Mtrx 4700: Experimental Robotics

Navigation and Mapping

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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		

Agenda

- Introduction
- Autonomous Navigation
- Localisation
- Mapping
- The SLAM Problem
- Autonomous Exploration
- Conclusions

Introduction

- Deployment of Autonomous Systems in unknown environments remains difficult
- Requires reliable, long-term autonomous navigation
- One of the fundamental questions in robotics is "Where am I?"
- Navigation : Localisation and Mapping
- Naturally leads to 'Simultaneous Localisation and Mapping' (SLAM)

Autonomous Navigation

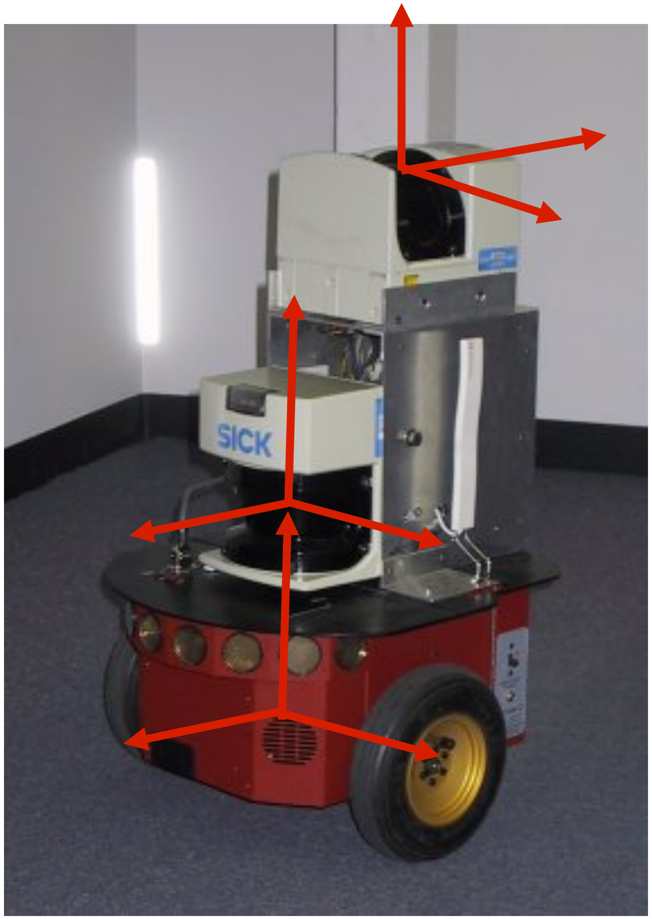
- Fundamental competence for mobile robotics
- Two major components
  - Localisation
    - Vehicle models
    - Internal sensing (INS, laser, vision, maps)
    - External sensing (GPS, LBL, off-board cameras)
  - Mapping
    - Raw maps vs. Feature maps
    - Representation?

Localisation

- There are two fundamental sources of localisation information
  - Proprioceptive sensors
    - Include encoders, inertial sensing, and sensors capable of observing the internal state of the system
    - Generally give us a differential equation which relates to the motion of the vehicle
  - Exteroceptive sensors
    - Include laser, sonar, vision, GPS, acoustic positioning systems, off-board sensors capable of observing vehicle such as radar and vision
    - Generally relies on solving geometric constraints to identify the position or pose of the vehicle

Mobile Robotic Kinematics

- Recall from Week 2 that we suggested Kinematics plays an important role in mobile robotics
- We typically assign a frame to the some location on the vehicle
- Additional frames are assigned to the sensors
- We use kinematic relationships to estimate where objects of interest are in the environment



Mobile Robot Kinematics

- A vehicle model describes how the motion of the vehicle evolves over time
- The complexity of the model will depend largely on the accuracy with which the motion must be tracked
- It will also depend on the nature of the mechanism – a vehicle model of a legged robot will necessarily be more complicated than a two wheeled vehicle

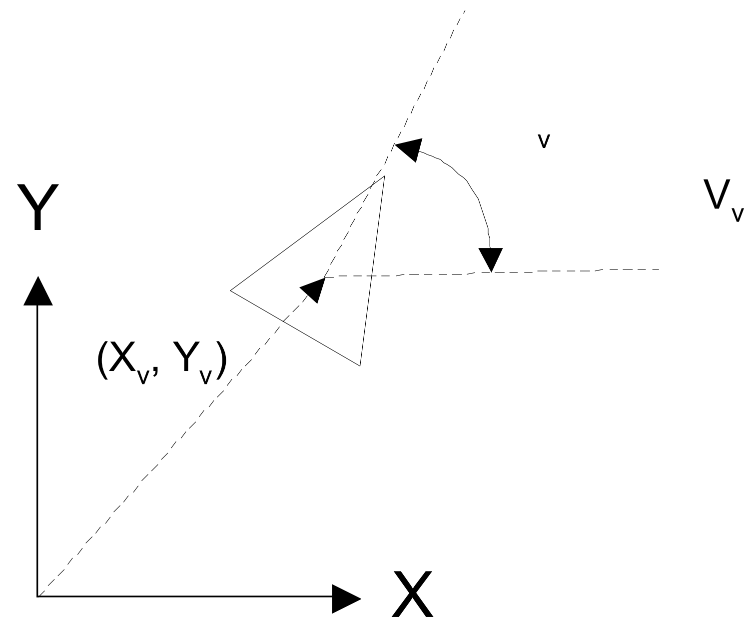
Vehicle Model

- For a mobile vehicle, we are usually interested in the vehicle pose
- If we can measure the vehicle velocity and sense heading changes we can write a differential equation describing the evolution of the vehicle pose

$$\dot{x}_v = V_v \cos(\psi_v) + v_x$$

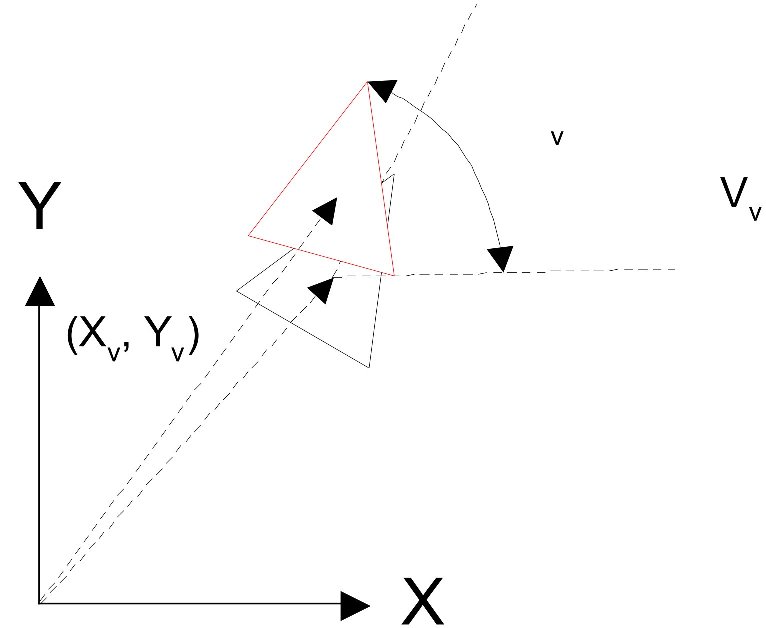
$$\dot{y}_v = V_v \sin(\psi_v) + v_y$$

$$\dot{\psi}_v = (\dot{\psi}_{turnrate}) + v_\psi$$



Vehicle Model

- To implement this on a digital controller, we discretize the update equations

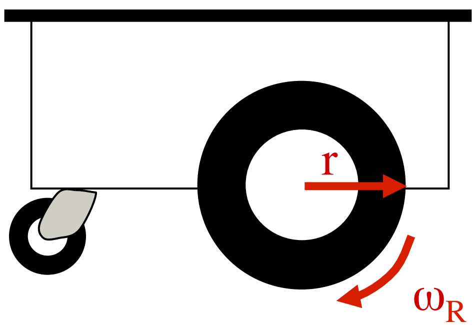


$$x_v(k) = x_v(k-1) + \Delta t \cdot V_v(k-1)\cos(\psi_v(k-1))$$

$$y_v(k) = y_v(k-1) + \Delta t \cdot V_v(k-1)\sin(\psi_v(k-1))$$

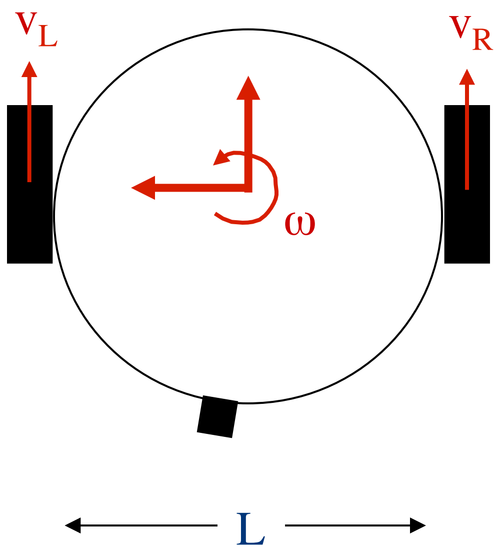
$$\psi_v(k) = \psi_v(k-1) + \Delta t \cdot \dot{\psi}_{turnrate}(k-1)$$

Vehicle Model – Differential Drive



$$v_L = r_L \times \omega_L$$

$$v_R = r_R \times \omega_R$$

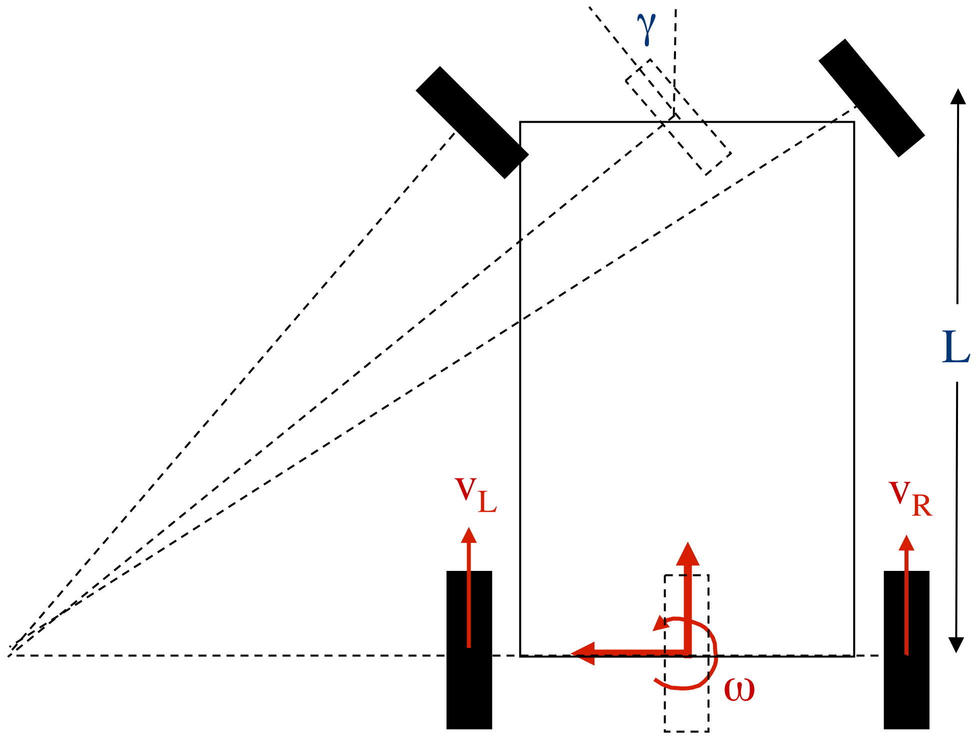


$$v = \frac{v_L + v_R}{2}$$

$$\omega = \frac{v_L - v_R}{L}$$

- A vehicle like our pioneers relies on differential drive (i.e. two powered wheels) velocity and turn rate is achieved by turning the two wheels
- If one wheel turns, the body centre will move at half the instantaneous velocity. The body will rotate about the stationary wheel

Vehicle Model – Differential Drive



$$v_L = r_L \times \omega_L$$
$$v_R = r_R \times \omega_R$$

$$v = \frac{v_L + v_R}{2}$$
$$\omega = \frac{v\tan(\gamma)}{L}$$

- More complex vehicles, such as a car, are often modelled using the tricycle model
- Velocity and turn rate is measured about the centre of the rear axis
- The angle, γ, of the front steering wheel, determines the turn rate of the vehicle

Vehicle Model

- How do we sense motion of the vehicle?
- For a wheeled vehicle we can use encoders to measure wheel rotation. This can tell us something about how the vehicle is moving over the ground
- For other vehicles, such as airborne and underwater, other sensors must be employed

Sensing

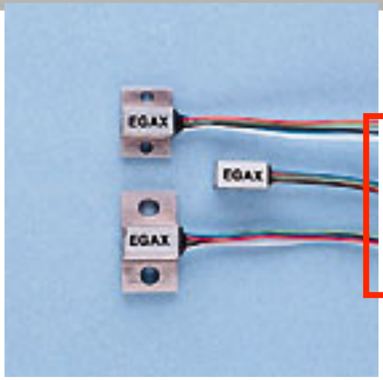
- In the last two lectures, we have looked at sensors suitable for observing the environment around a vehicle. These have included vision and laser, although we have also touched on things like radar
- We will now look more closely at sensors suitable for use in navigation

Proprioceptive Sensing

- What quantities might we be interested in measuring?
  - Position
  - Velocity
  - Acceleration
  - Heading
- How can we sense these quantities? In some instances we can observe them directly – in others we must infer them

Acceleration

- Accelerometers used to measure
  - Vibration
  - Accelerations of a moving body
- All accelerometers operate by measuring relative displacement of a small mass constrained within an accelerating case
- An accelerometer' s output is produced by transducing the deflection of the elastic restraint into an electrical signal. The signal is proportional to the displacement of the proof mass
  - Distortion of a piezo
  - Motion of a cantilever
  - Strain on mass restraints



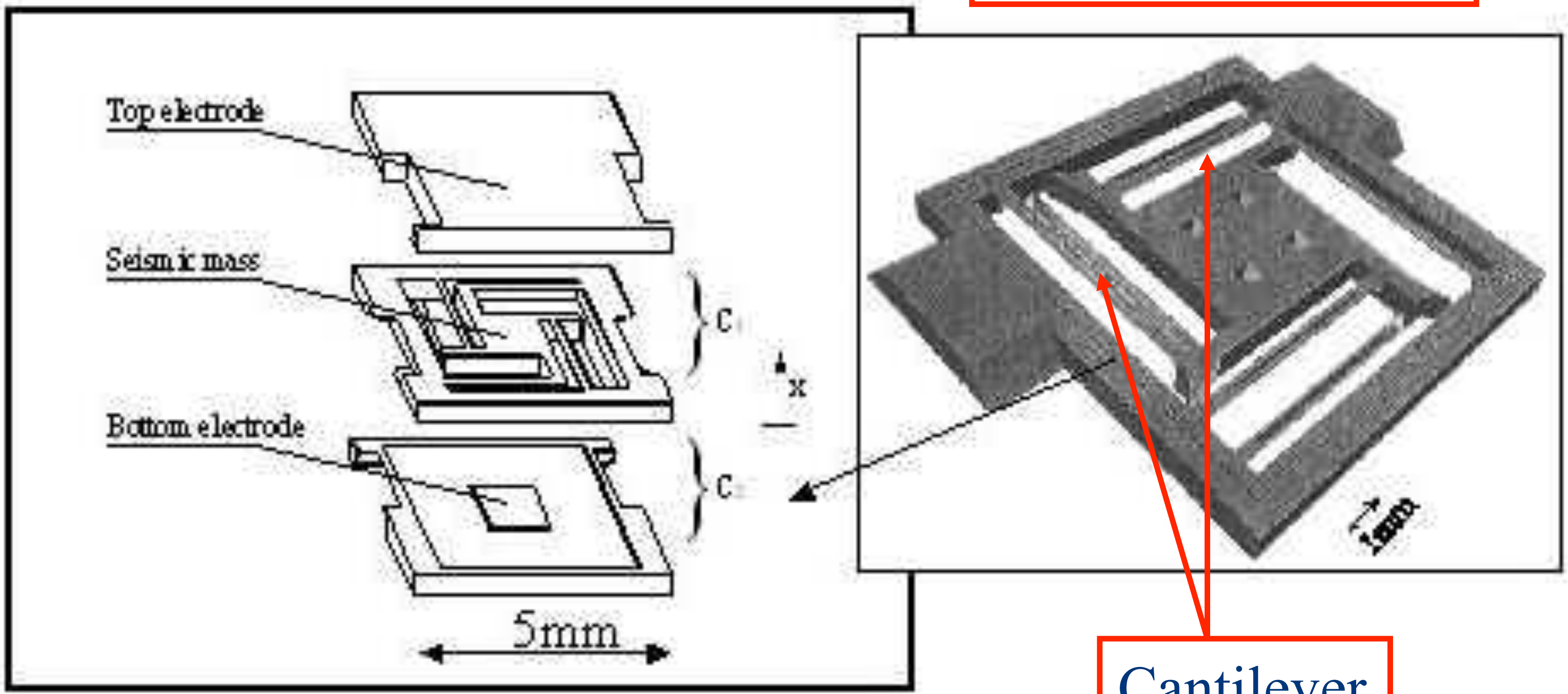
Single Axis, 10,000g

Shielded for Severe environment

EMI shielded

Silicon Machined Accelerometers

Used in eg air-bags



Cantilever beams

Accelerometers

Total Force (Newton's Second Law)

$$F - g = m\ddot{x}$$

Specific Force

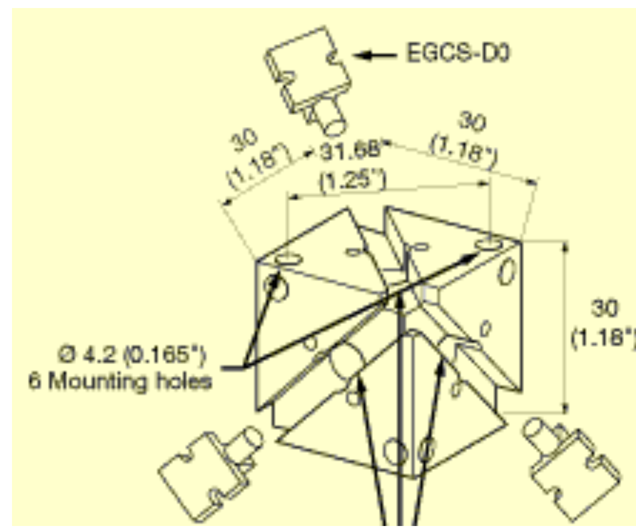
$$\frac{F}{m} = \ddot{x} + \frac{g}{m}$$

- Accelerometers measure specific force, not acceleration
- When the case is accelerated in zero g, the spring will deflect allowing us to measure the acceleration.
- When the case is placed upright on a table, it will measure the influence of gravitation because the spring will deflect with the weight of the mass.
- The deflection of the elastic restraint is directly influenced by the total force on the mass and not only by its acceleration.
- When measuring arbitrary accelerations in a gravitational field, the output is a linear combination of the two effects and the contribution of each cannot be deduced from the accelerometer output alone

Tri-axial Accelerometers

- Triaxial accelerometers used in mobile systems
  - In high-performance cars
  - Inside rotating elements of turbines
  - In aircraft elements
- Can be used to estimate gravity vector
- Provide vibration information
- Provide short-term position data

Triple axis
Accelerometer
For racing cars



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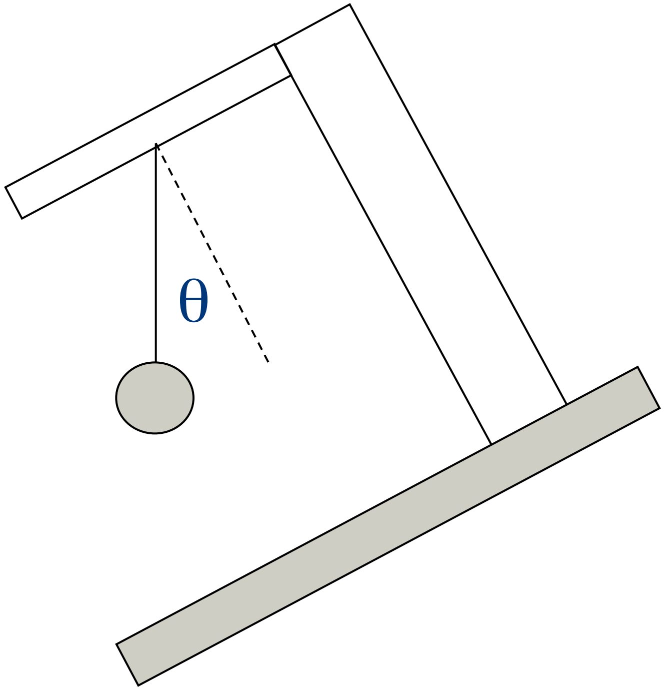
Inclinometer

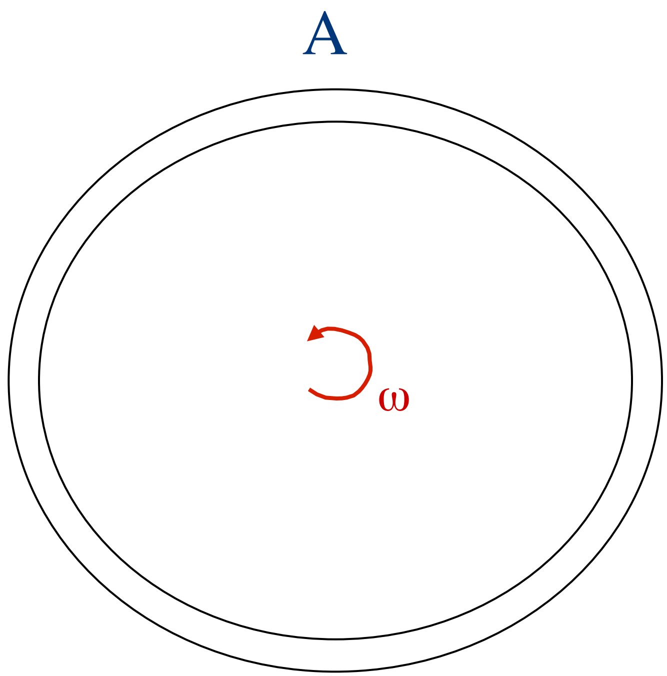


- An inclinometer measures the inclination of a body by estimating the gravity vector
- In an analogous manner to which gravity affects accelerometer readings, accelerations will affect the inclinometer reading

Compass

- A compass measures the local magnetic field
- This can be used to infer the direction of North
- Other sources of magnetic fields must be taken into account
  - Fixed magnetic fields from metals and other sources in the environment. The processes of metal fabrication often result in latent magnetic fields
  - Electromagnetic sources, such as motors. These are much more difficult to account for

Gyroscope



$$t^{+} = \frac{2\pi r + r\omega t_{+}}{c}$$

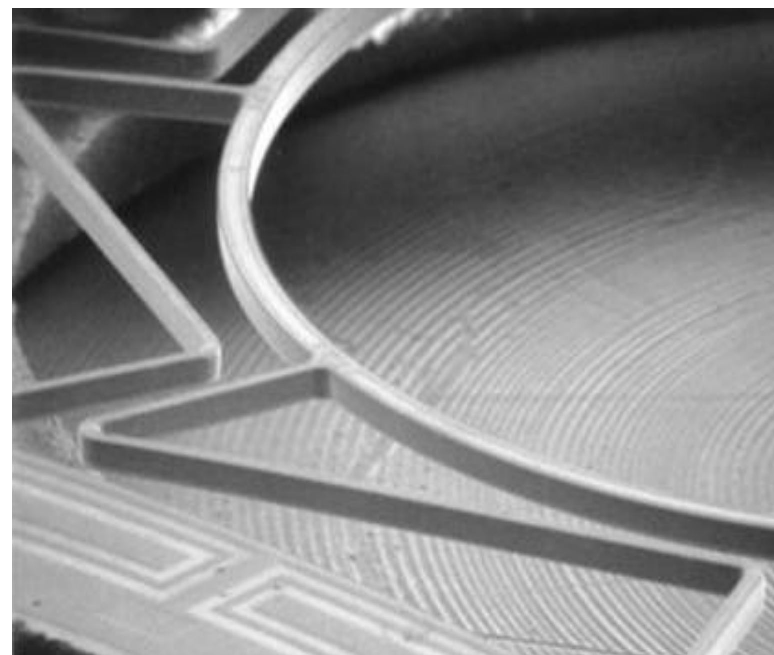
$$t^{-} = \frac{2\pi r - r\omega t_{-}}{c}$$

$$\Delta t \simeq \frac{4\pi r^{2}\omega}{c^{2}}$$

- A gyroscope measures the rotational rate of a body
- Early gyros were mechanical and relied on sensing the torques induced by a change of a spinning mass
- More recent gyros rely on optical properties
  - Ring laser gyros convert differences in arrival time into beat frequency
  - Fiber optic gyros increase the pathlength by using coils of fibre optic cable

Silicon Gyroscopes

- Structural arrangement of silicon which records centrifugal acceleration and thus angular speed
- Use strain-gauge bridges and/or piezo structure to record deformations
- Multiple component elements to calibrate other accelerations



Inertial Systems

- Together in an orthogonal arrangement of accelerometers and gyroscopes, these comprise an inertial measurement unit (IMU)
- An IMU that is used for navigation is called an inertial navigation system (INS)
- These are widely used in aircraft and missile navigation and guidance. They are also seeing increasing integration into robotic and other autonomous guidance systems

Aerospace INS

Ballistic Missile

Aircraft

http://www.littongcs.com/products/2guidance/space/overview.html

Tachometers

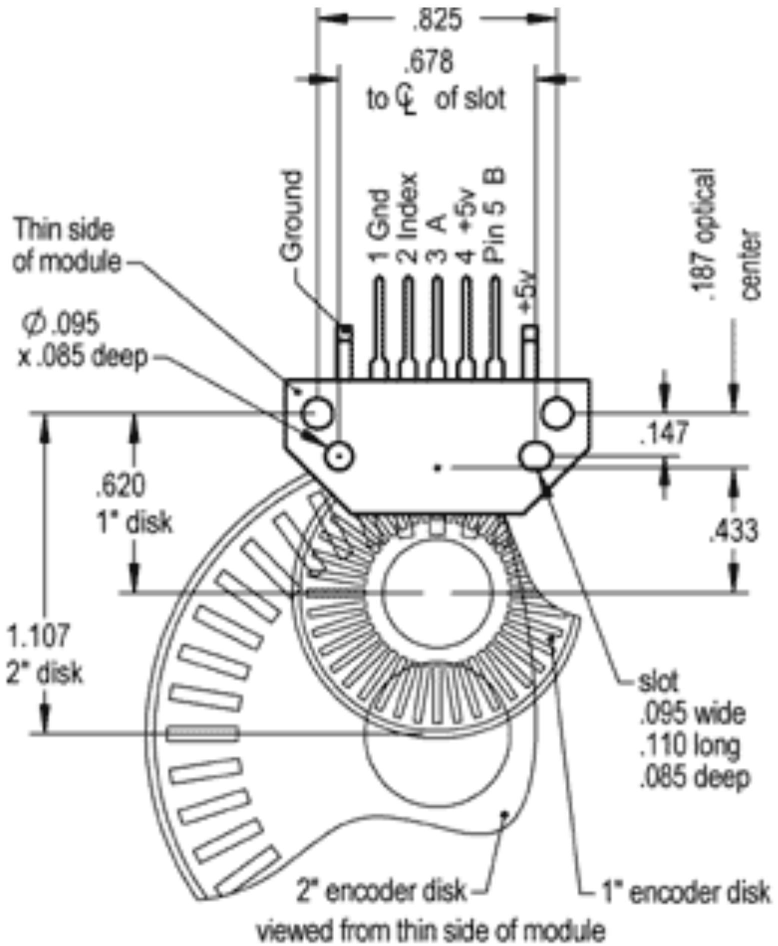
- Measurement of rotary speed using a DC generator
- Essentially a motor running in reverse
- Used to be common to have these attached to motors to enable direct analog feedback
- Much less common now with digital control (use incremental encoders)

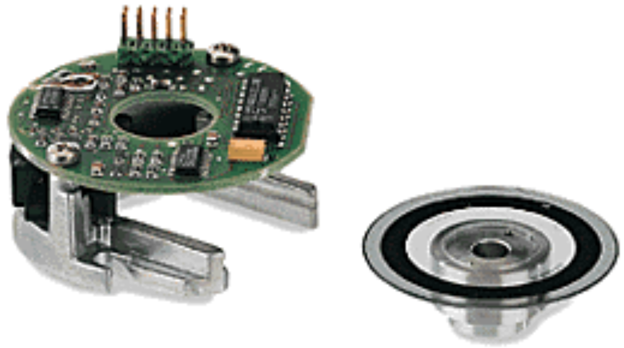
Tacho generator for large industrial plant (GE)

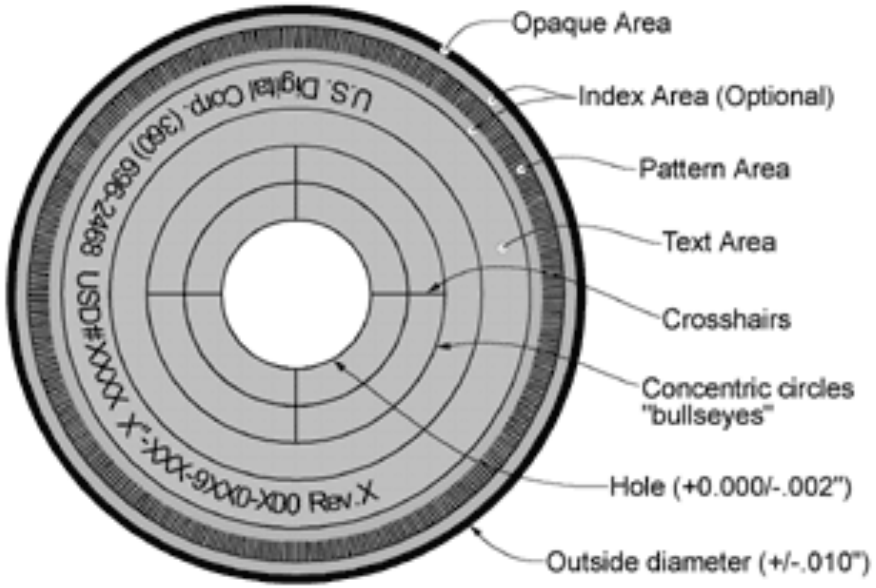
Optical Encoders

- Encoders are digital Sensors commonly used to provide position feedback for actuators
- Consist of a glass or plastic disc that rotates between a light source (LED) and a pair of photo-detectors
- Disk is encoded with alternate light and dark sectors so pulses are produced as disk rotates

Encoder Internal Structure







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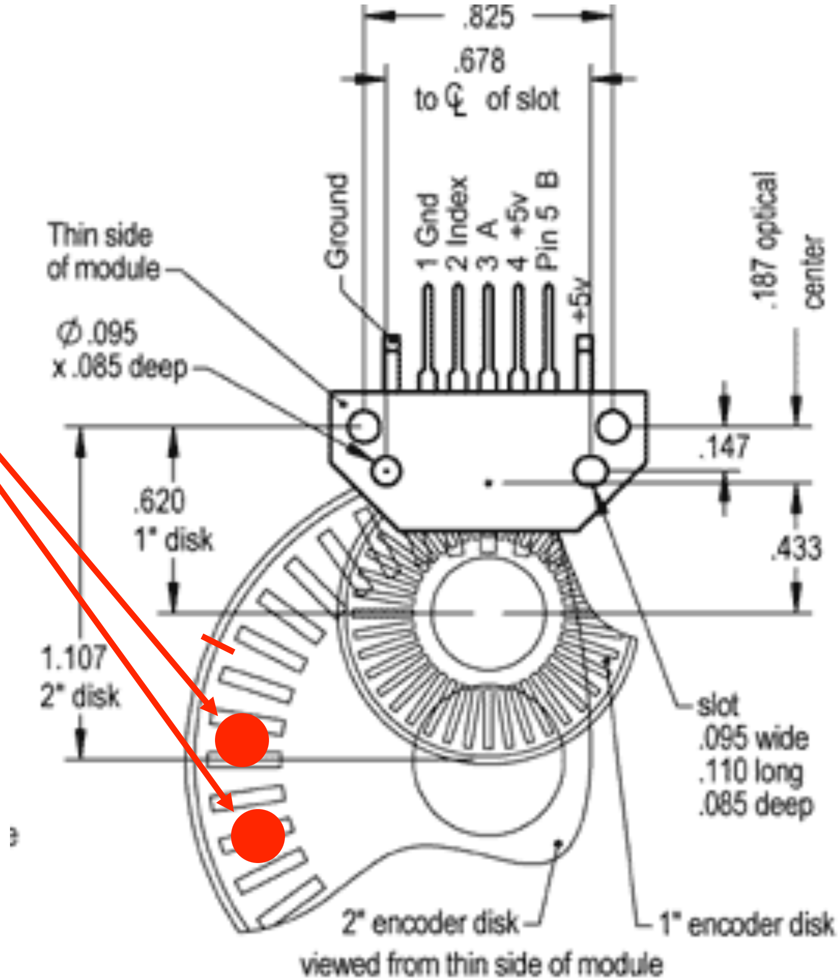
Incremental Encoders

- Pulses from leds are counted to provide rotary position
- Two detectors are used to determine direction (quadrature)
- Index pulse used to denote start point
- Otherwise pulses are not unique

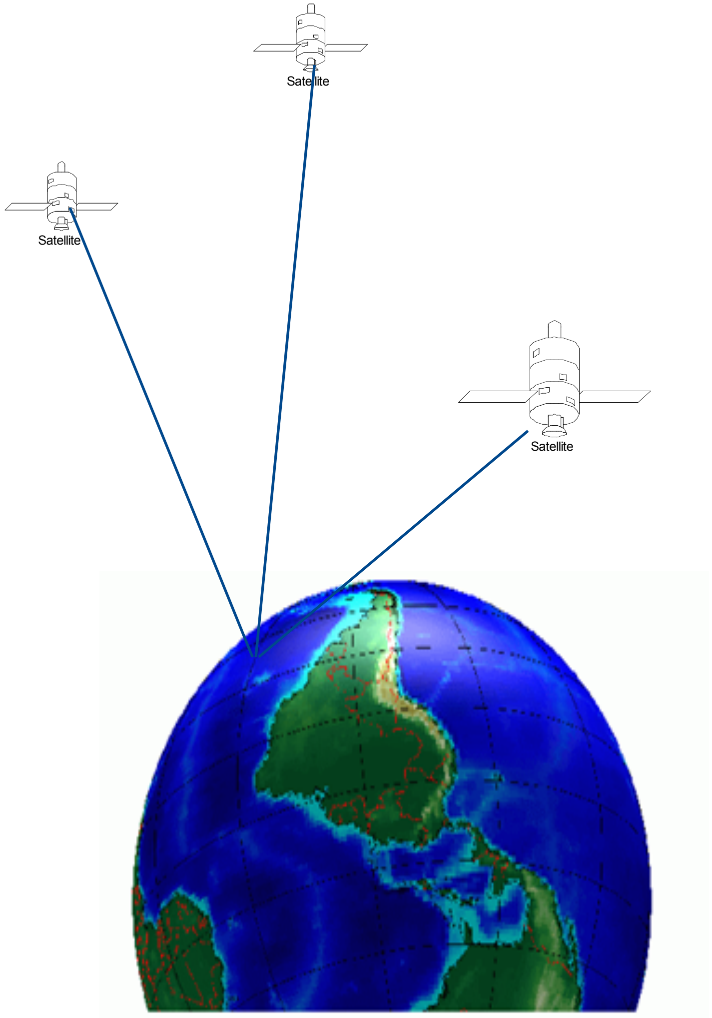


Exteroceptive Sensing

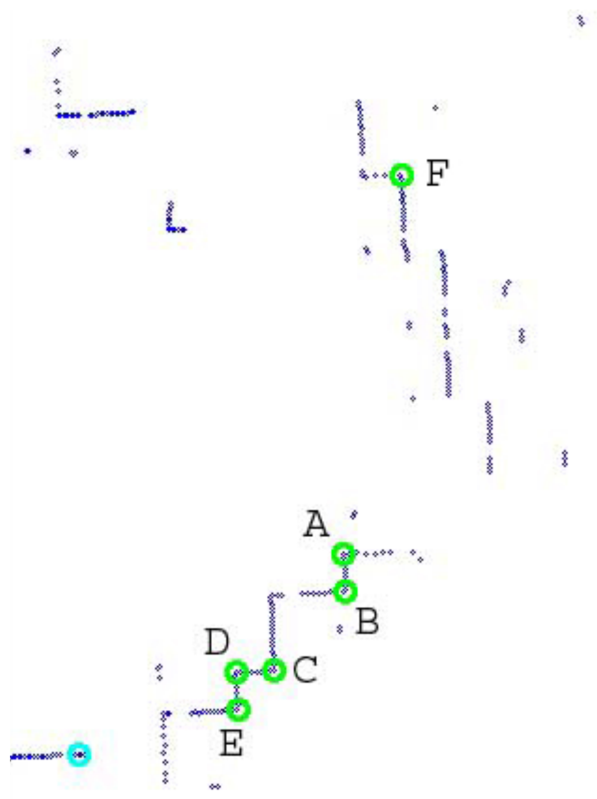
- What quantities might we be interested in measuring?
  - Range
  - Bearing
  - Temperature
  - Light intensity
- How can we sense these quantities? In some instances we can observe them directly – in others we must infer them

GPS

- The Global Positioning System consists of a number of satellites orbiting the earth
- The satellites transmit time coded signals
- Receivers on earth listen for the signal and effectively triangulate position
- Only works when sufficient satellites are in view



Lasers



- We have seen how laser range finders give us access to high resolution range and bearing information about the environment
- We have also looked at methods for identifying features in this data. This includes lines and corners
- If we have a map of an environment we can match observations against the map to provide us with positioning information
- Other methods exist which use the raw laser data for localisation

Vision

- We have examined a few techniques for extracting corners and lines from images
- These features can be used with appropriate camera models to provide observations of elevation and azimuth to these features

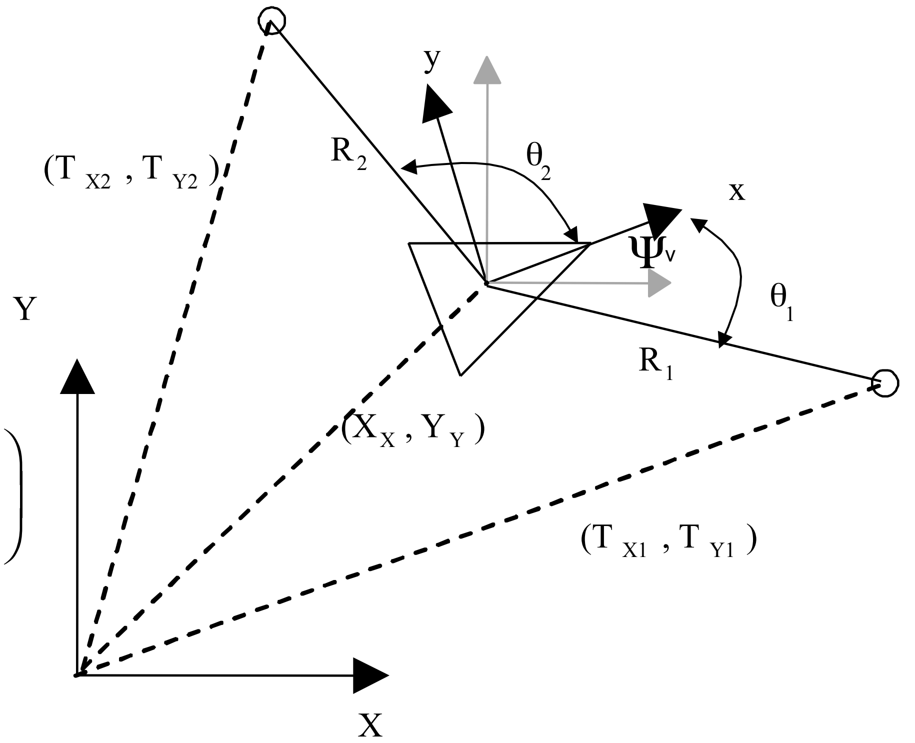
Beacon Based Navigation

- What if I knew the location of some features in the environment?
- Observations of the relative position between myself and these beacons would tell me something about my own position

$$\psi_v = \tan^{-1}\left(\frac{T_{Y2}-T_{Y1}}{T_{X2}-T_{X1}}\right) - \tan^{-1}\left(\frac{R_2\sin\theta_2 - R_1\sin\theta_1}{R_2\cos\theta_2 - R_1\cos\theta_1}\right)$$

$$X_v = T_{X1} - R_1\cos(\theta_1+\psi_v)$$

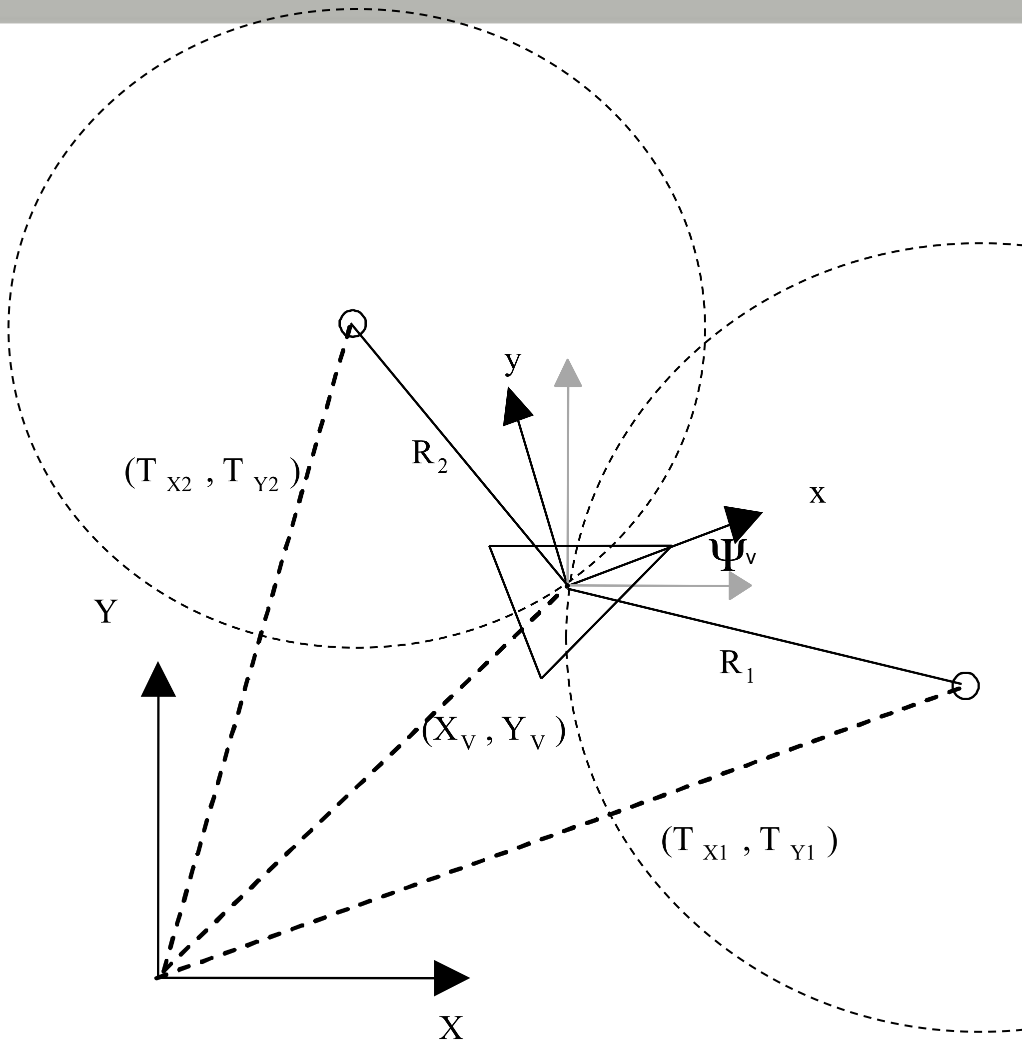
$$Y_v = T_{Y1} - R_1\sin(\theta_1+\psi_v)$$



Beacon Based Navigation

- Other systems provide range or bearing only observations to these beacons
- These can also yield appropriate methods for estimating the position or pose of the vehicle

$$(X_v - T_{X1})^2 + (Y_v - T_{Y1})^2 = R_1^{\,2}$$
$$(X_v - T_{X2})^2 + (Y_v - T_{Y2})^2 = R_2^{\,2}$$



Data Fusion

- Based on the preceding development, we may have a number of sources of information about how a vehicle is moving
- We need a mechanism for putting this information together in a consistent manner
- This is referred to as data fusion

Data Fusion

- In essence, data fusion methods are designed to provide us with the best estimate of the our states of interest x_k given the information available to us

$$P(x_k \mid Z^k, U^k, x_0)$$

where

  - x_k is the state at time k
  - Z^k is a sequence of observations up to time k
  - U^k is a sequence of actions up to time k
  - x_0 is the initial state
- How *best* is defined depends on the situation. We also need to make decisions about how to model any potential errors in the sensors

The Estimation Process

- Recursive three stage update procedure

① Prediction

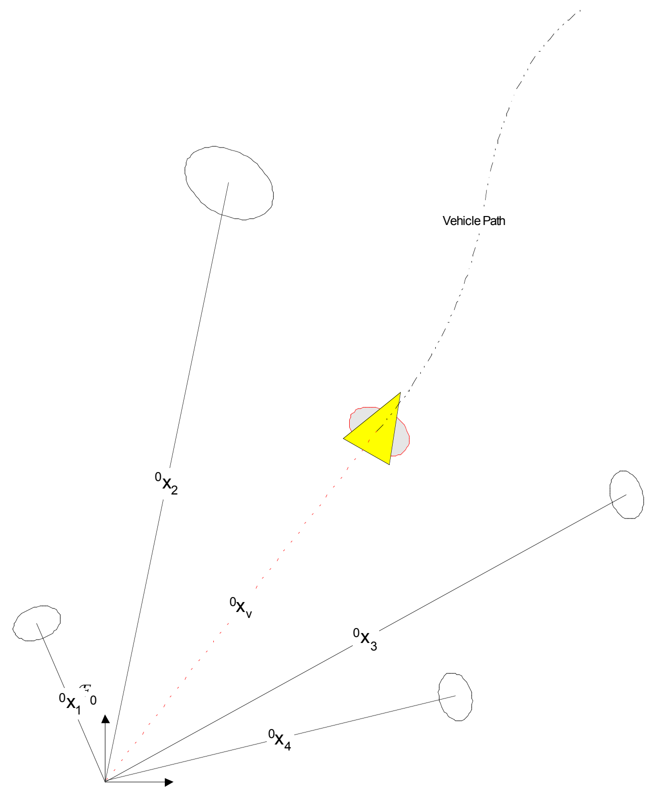
Use vehicle model to predict vehicle position

② Observation

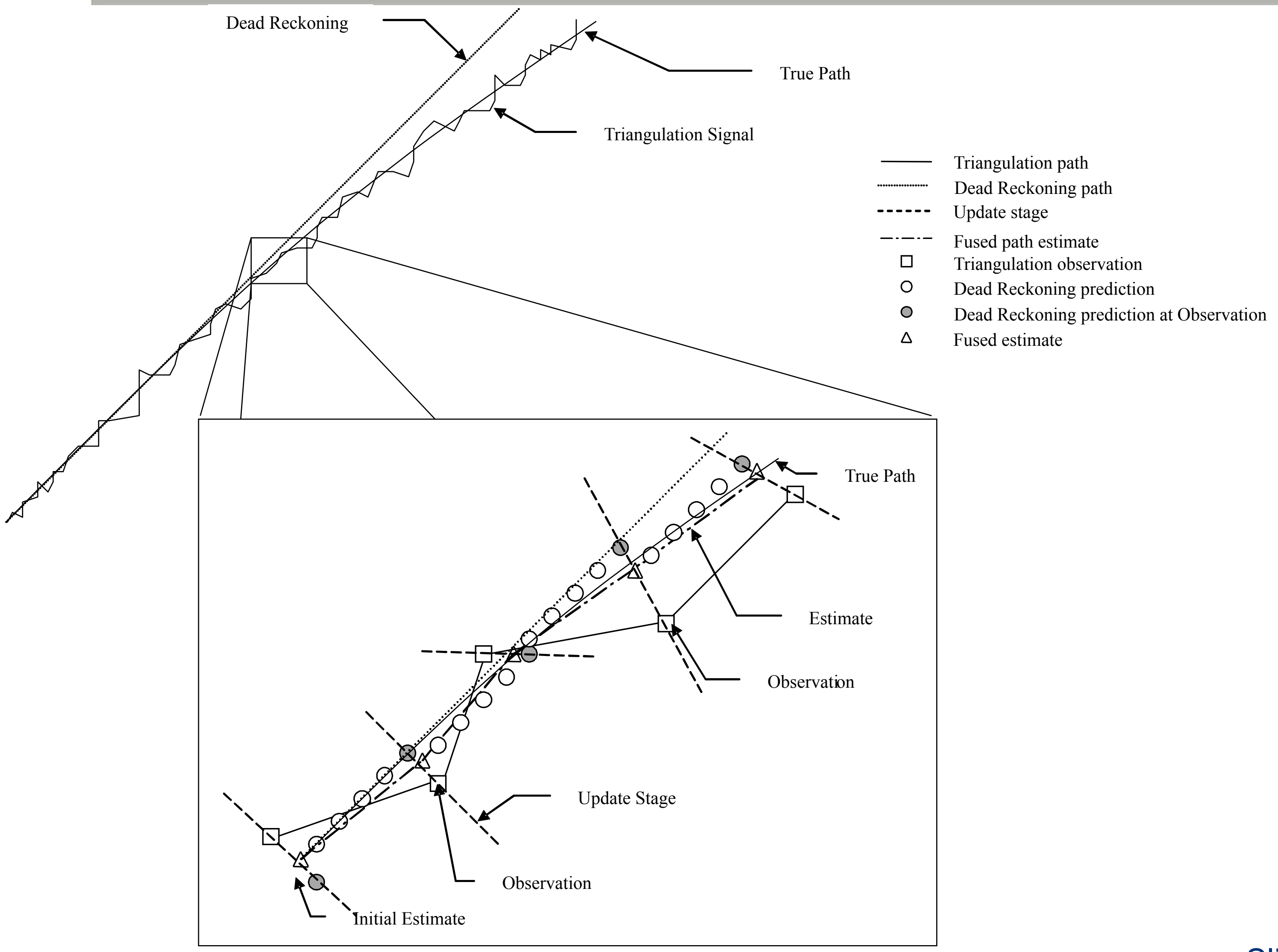
Take feature observation(s)

③ Update

Validated observations used to generate optimal estimate



Data Fusion



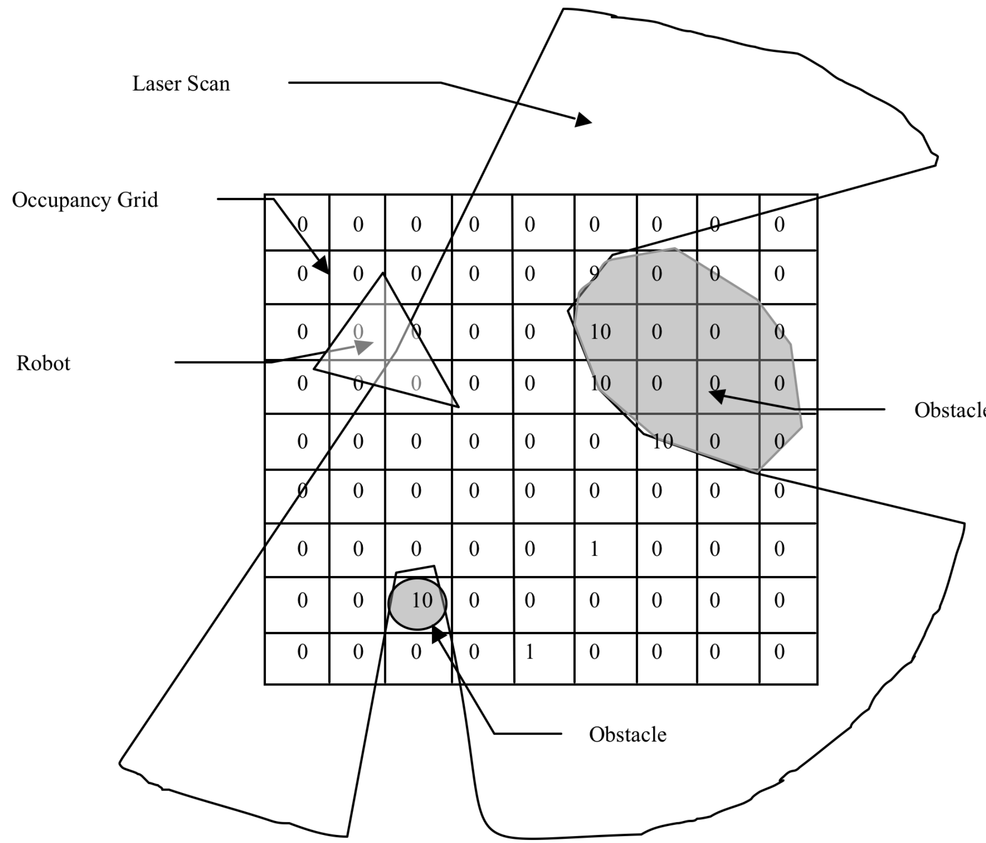
Dead Reckoning
True Path
Triangulation Signal
Triangulation path
Dead Reckoning path
Update stage
Fused path estimate
Triangulation observation
Dead Reckoning prediction
Dead Reckoning prediction at Observation
Fused estimate
True Path
Estimate
Observation
Update Stage
Observation
Initial Estimate

Mapping

- Assuming that we know where the vehicle is, what can we do?
- We might wish to build a map of the environment in which the vehicle is moving
- What will be in this map?
- This will depend on the requirements of the application

Occupancy Grid

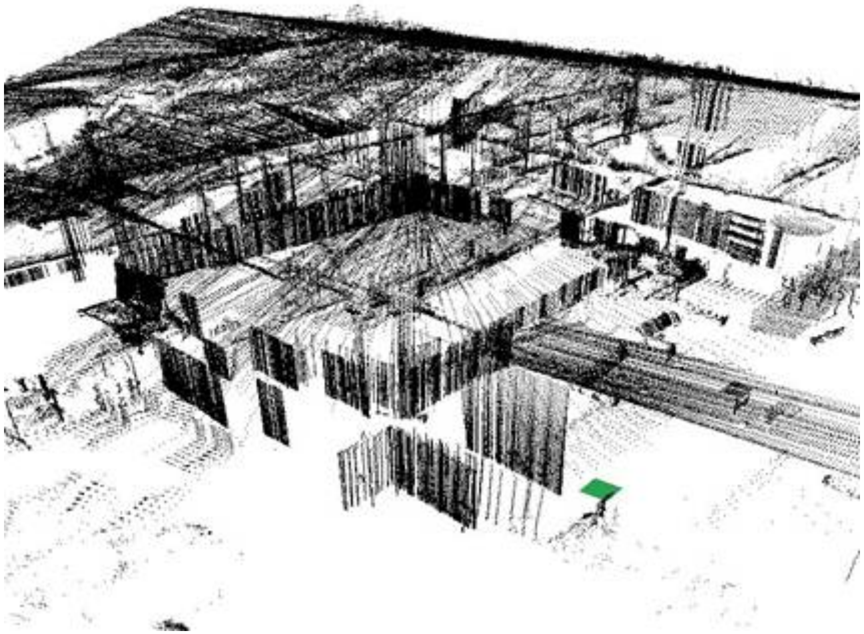
- A simple approach to mapping is to discretize the environment and map occupied and free space

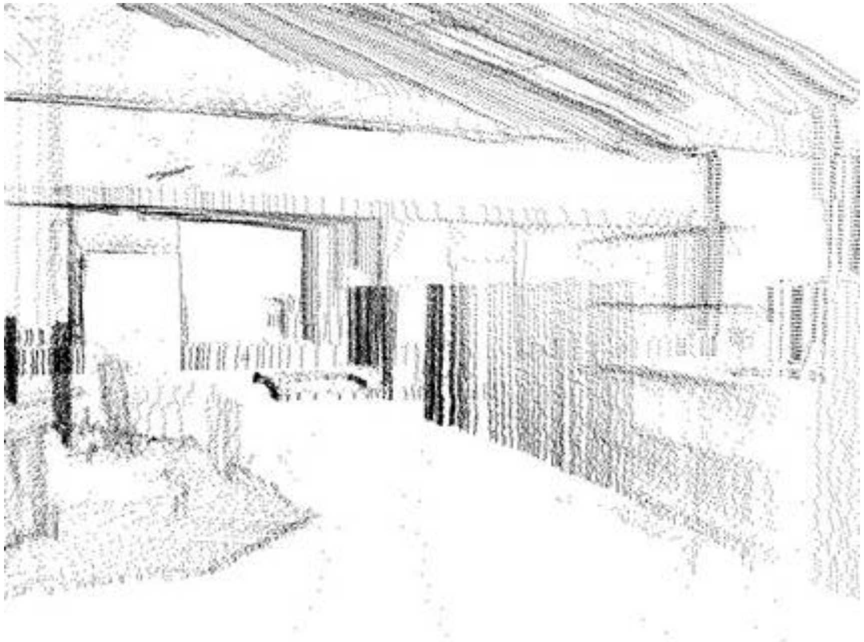


3D Mapping

- We might wish to generate a richer description of an environment
- 3D models can be built using a small indoor robot
- We are looking at methods for building more compact models of this data

3D Point Set





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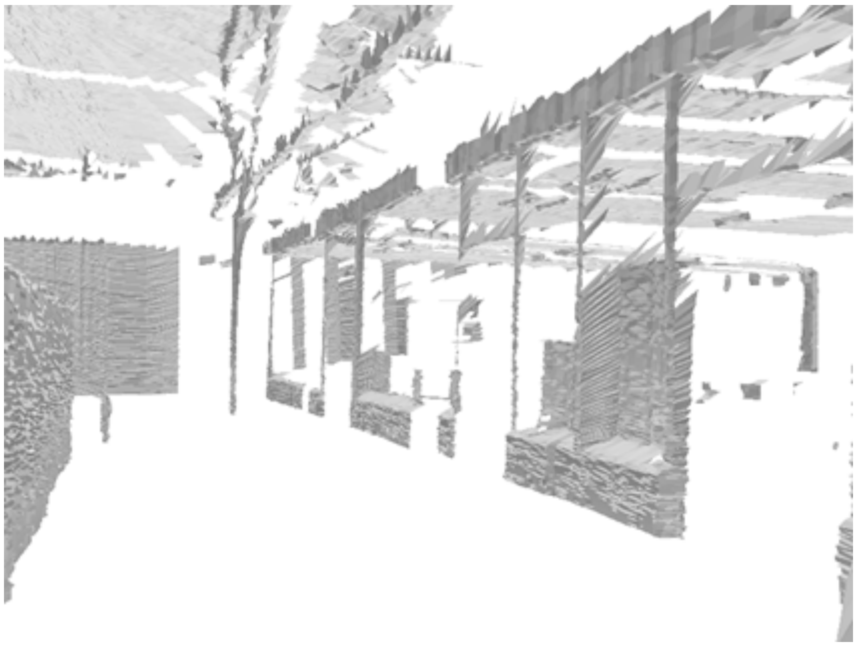
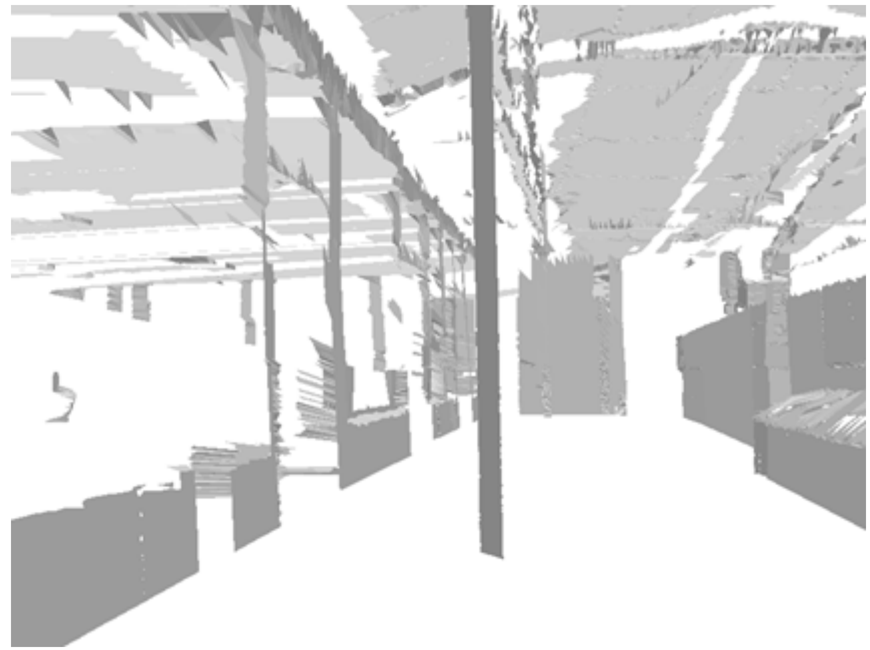
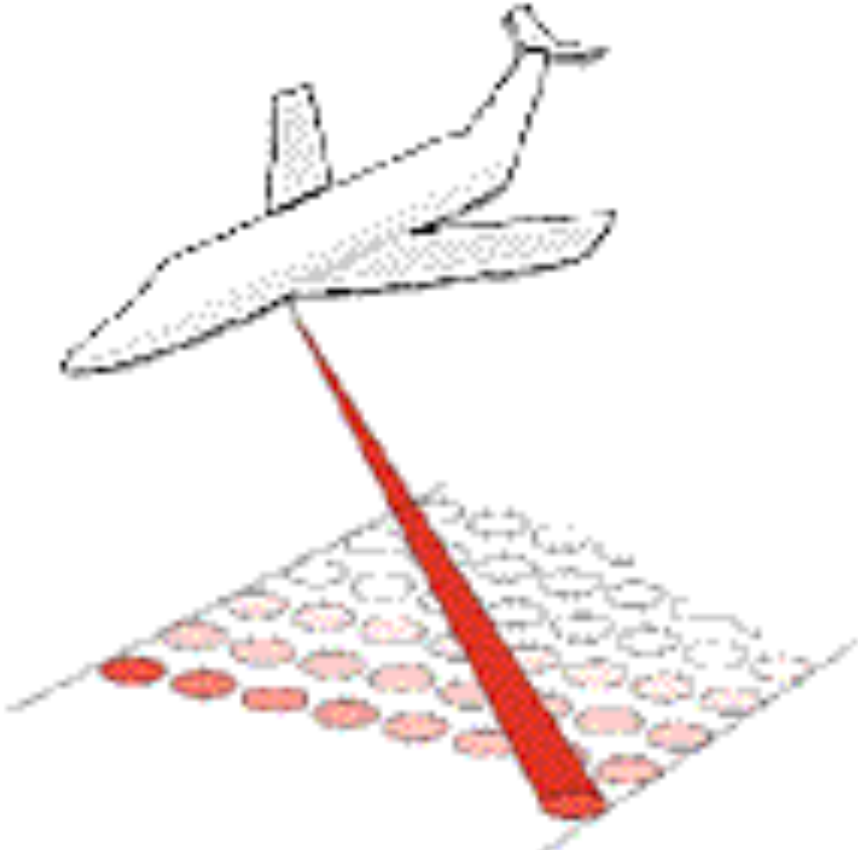
3D Plane Fitting





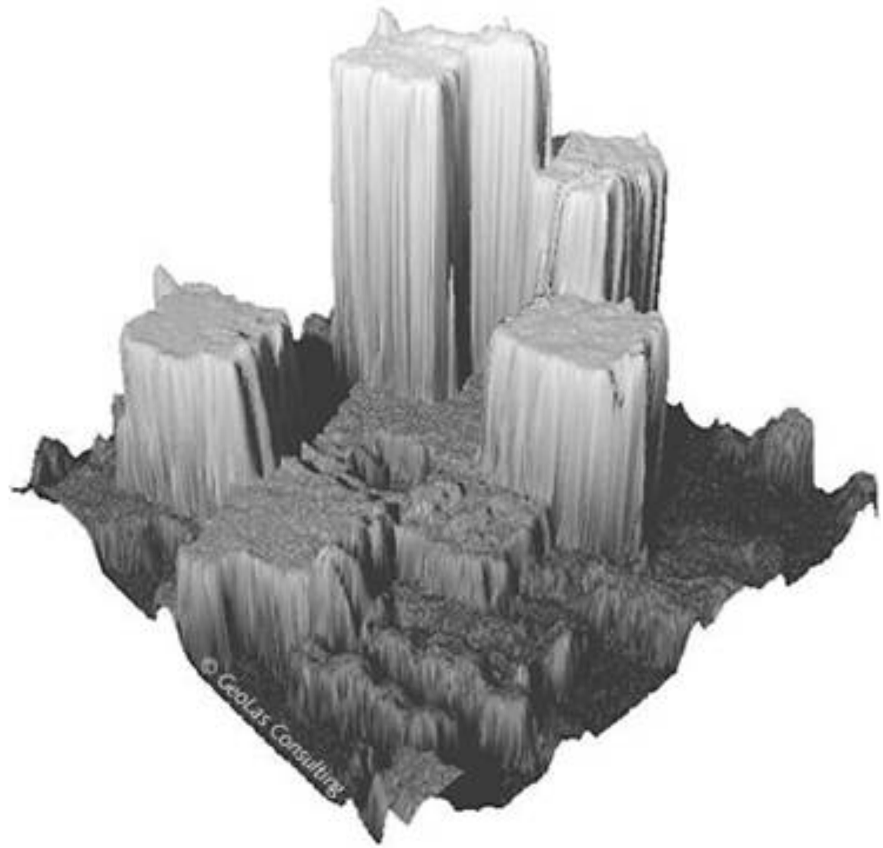
IMAGING LASER ALTIMETRY

- LASER AND RADAR ALTIMETERS USE TIME OF FLIGHT TO MEASURE THE DISTANCE TO THE GROUND.
- HIGH QUALITY IMAGES ARE PRODUCED BY COMBINING ACCURATE HEIGHT MEASUREMENTS WITH DGPS POSITIONING.

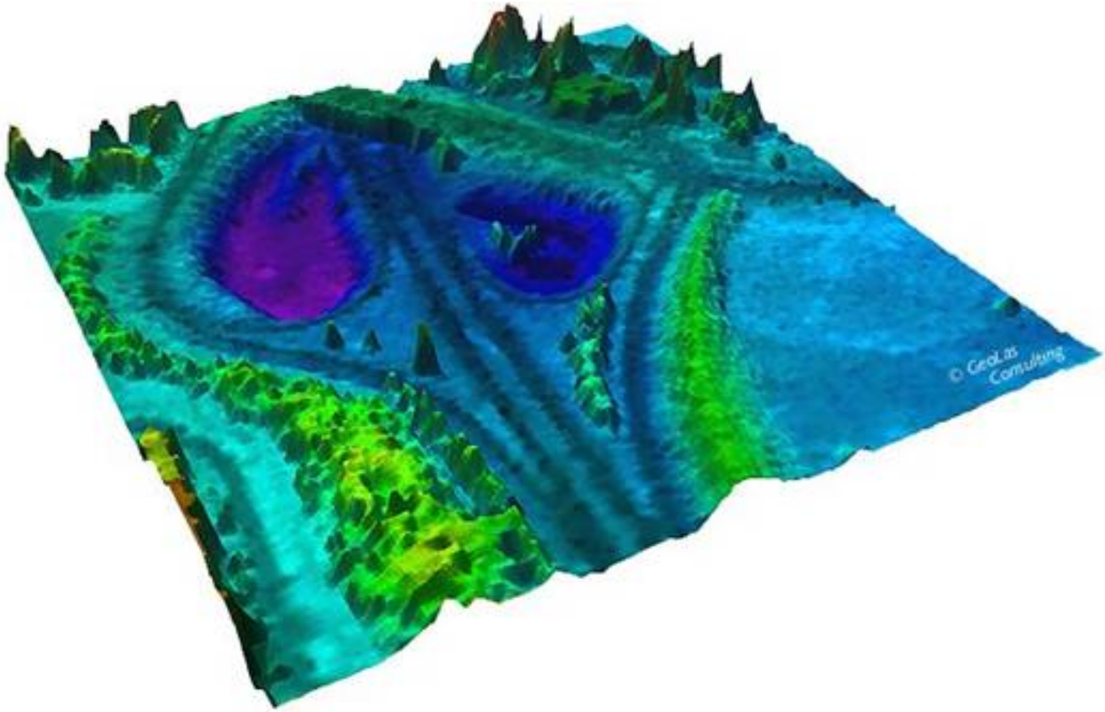


IMAGING LASER ALTIMETRY

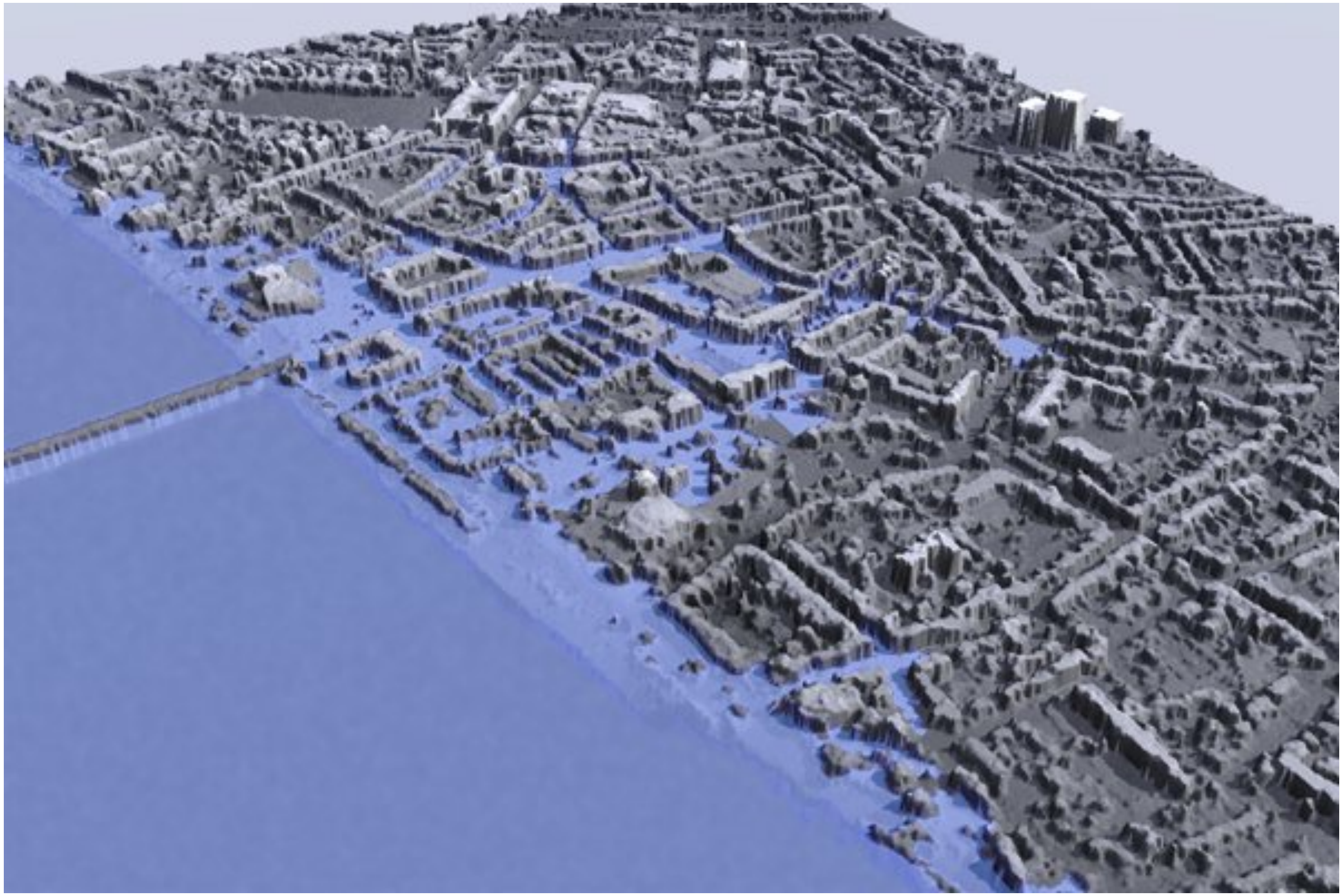
BUILDINGS



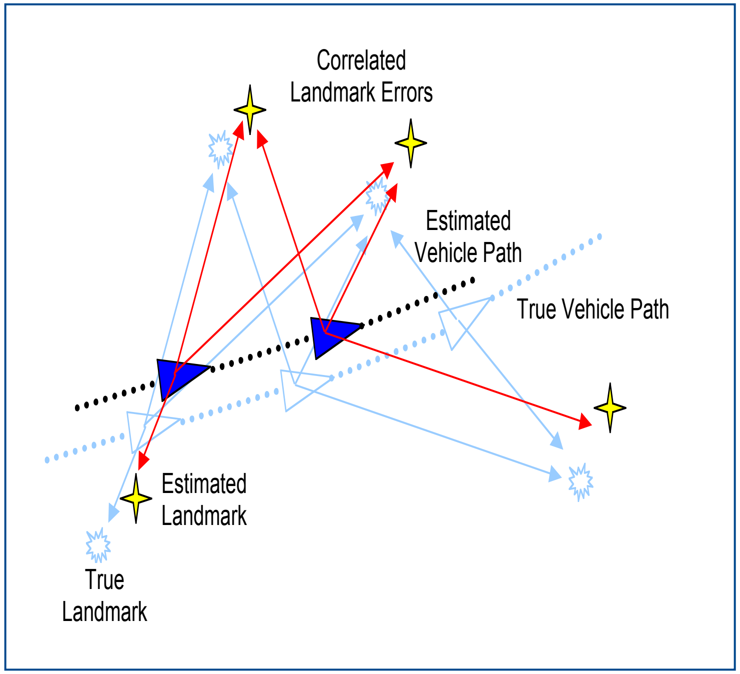
IMAGING LASER ALTIMETRY
HIGHWAY



IMAGING LASER ALTIMETRY
BONN FLOODED BY THE RHINE



The SLAM Problem



- Simultaneous Localisation and Map Building (SLAM)
- Start at an unknown location with no a priori knowledge of landmark locations
- From relative observations of landmarks, compute estimate of vehicle location and estimate of landmark locations
- While continuing in motion, build complete map of landmarks and use these to provide continuous estimates of vehicle location

The Estimation Process

- Recursive three stage update procedure

① Prediction

Use vehicle model to predict vehicle position

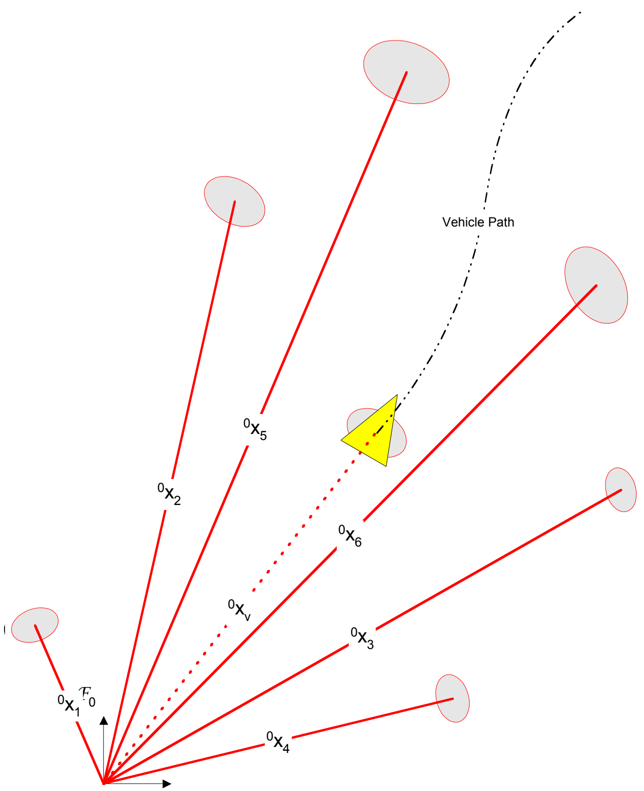
② Observation

Take feature observation(s)

③ Update

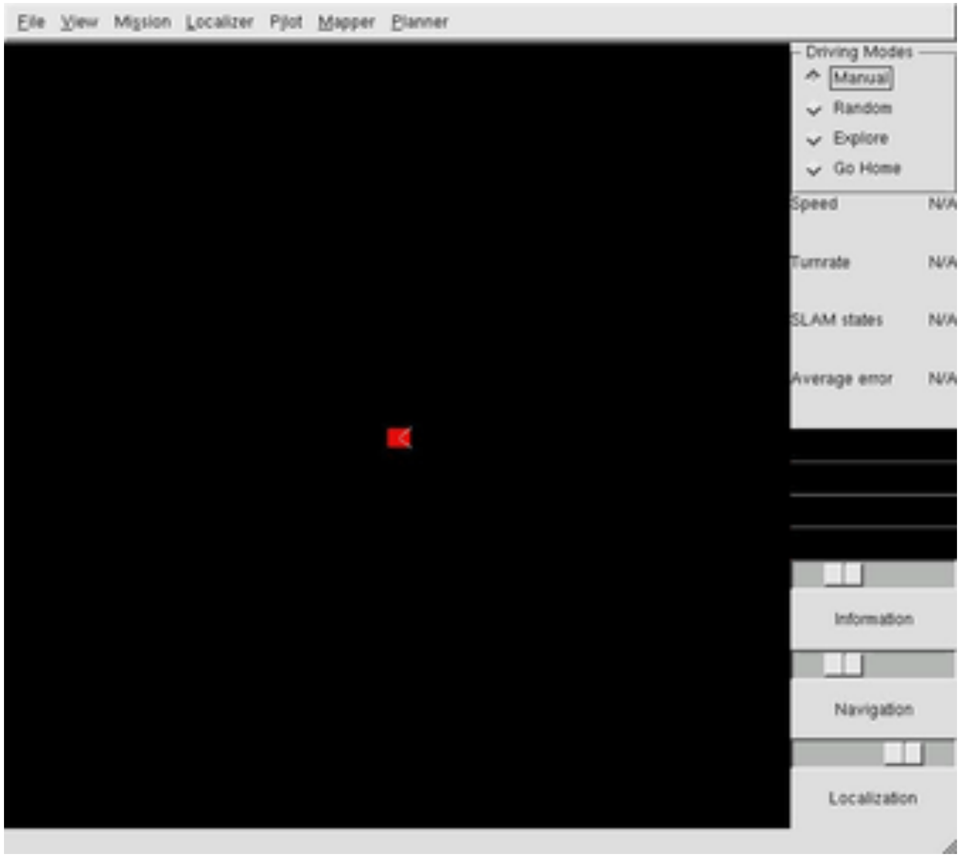
Validated observations used to generate optimal estimate

Initialise new target

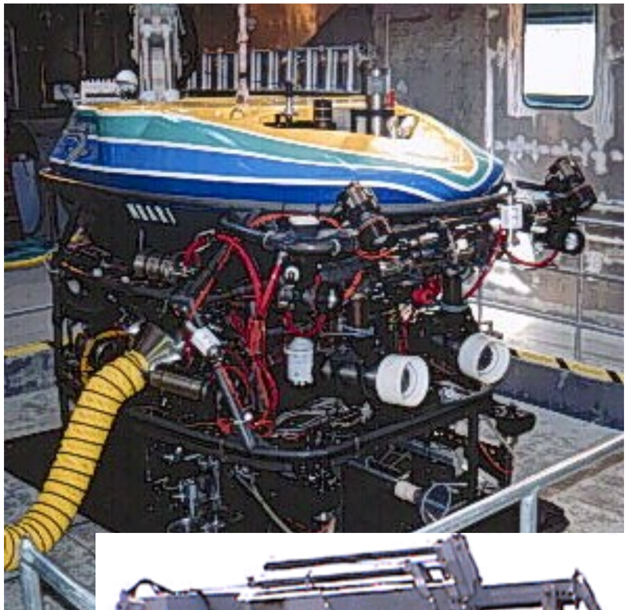


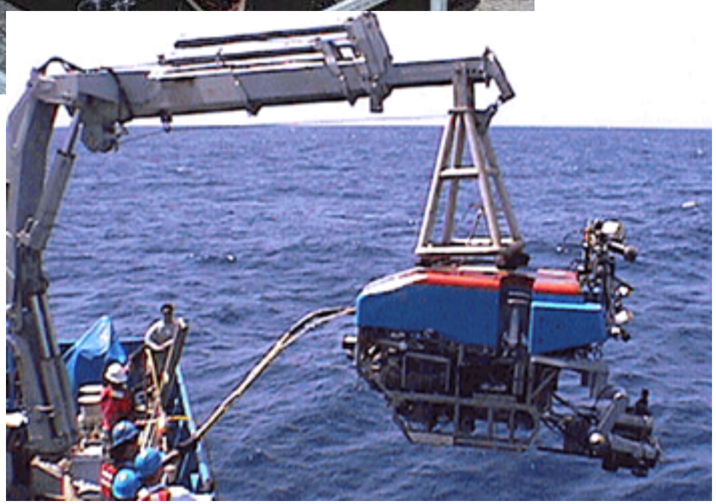
Algorithms for Mapping and Exploration

- Building Maps
  - Unknown Environment
  - Sensing and navigation
  - Locating areas of interest
- Applications
  - Security
  - Tour Guide
  - Domestic



Underwater Vehicles

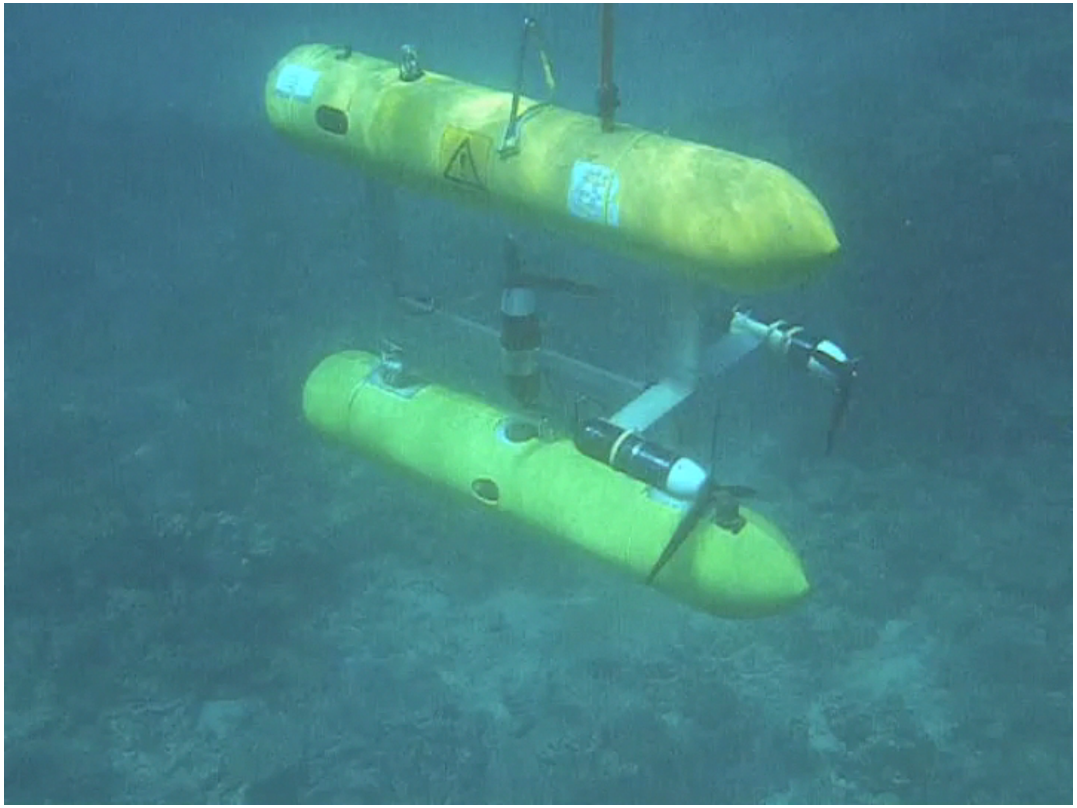




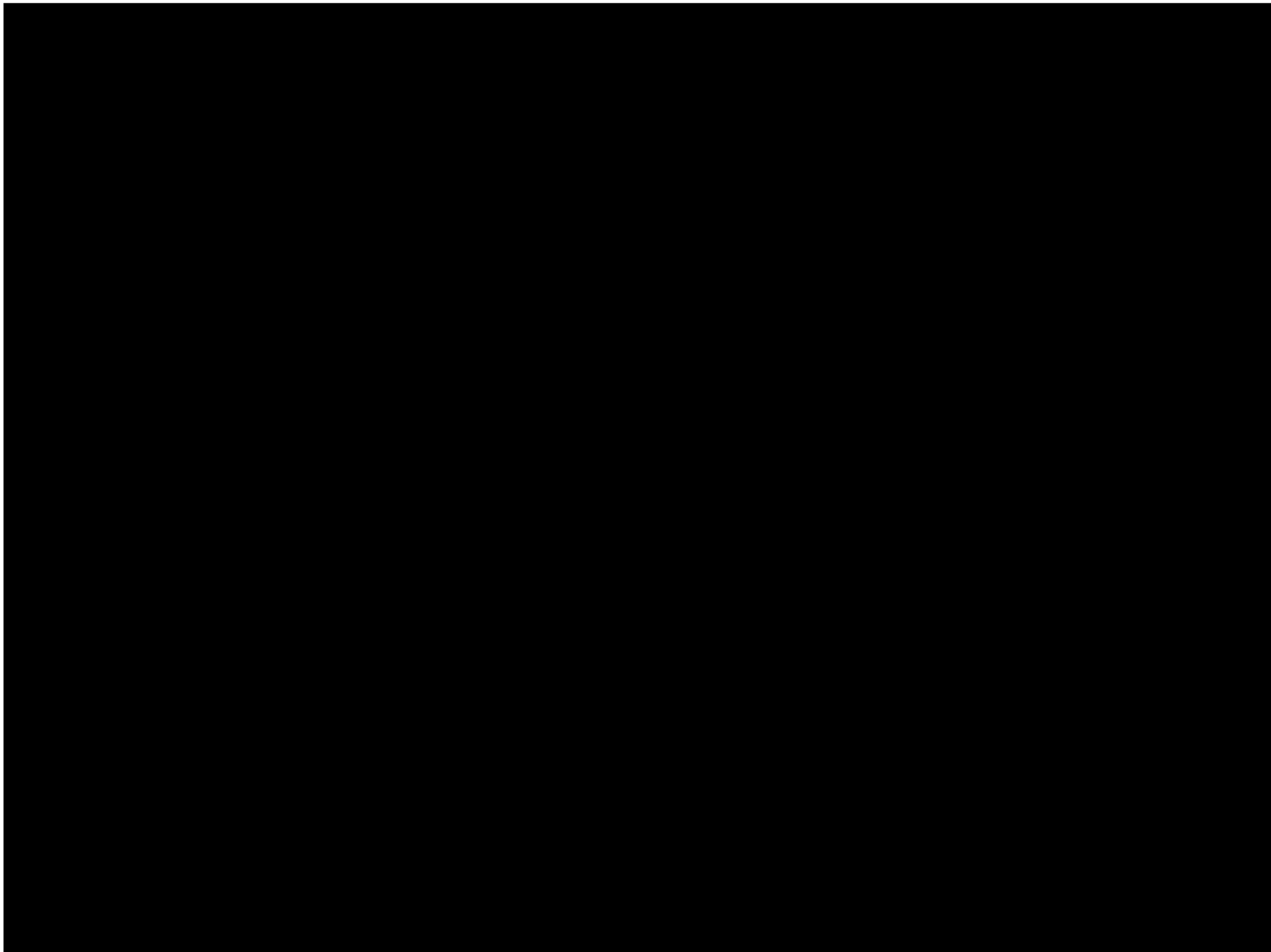
- GPS is not available underwater. The high frequency carrier signal is attenuated very quickly by water
- Many systems rely on acoustic positioning to determine the position of the vehicle
- We are currently developing methods for applying SLAM in highly unstructured underwater environments

Autonomous underwater vehicle

- Flexible, mobile, high resolution data collection device
- Sensors include
  - Vision (stereo)
  - Sonar (multibeam, imaging and fwd obstacle avoidance)
  - DVL
  - Compass
  - Pressure
  - Water Chemistry
- Mission Time up to 12 hours

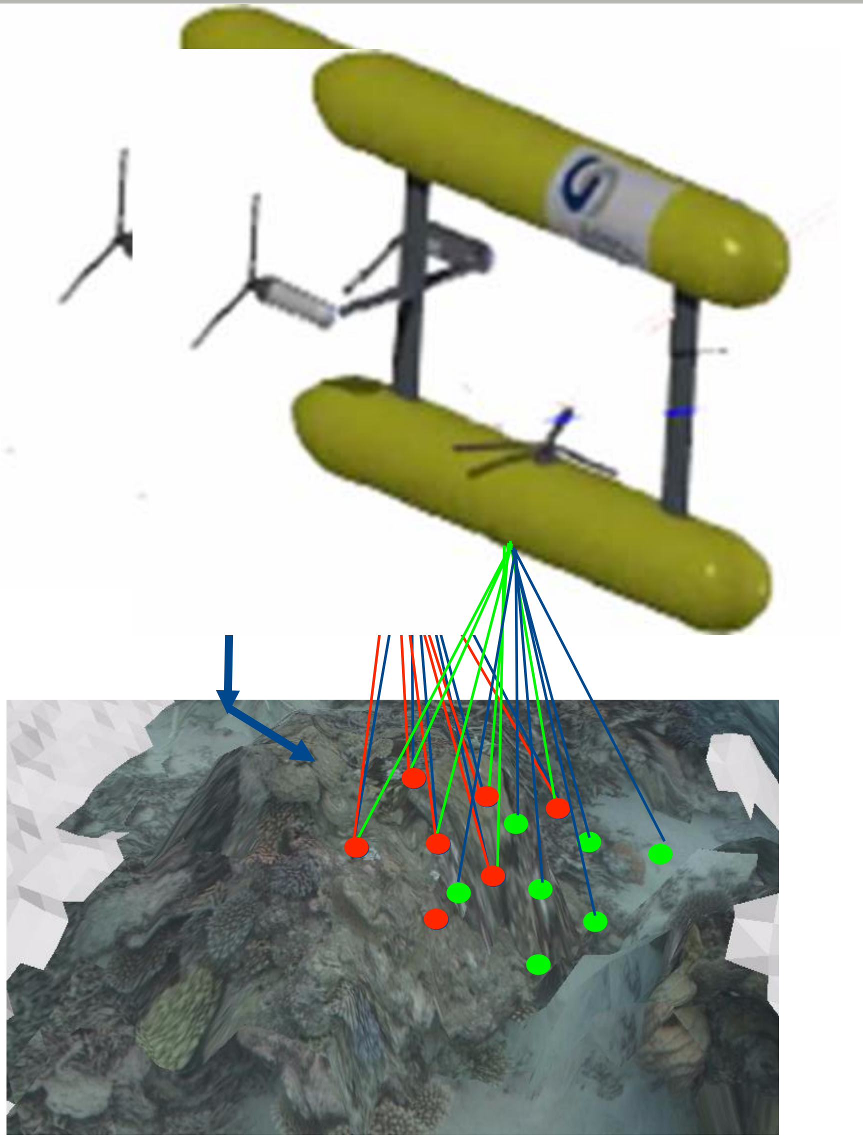


AUV Platform - Imaging



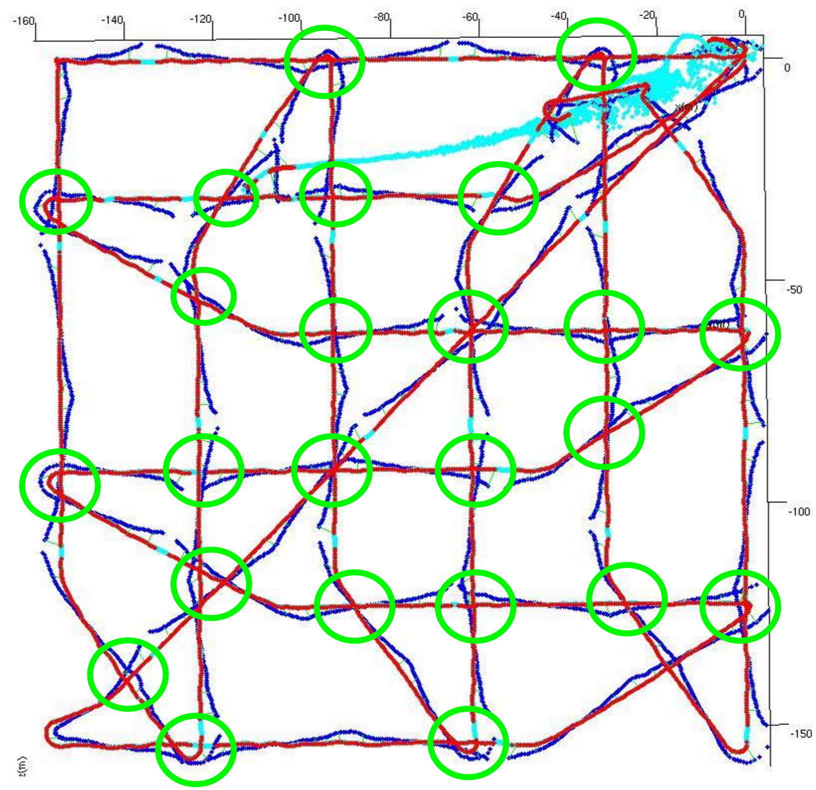
Stereo Odometry

1. Find Features in Left Image
2. Measure Altitude and bound search for features in Right Image
3. Estimate Feature Locations
4. Check consistency with Epipolar Geometry
5. Use DVL displacement to estimate motion to next pair. Find correspondences
6. Confirm consistency using RANSAC
7. Bundle adjustment to refine estimate

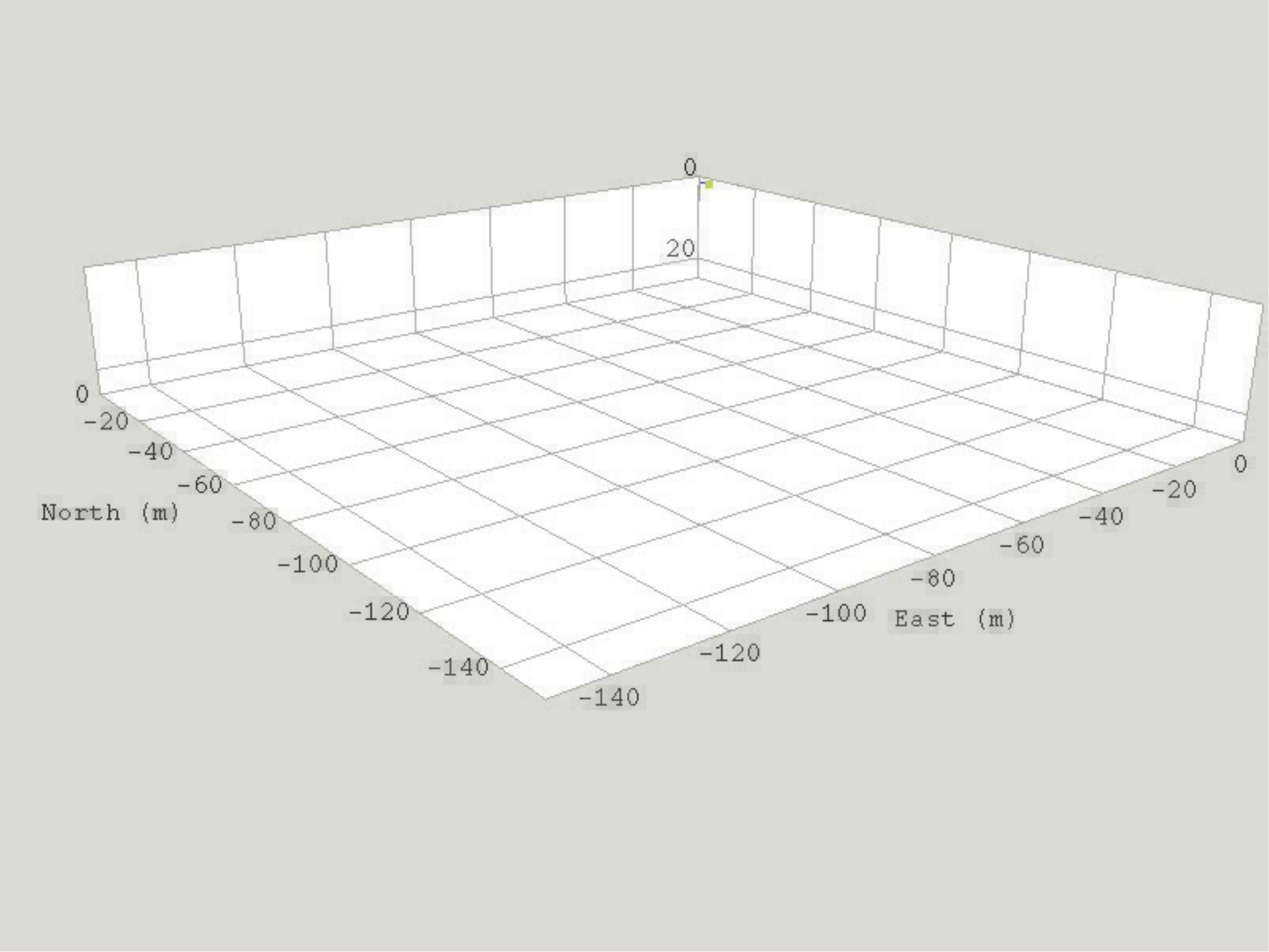


Managing Loop Closure

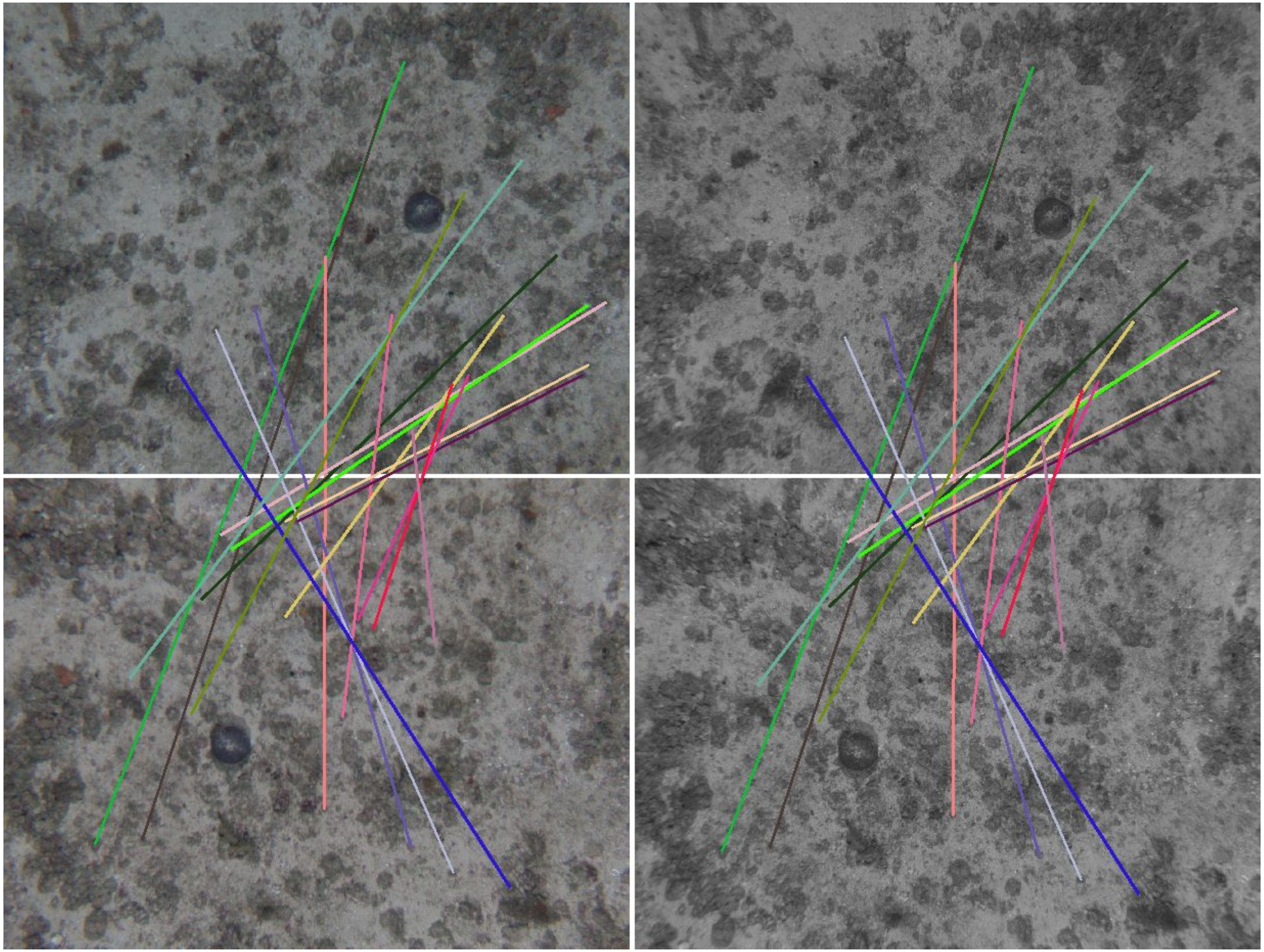
- Given the planned vehicle path, we can manage the search for loop closure based on our estimate of the vehicle pose
- Characterization of the drift rates allows us to bound the search area
- Incorporating the pose estimates into the SLAM state – rather than feature poses – will allow us to manage the complexity of the mapping process



Simultaneous Localisation and Mapping



Simultaneous Localisation and Mapping



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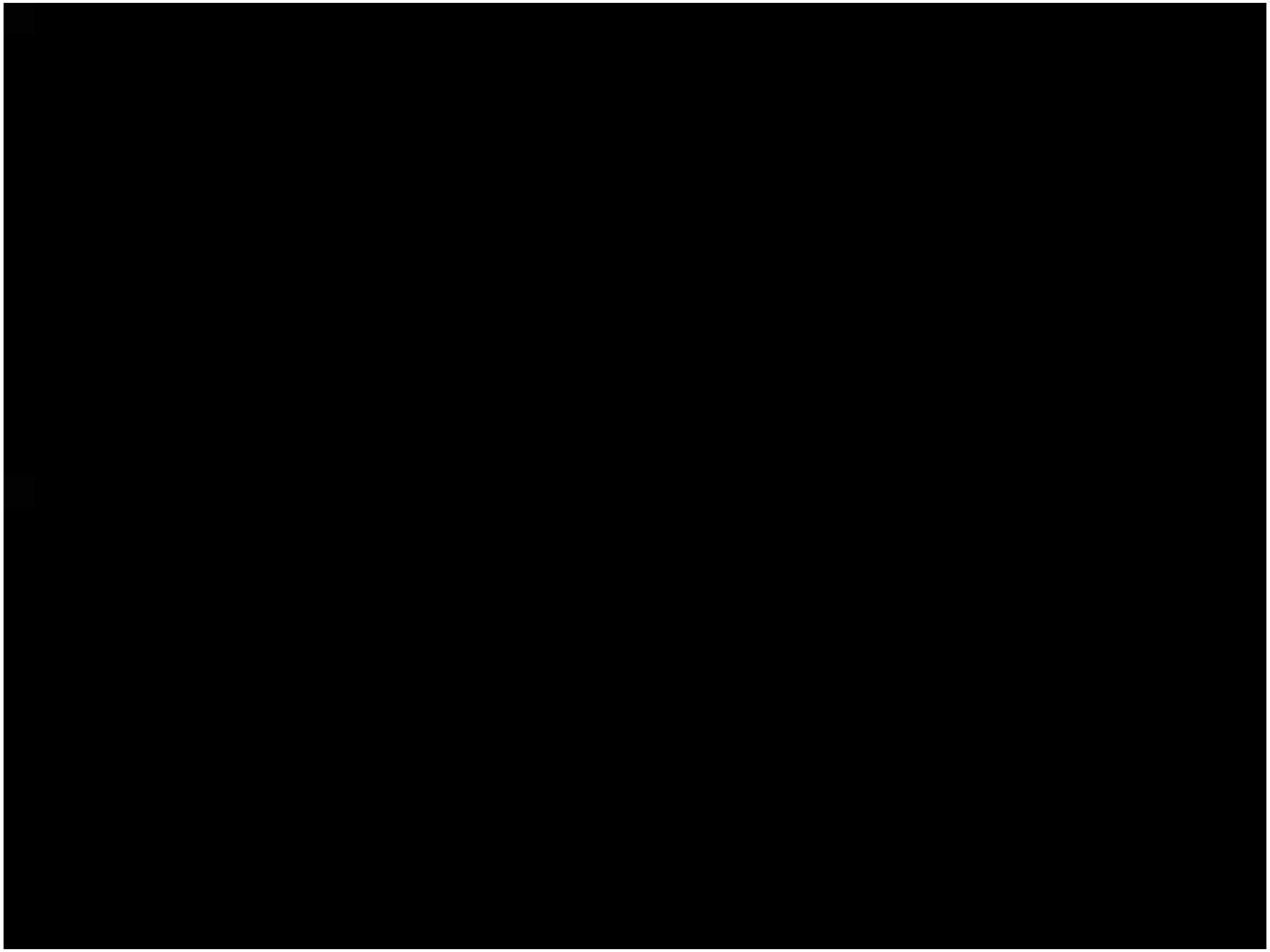
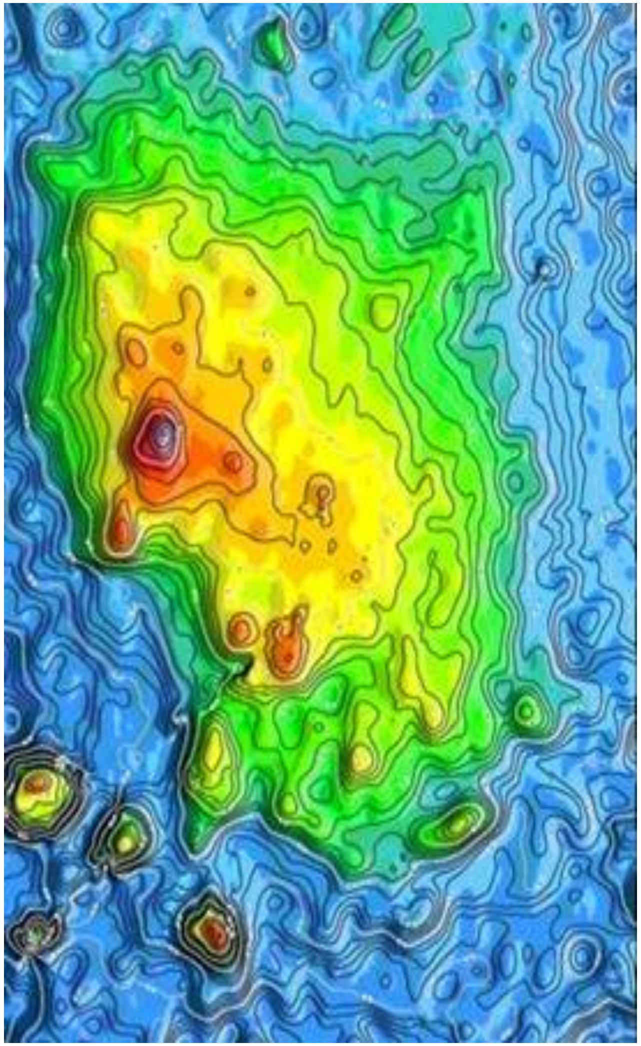
Surveys on the Great Barrier Reef



Terrain Elevation Maps

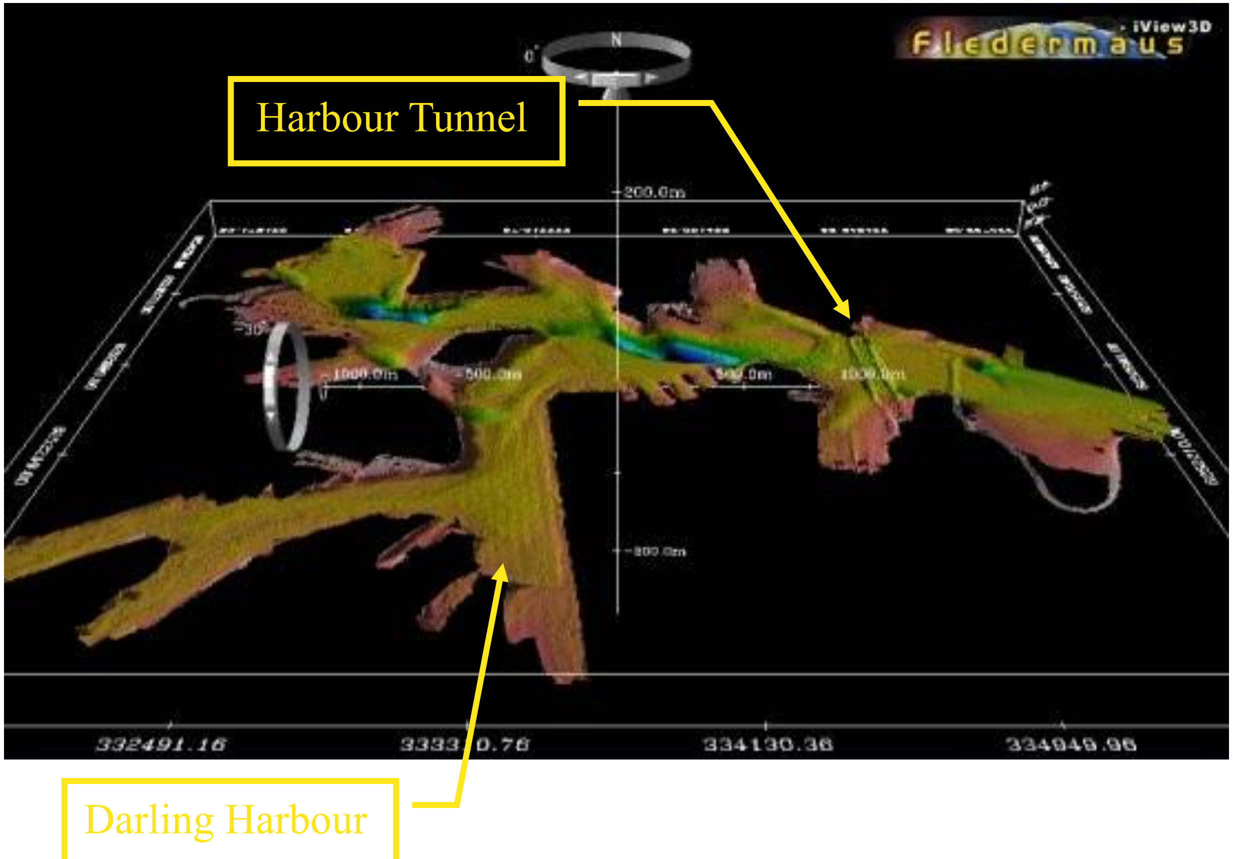
- What about more complex map information?
- Terrain elevation maps available for some deployment areas
- Observations of altitude can be used to bound likely position of vehicle



Sydney Harbour Demonstrations

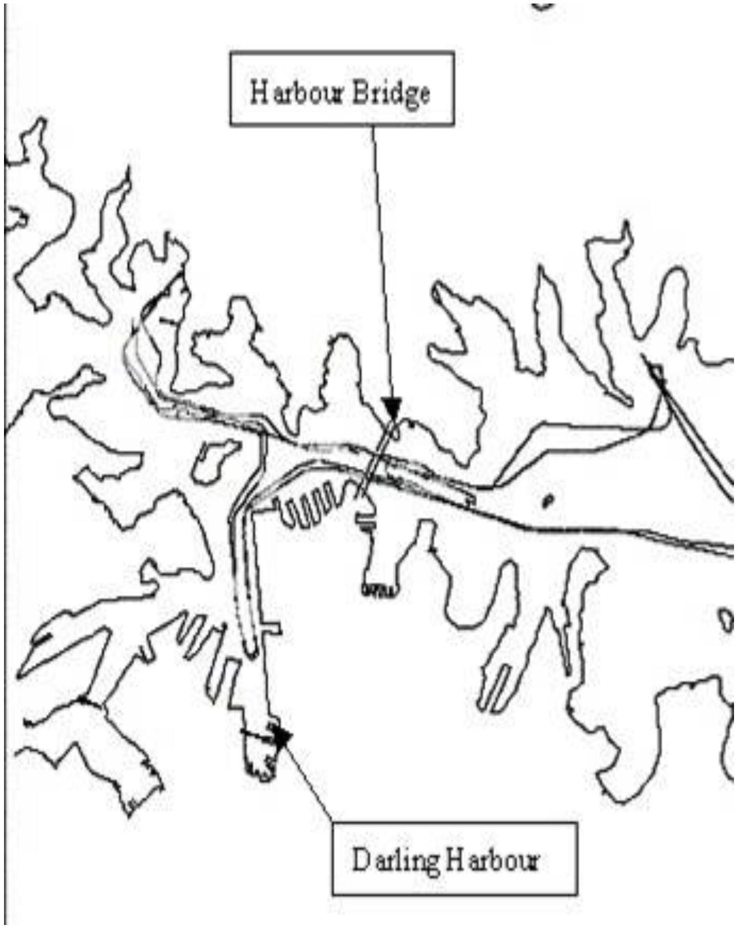
- Sydney Harbour presents an ideal environment in which to validate these algorithms
- Detailed bathymetric maps of the harbour are available
- A beautiful spot for field work as well!

Sydney Harbour Bathymetry



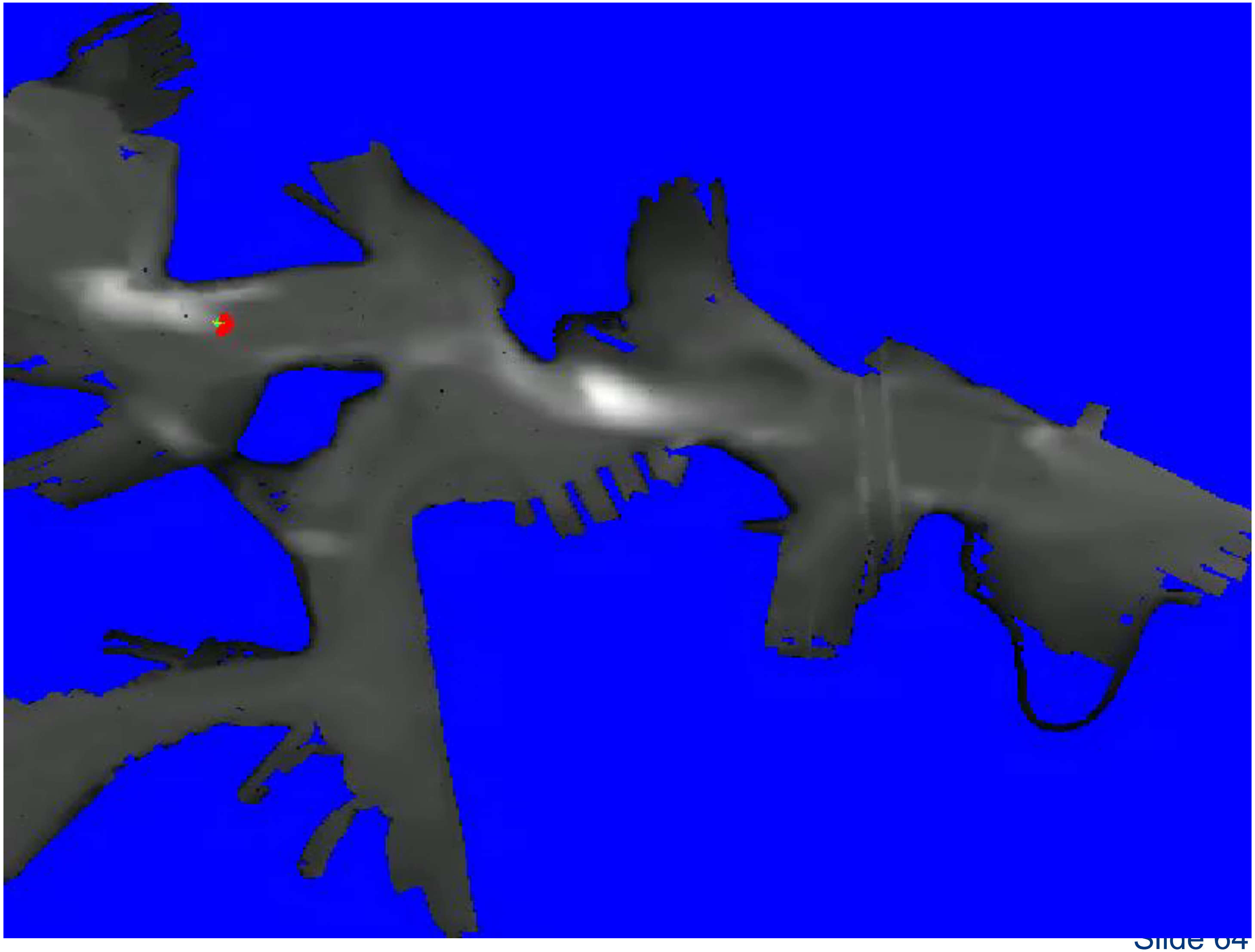
- Sydney Harbour Bathymetry from DSTO Shallow Water Survey
- Bathymetric data collected using multi beam echo sounder
- Resolution of 1m over extent of inner harbour

Ship transect

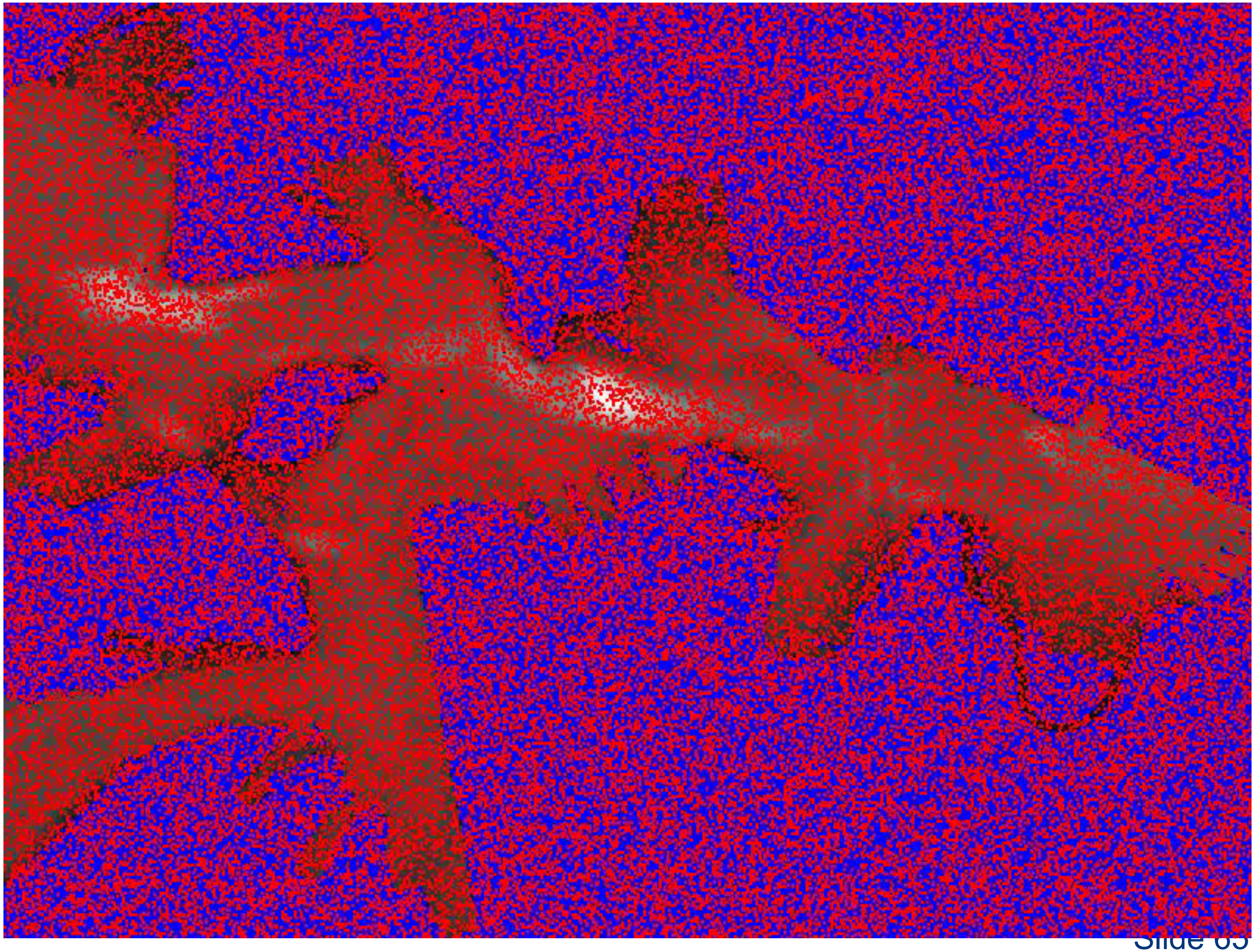


- Ship data from DSTO, including GPS position and depth soundings taken at 5s intervals, during transect of the Harbour
- Particle based localisation and tracking of ship using depth soundings has been demonstrated using logged data

Particle Tracking of Ship Transect



Particle Tracking of Ship Transect Lost



Conclusions

- There are three fundamental competencies to enable deployment of autonomous systems
- A vehicle model tells us something about how the vehicle moves
- Localisation information can be fused to give us an idea of where we are
- Mapping allows us to infer something about the environment