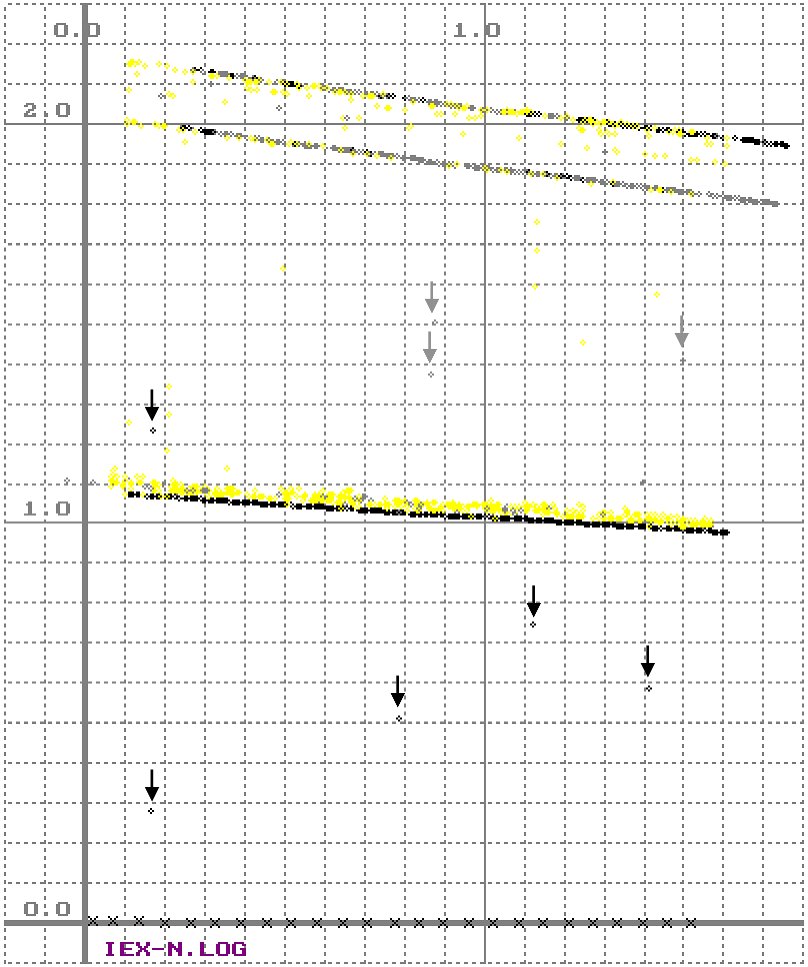
Interference from another sensor

- Double/Double with same separations
- Many errors!



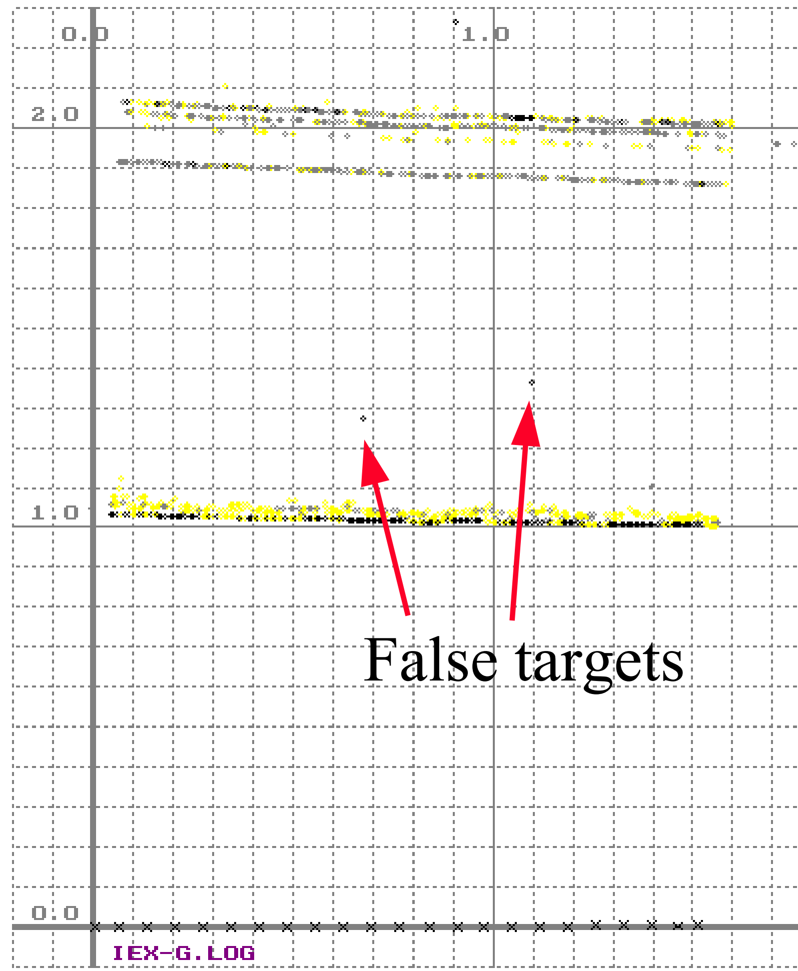
Interference from another sensor

- Random/Random
- Low error rate
- Errors not repeated



Interference from another sensor

- Random sensor / Single interference
- Environmental 'fakes' caused by two targets
- One single transmitted pulse can cause this



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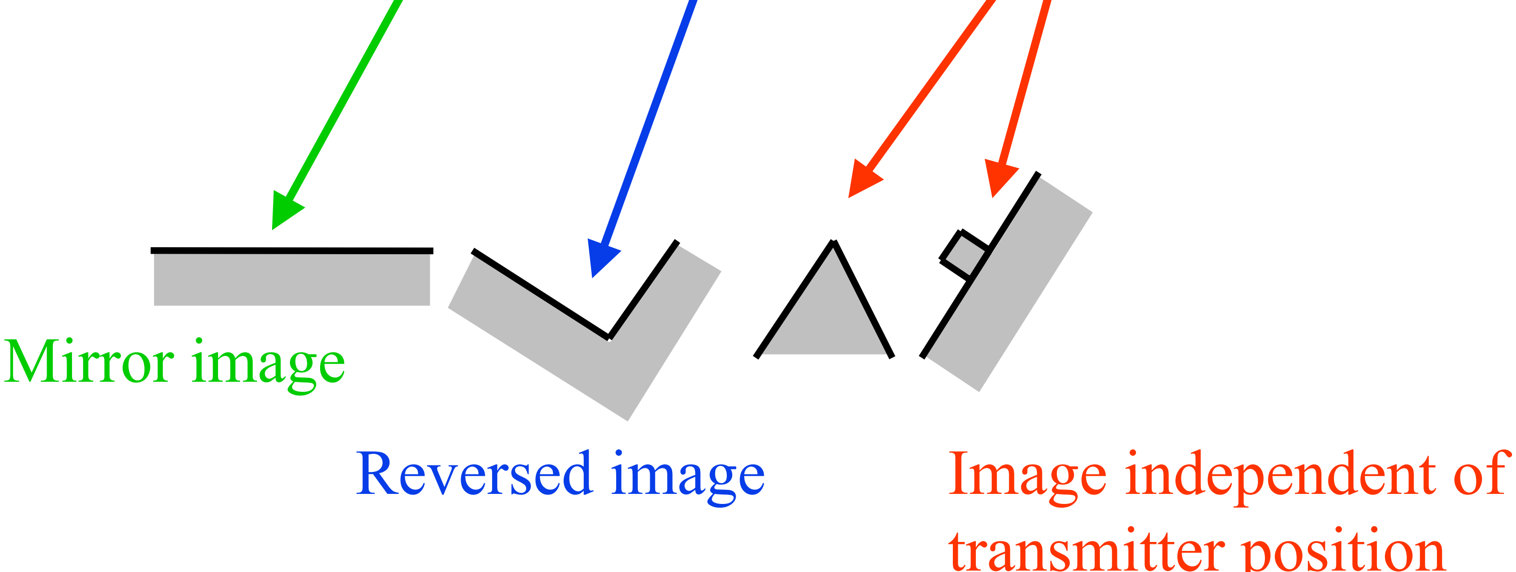
Classification

- *Two transmitter positions are required to classify into **plane**, **corner** and **edge**.*

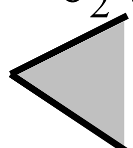
  [Kleeman & Kuc IJRR 1995]

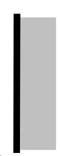


Previous Work on Classification

[Kleeman & Kuc IJRR 1995]

- ***Two*** measurement cycles (each ~50 msec):
  - – Transmit T1 and measure target bearing θ_1
  - – Transmit T2 and measure target bearing θ_2
  - – If *delta* = θ_1 - θ_2 is:

    0 => edge 

    < -*threshold* => plane 

    > *threshold* => corner 

    where threshold = $\frac{1}{4}\tan^{-1}\left(\frac{ReceiverSeparation}{2\times RangeOfTarget}\right)$
- T1 and T2 spaced by 25 cm

Single Cycle Classification

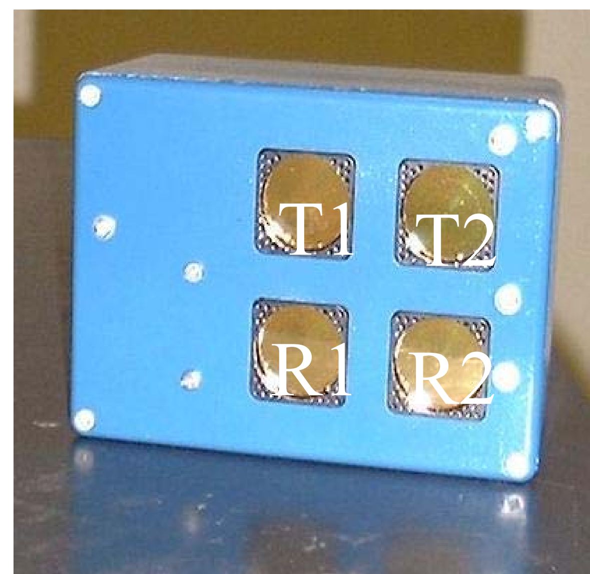
[Heale and Kleeman IROS 2001]

- ***One*** measurement cycle strategy (~32 msec)
- T1 and T2 ***4 cm*** apart (cf 25 cm previously)
- Transmit T1 then T2 with short known delay (~ 200 usec)
- time of flights T1 to R2

= T2 to R1 for vertical targets

=> double pulse coding

+ classification



Single Cycle Classification

- *Classification in one cycle* – using either:
  - delta = $\theta_1 - \theta_2$ or
  - Maximal Likelihood Estimation (MLE)
  - Delta - fast and simple
  - MLE - uses range and angle information, requires measurement covariance, gives classification probability and improves range estimate.

Classification and Noise [IROS2001].

- Classification is more reliable when the pulse separation is short
- Classification is still reliable when transmitter separation is small.
- Interference rejection comes for free - double pulse coding T1 -T2.

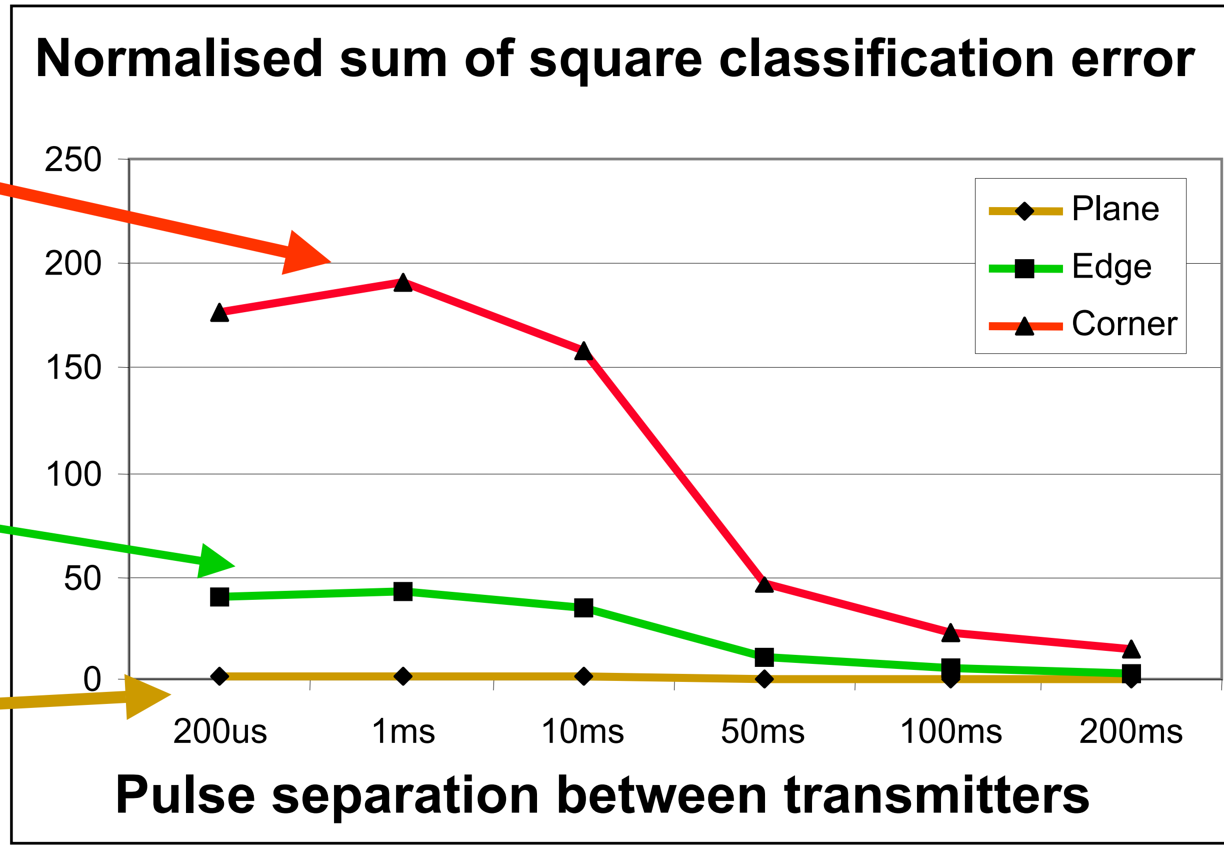
Maximum Likelihood Estimate

Classifying a Plane with MLE

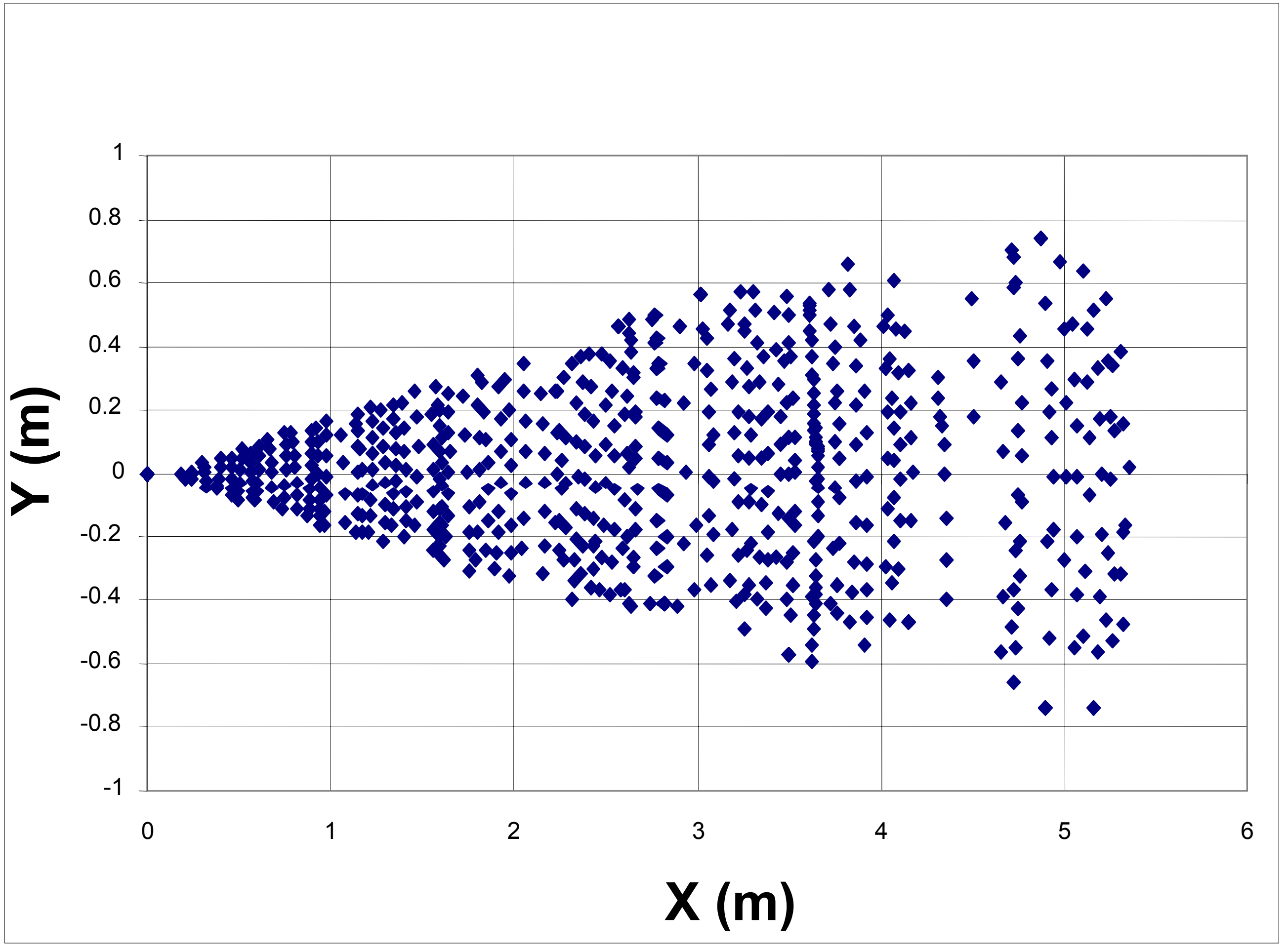
Large error when fitting plane measurements to corner model

Error when fitting plane measurements to edge model

Plane fits well!



Area of Plane Recognition



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- Interference Rejection and Pulse Coding
- Classification
- SLAM
- Conclusions and Future Work

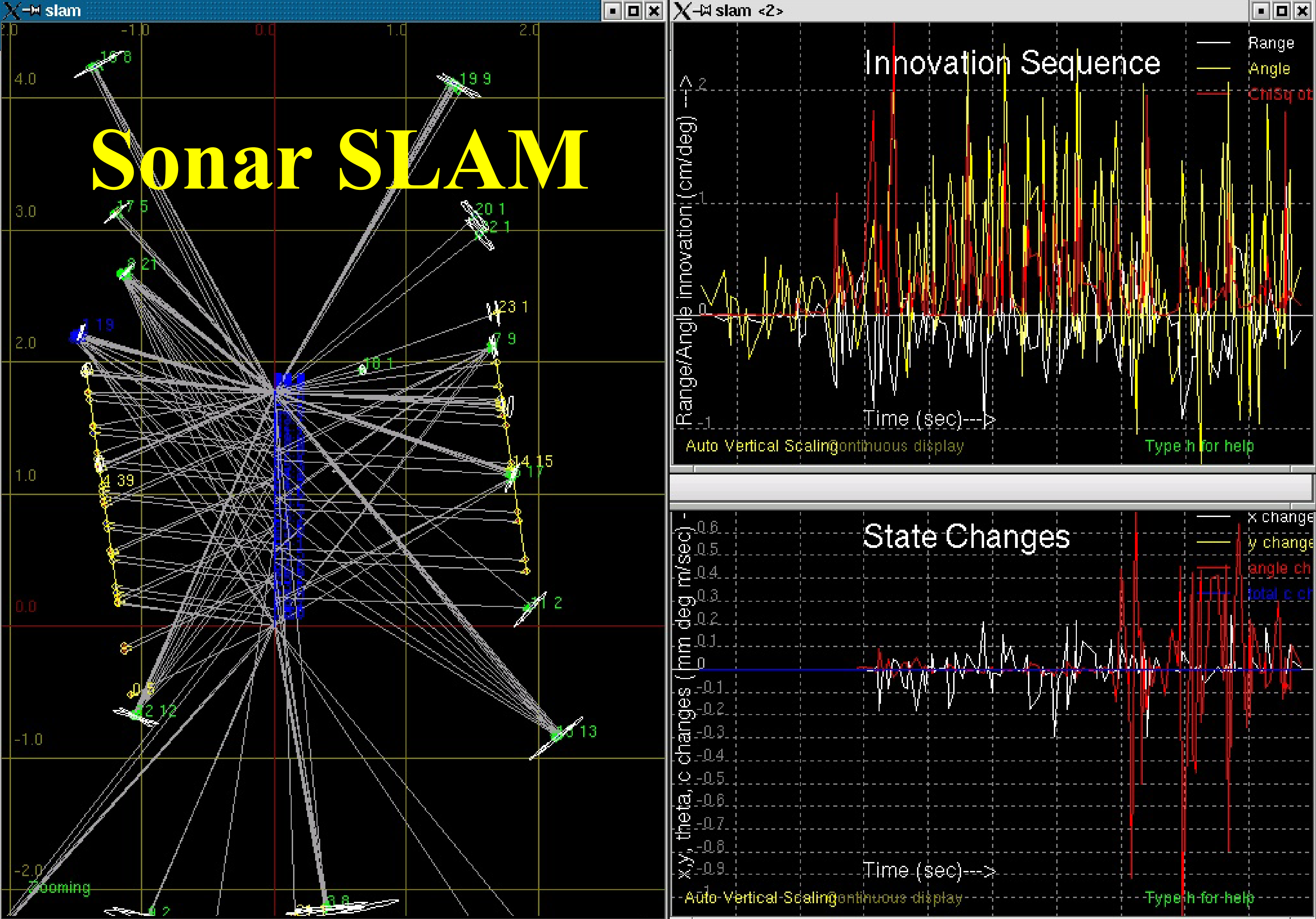
Simultaneous Localisation and Mapping (SLAM)

- Key problem for autonomous robotics:
  - starting in unknown environment
  - solving SLAM requires estimation of errors in robot pose and map information and their *correlation*. Error corrections can then propagate!

SLAM

- Classic Kalman Filter Solution:
  - computation per step and memory scales as n^2, n=number map features
  - association problem
  - kidnapped robot
  - loop closing
  - multi-sensor fusion with inconsistency, noise..

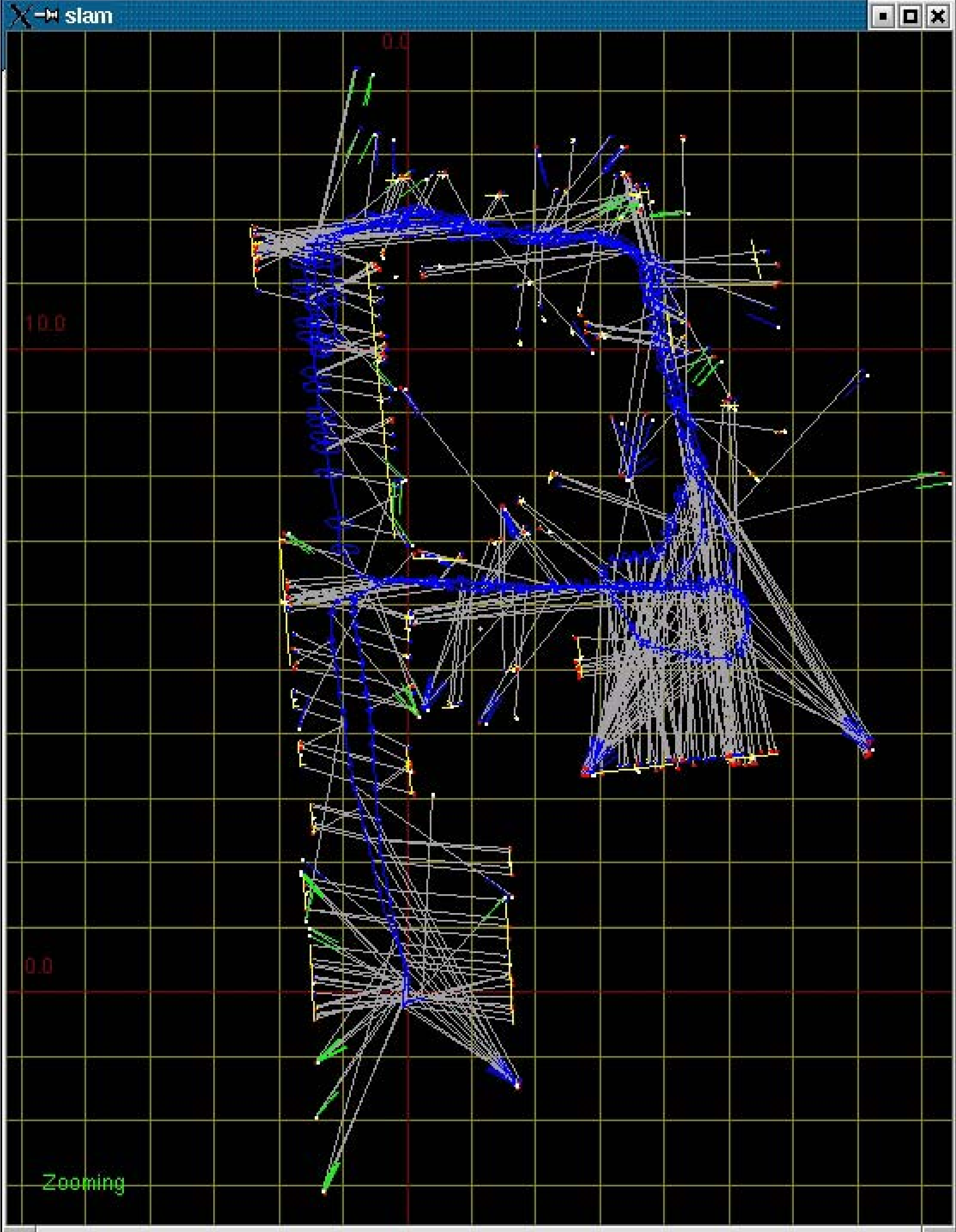
Autonomous Exploration



Sonar SLAM
slam
slam <2>
Innovation Sequence
Range
Angle
Range/Angle innovation (cm/deg) --->
Time (sec)--->
Auto Vertical Scaling
continuous display
Type h for help
State Changes
x change
y change
angle ch
x,y, theta, c changes (mm deg m/sec) --->
Zooming

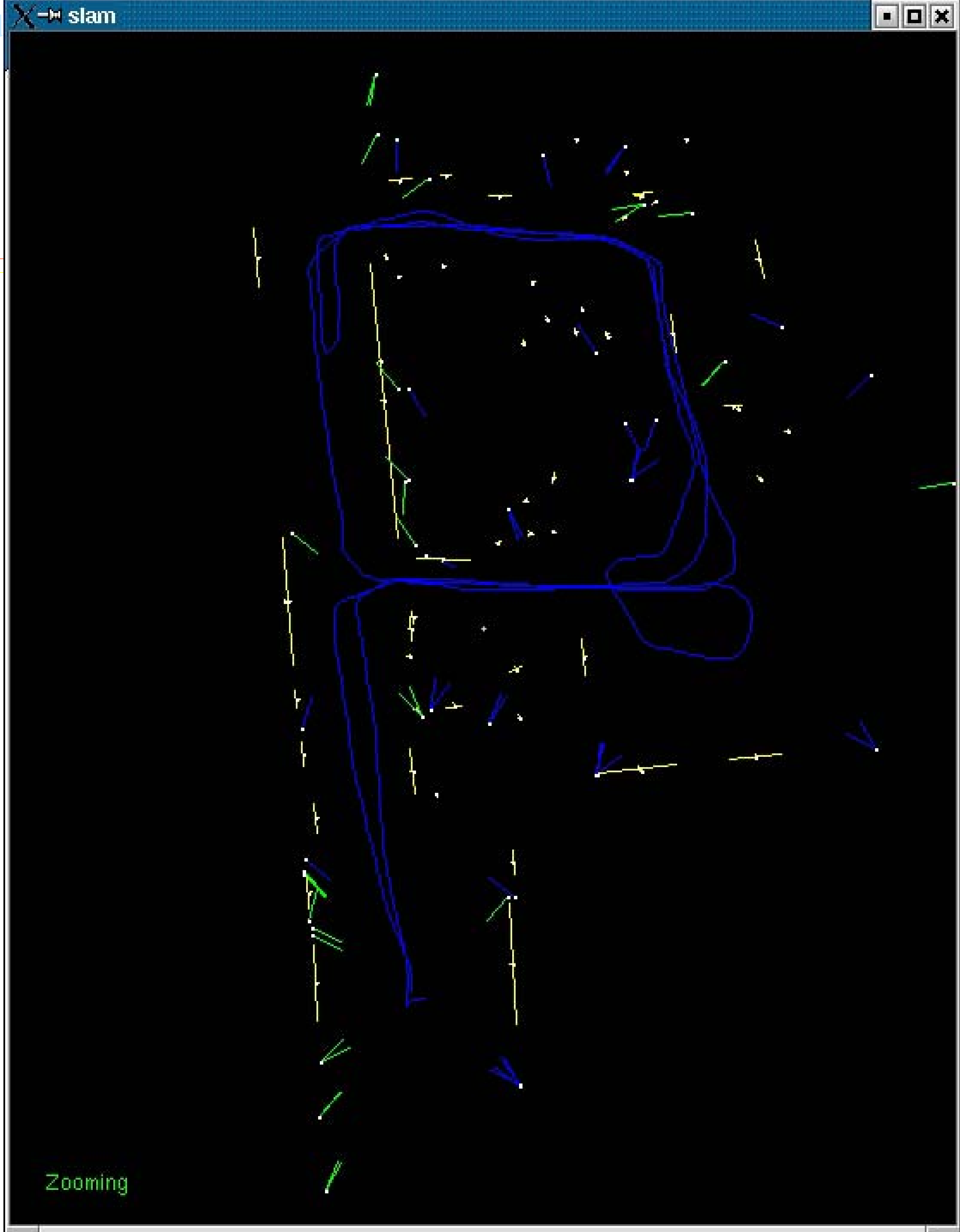
SLAM with Loops

Map with all measurements



SLAM with Loops

Final map

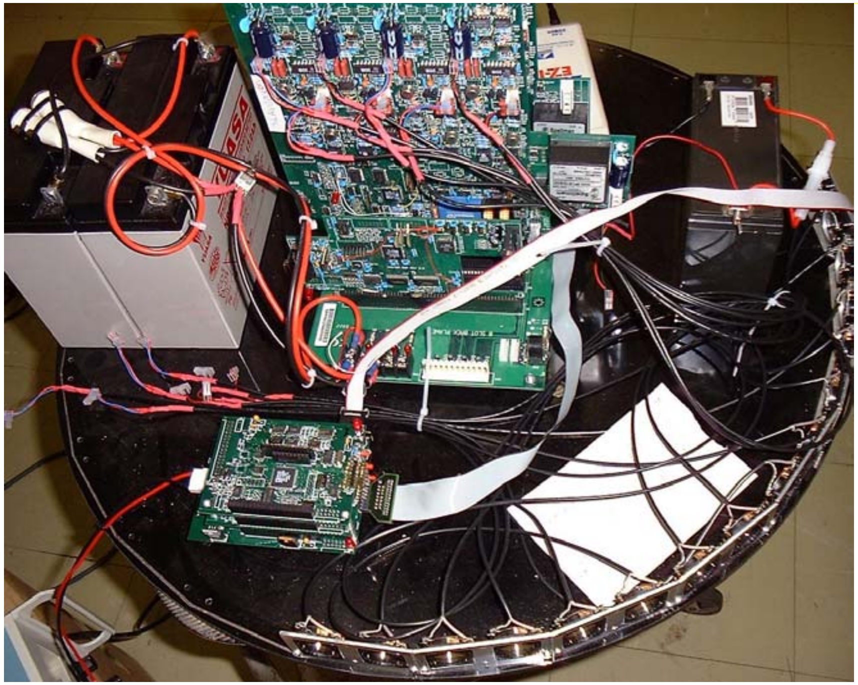


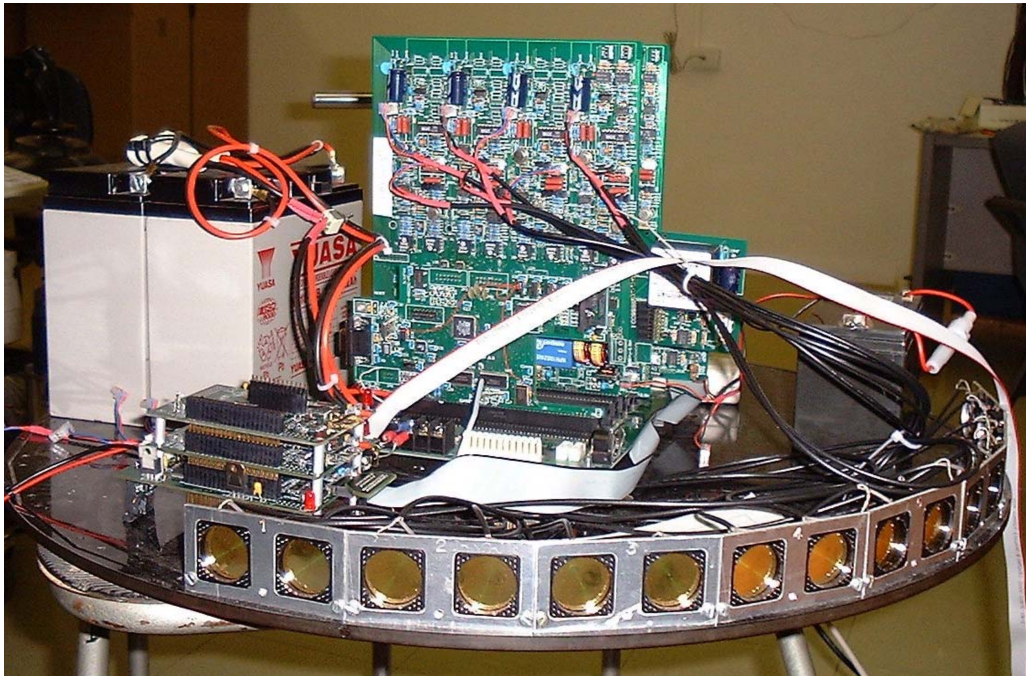
Contents

Conclusions and Future Work

- Sonar results achieved so far …..
  - real time optimal range and bearing estimation
  - on-the-fly single cycle classification
  - interference rejection
  - motion compensation
  - SLAM
- Future work:
  - Fusion with laser, DSP sonar ring, optimal exploration, synergies of 10+ sensors.

DSP Sonar Ring – work in progress





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