An Introduction to Mobile Robotics

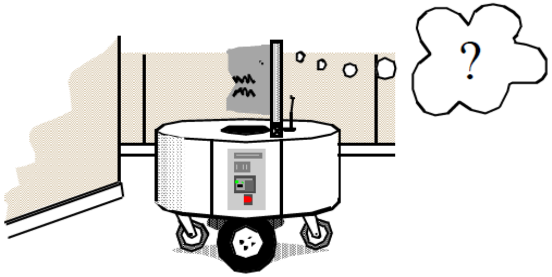
Who am I.

Steve Goldberg

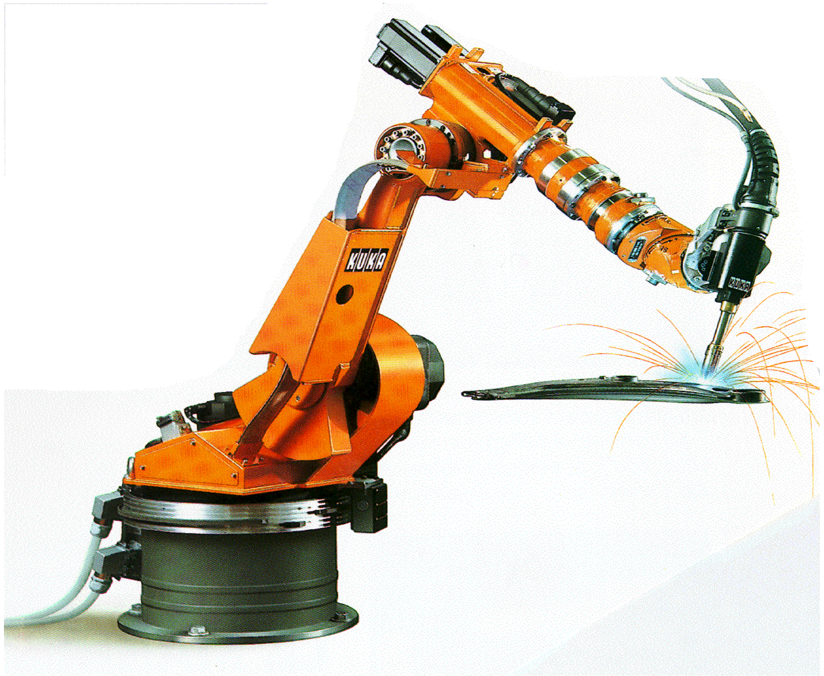
- 15 years programming robots for NASA/JPL
- Worked on MSL, MER, BigDog and Crusher
- Expert in stereo vision and autonomous navigation
- Currently Telecommuting for NASA/JPL and SpaceX

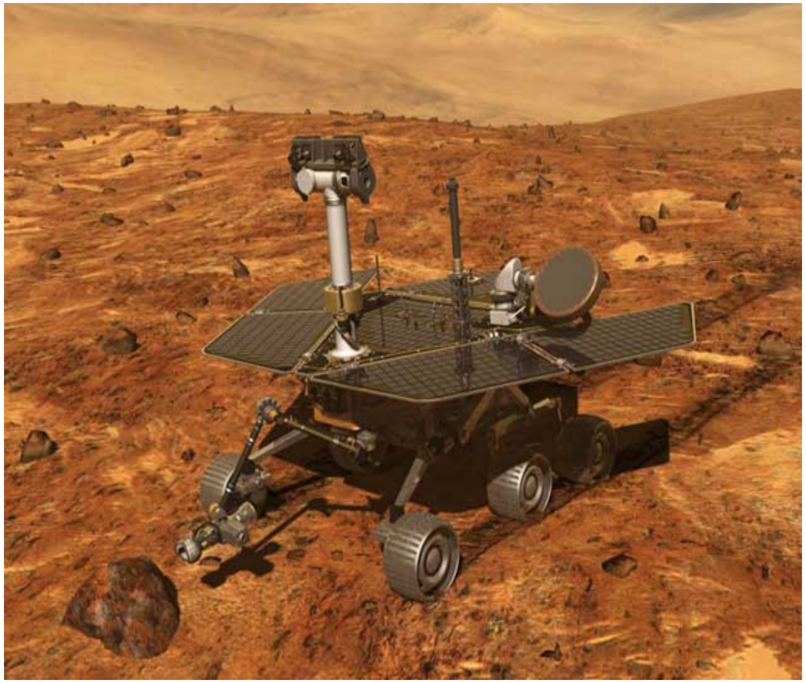
An Introduction to Mobile Robotics

- Mobile robotics cover robots that roll, walk, fly or swim.
- Mobile robots need to answer three fundamental questions
    - Where am I
    - Where am I going
    - How do I get there
- To answer these questions the robot must first
    - Make measurements
    - Model the environment
    - Localize it self
    - Plan a path to its goal



Manipulators and Mobile Robots





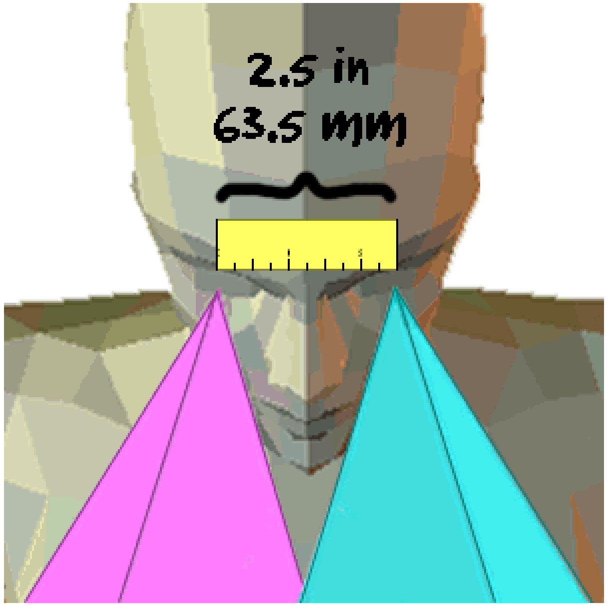
Typical Manipulators

- Operate in a constrained workspace
- Have absolute measurements of position
- May or may not need to perceive the world around them.

Typical Mobile Robots

- Can operate in unconstrained environments
- Need external sensing to determine position
- Need external sensing to avoid obstacles

Sensing



Sensing

- Any information a robot collects about it self or its environment requires sensing.
- Robots that want to learn, map and/or navigate need to collect information about their surroundings.
- All sensors have some degree of uncertainty
- Uncertainty can be reduced by multiple measurements.

Sensing 1

- Two things to sense
  - Its own state (Proprioceptive)
    - Motor speed, battery voltage, joint angles, etc
  - The world (Exteroceptive)
    - Everything and anything about the world around it self
- Two types of sensors
  - Active
    - Project energy out to measure it's return
  - Passive
    - Sense the natural energy around it self

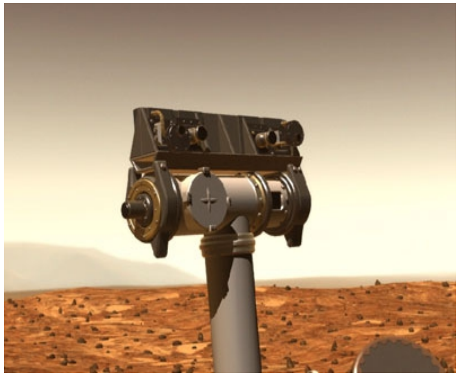
Sensing 2

Passive Proprioceptive

- Thermometer
- Potentiometers
- Accelerometer

Passive Exteroceptive

- Cameras
- Contact sensors
- Compass



Active Proprioceptive

- Optical Encoder
- Gyroscopes

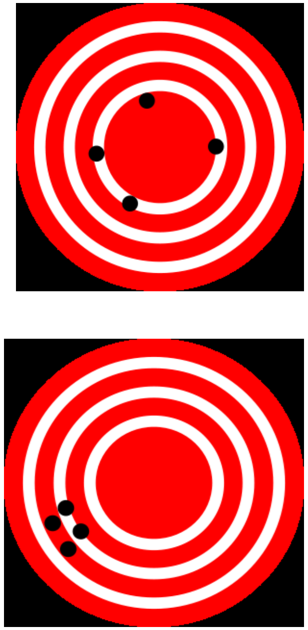
Active Exteroceptive

- Sonar
- Lasers
- GPS

Sensing 3

Sensing Terms

- Dynamic range
  - Upper and lower limits of a sensors input values
- Error
  - Difference between measured and true values
- Accuracy
  - Ability to produce measurements zero mean error
- Precision
  - Ability to reproduce a measurement when presented with the same input.



Sensing 4

- Types of Error
  - Systematic
    - Errors introduced by poor modeling of the sensor
  - Random Error
    - Non-deterministic behaviors
- Sources of Error
  - Environment
    - Low light, glossy surfaces
  - Calibration
  - Principally noisy methodologies

Sensing 5

Improving Measurements

- Improve calibration
  - Reduces systematic errors
- Combining multiple measurements
  - Reduces effect of random errors
    - Multiple measurements from single sensor
    - Multiple measurements from different sensors
  - Not all sensors just sense one thing

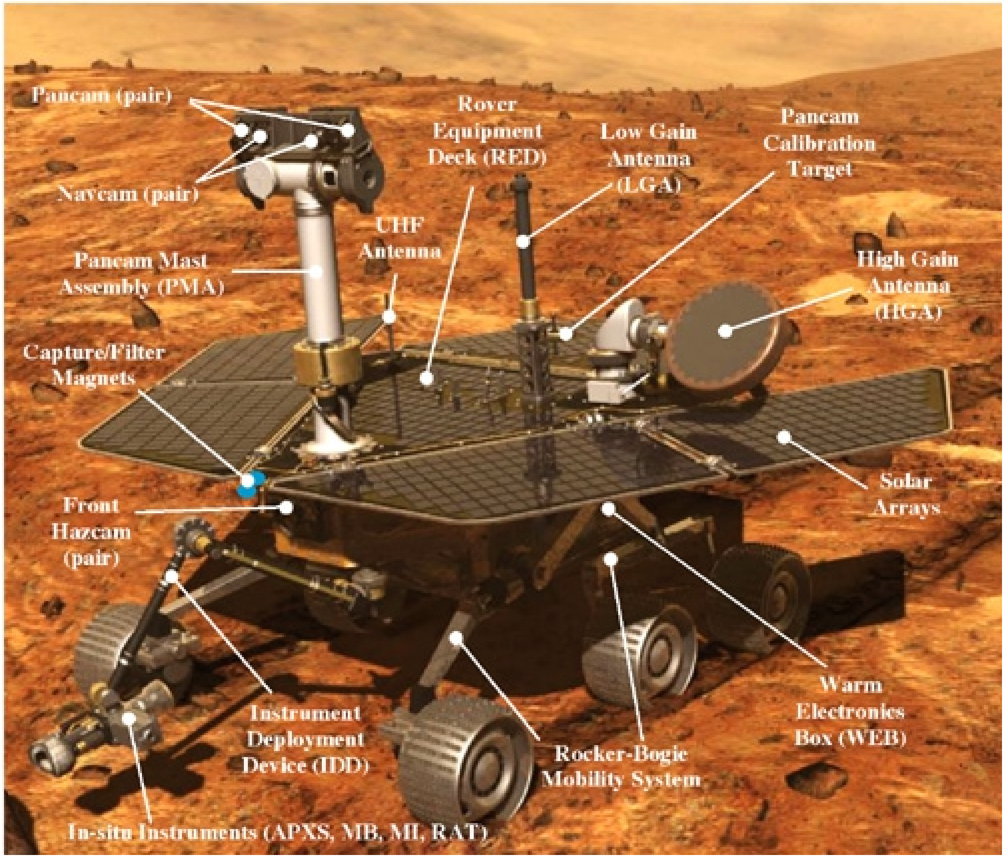
Sensing 6

- Multiple measurements from the same sensor
  - Requires time, latency
  - Introduces smoothing
  - Has little effect on systematic errors
- Multiple measurements from different sensors
  - Can be done simultaneously
  - Can reduce the effect of systematic errors
  - Requires more sensors

Sensing 7

Sensing on Mars Exploration Rovers

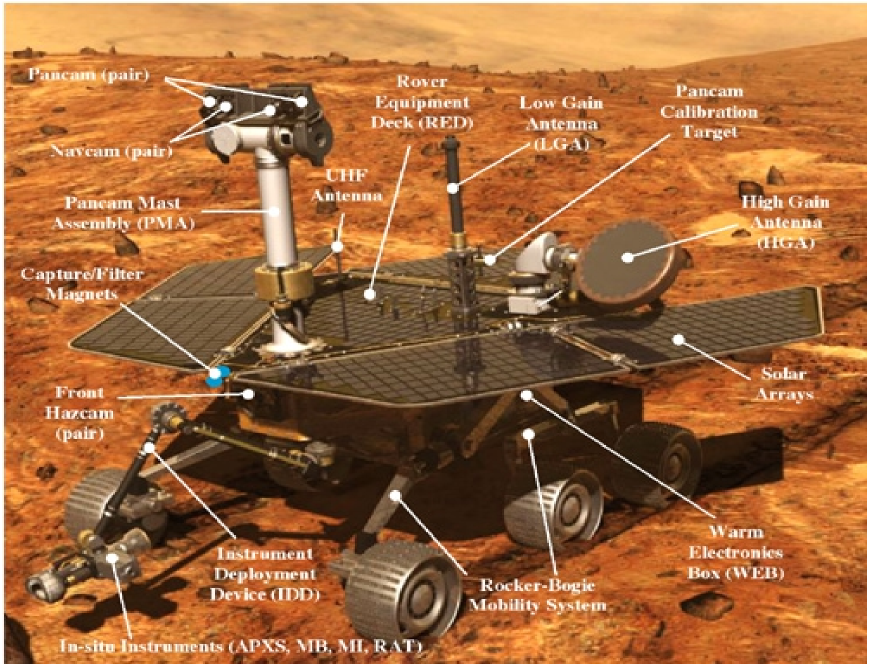
- Proprioceptive - thermometers, voltmeters, encoders
    - Useful in maintaining overall health of the vehicle
    - Keep robot from freezing to death
    - Keeps batteries charged
- Exteroceptive – cameras, spectrometers
    - Used to plan around and avoid obstacles
    - Perform scientific measurements



Sensing 8

How MER perceives its environment.

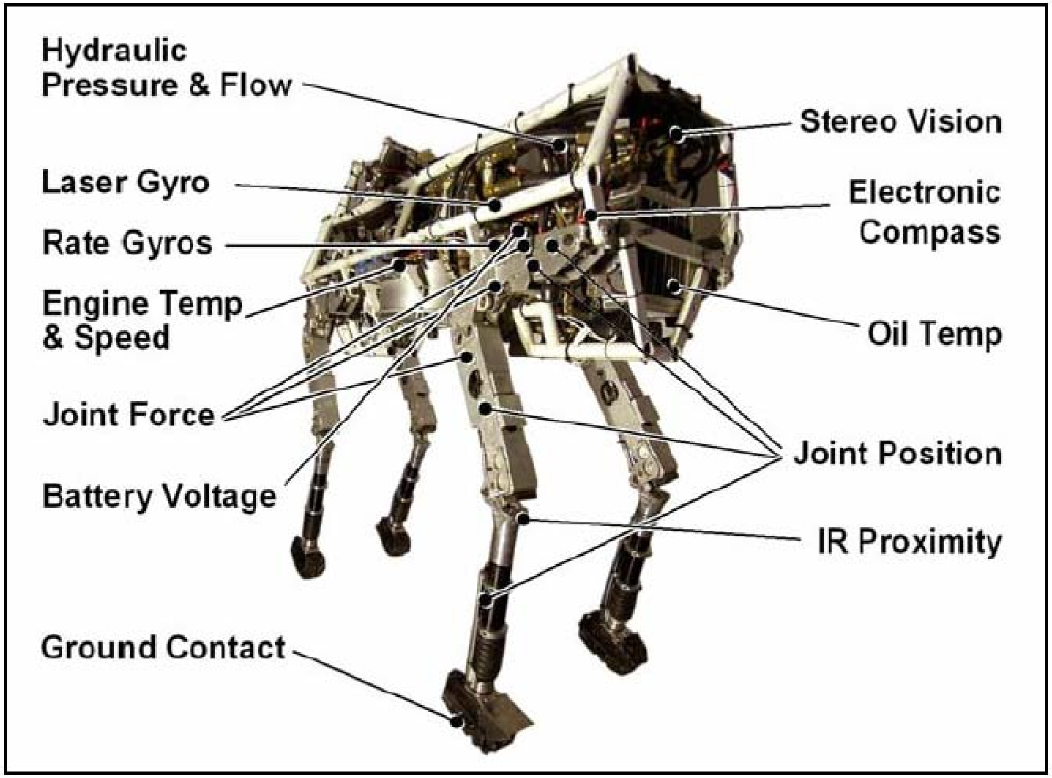
- Encoders
  - Measure wheel positions
  - Susceptible to slip in sandy soil
- Visual odometry
  - Uses stereo images to estimate vehicle motion
  - Fails to track in smooth flat areas
  - Combined with wheel odometry produce estimate of vehicle motion
- Stereo cameras
  - Determine distance to each pixel in the image
  - Build map of local area



Sensing 9

How BigDog perceives its environment

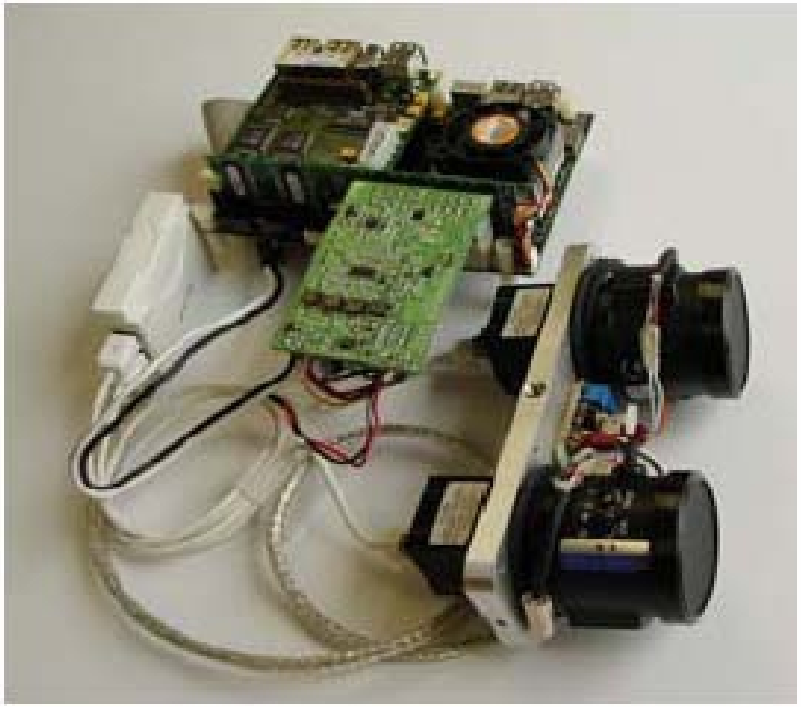
- Encoders measure joint positions
- Contact sensors
- Gyros measure body attitude
- GPS measures global position
- Stereo Vision measures odometry



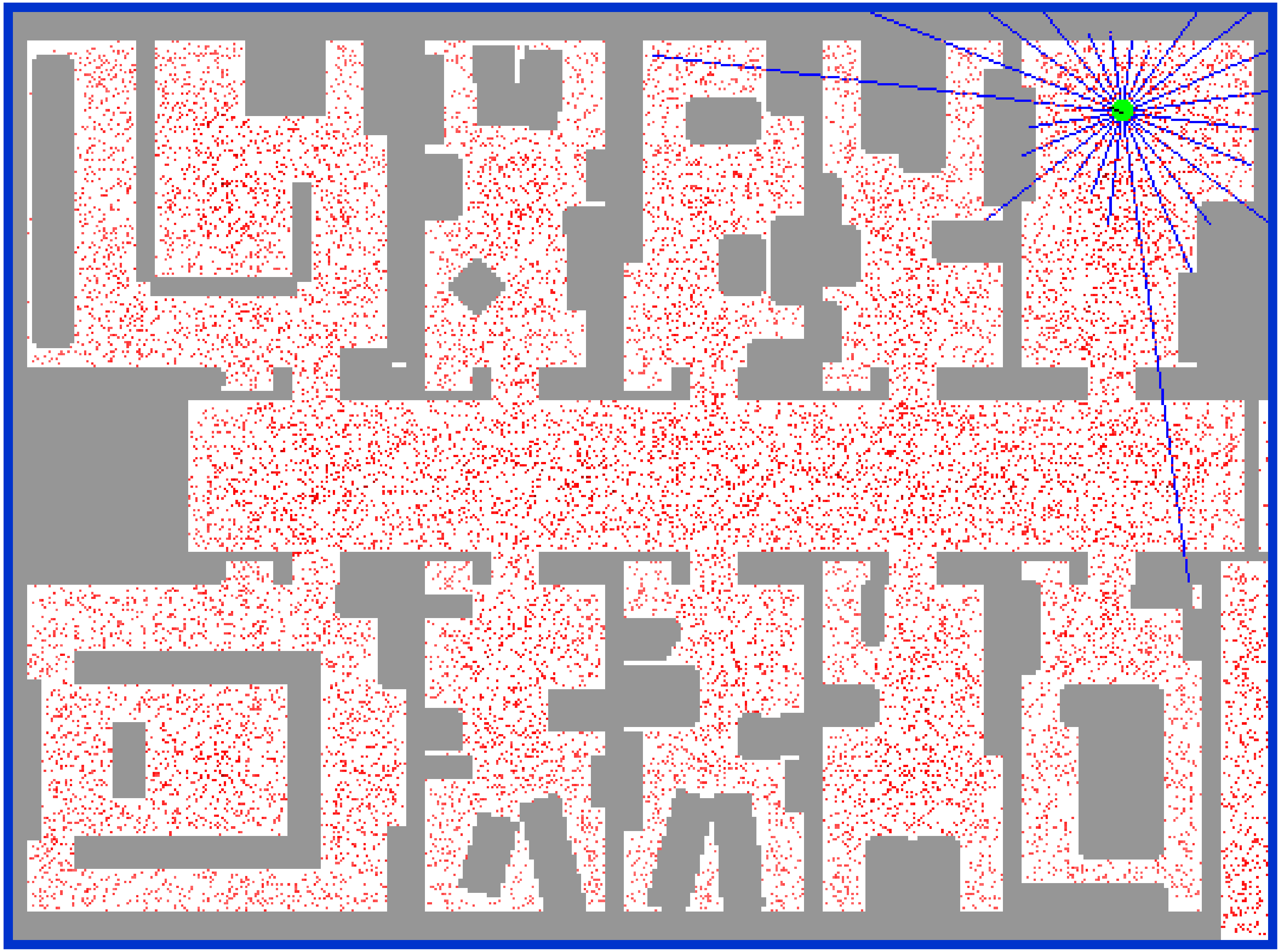
Sensing 10

BigDog Stereo Vision System 2005

- Pentium M
- Two Point Grey 1394 cameras
- Auto Iris lenses
- Computes 320x240 stereo depth maps at 30hz
- Computes visual odometry estimates at 30hz

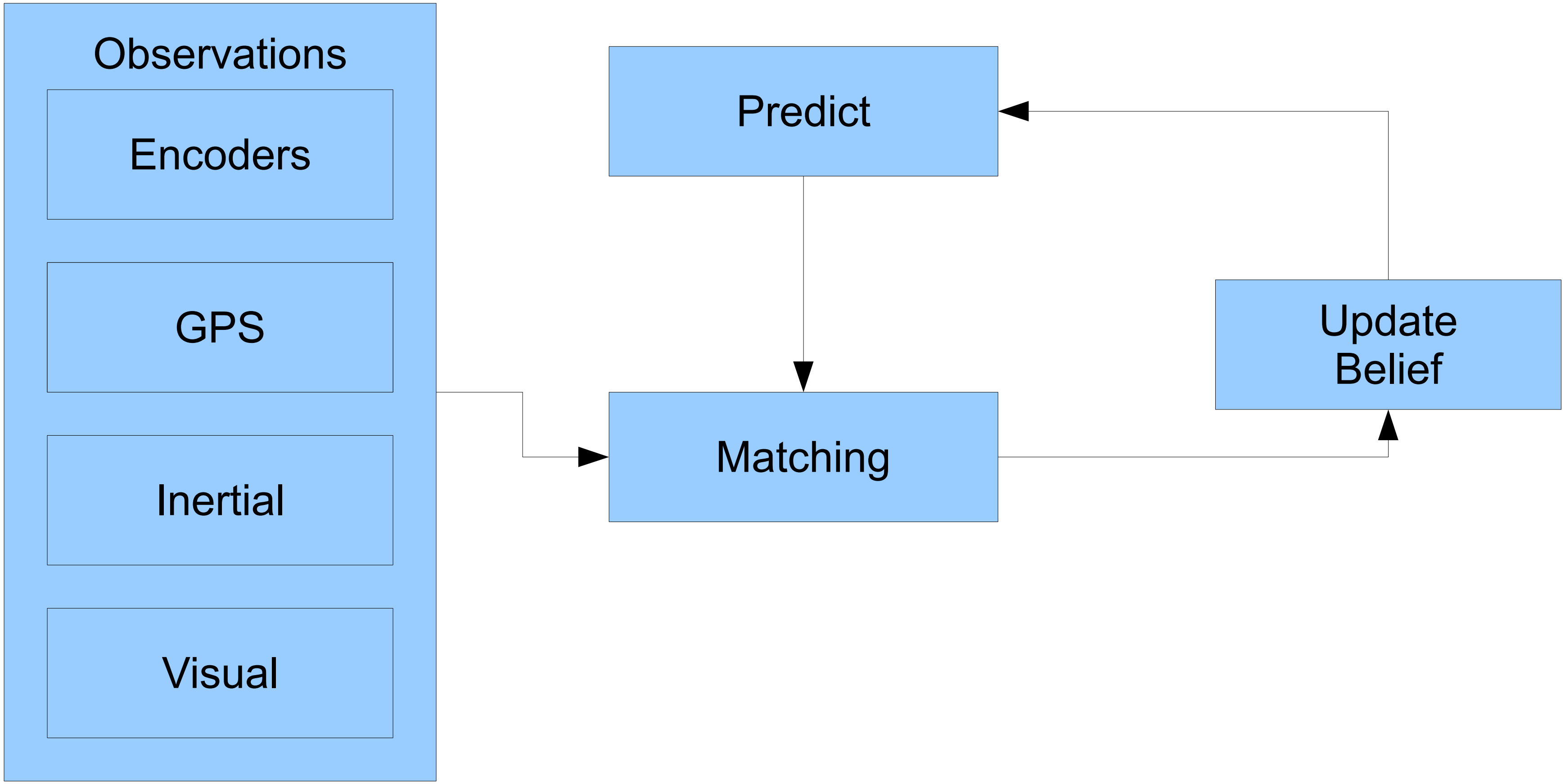


Localization



Localization

Determine the robots state in a state space



Localization 1

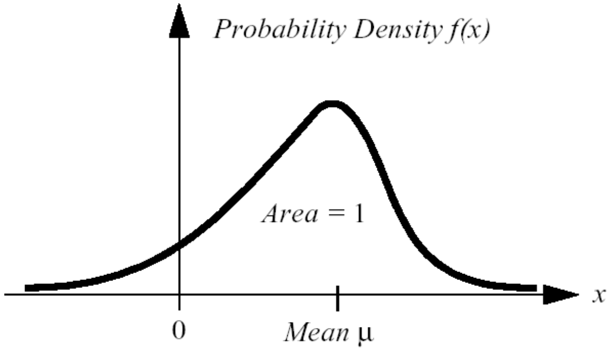
Dead reckoning

- Using only proprioceptive to determine location
  - Relative to initial conditions
  - Prone to drift and slip
  - Unbounded error growth
  - Easy
- Result: Over time, robot belief does not match reality.

Localization 2

Sensor Fusion

- Combining measurements from different sensors to reduce overall error
  - Using probability theory, multiple error models combine to produce better measurements
  - Any additional information, with properly modeled error, will only improve the measurement



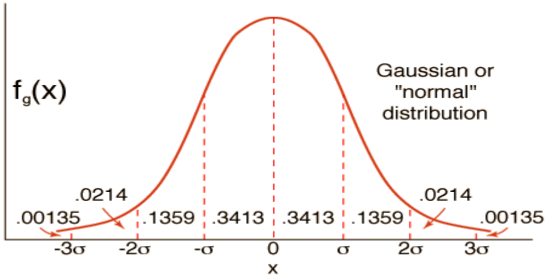
$$\int_{-\infty}^{\infty} f(x)\,dx = 1$$

Localization 3

Kalman filtering

- Assumes zero mean error
- Uses Gaussian PDF
- Require an initial estimate of state
- Depended on linear systems
- Fast

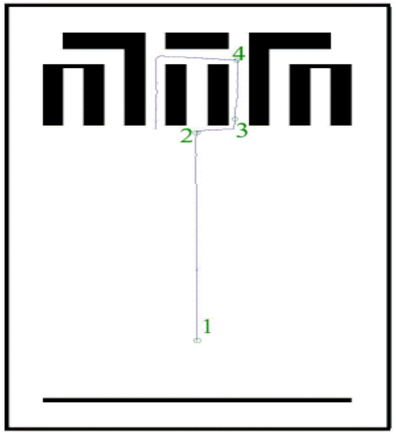
$\mu = 0 \text{ and } \sigma = 1$



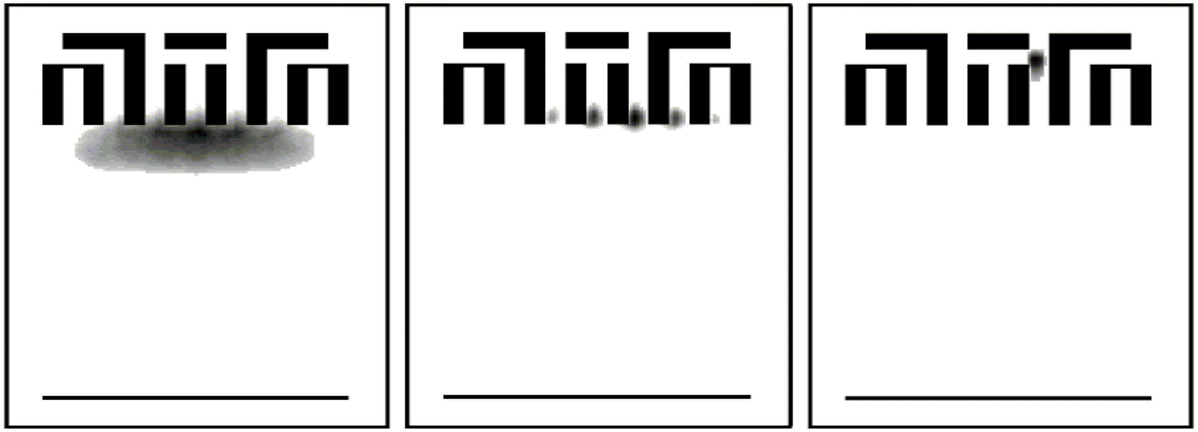
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

Localization 4

- Bayesian methods
  - Can model non-linear systems
  - Do not assume Gaussian PDF
  - Can produce likely solutions without initial estimate of state
  - Multiple belief system
  - Slower

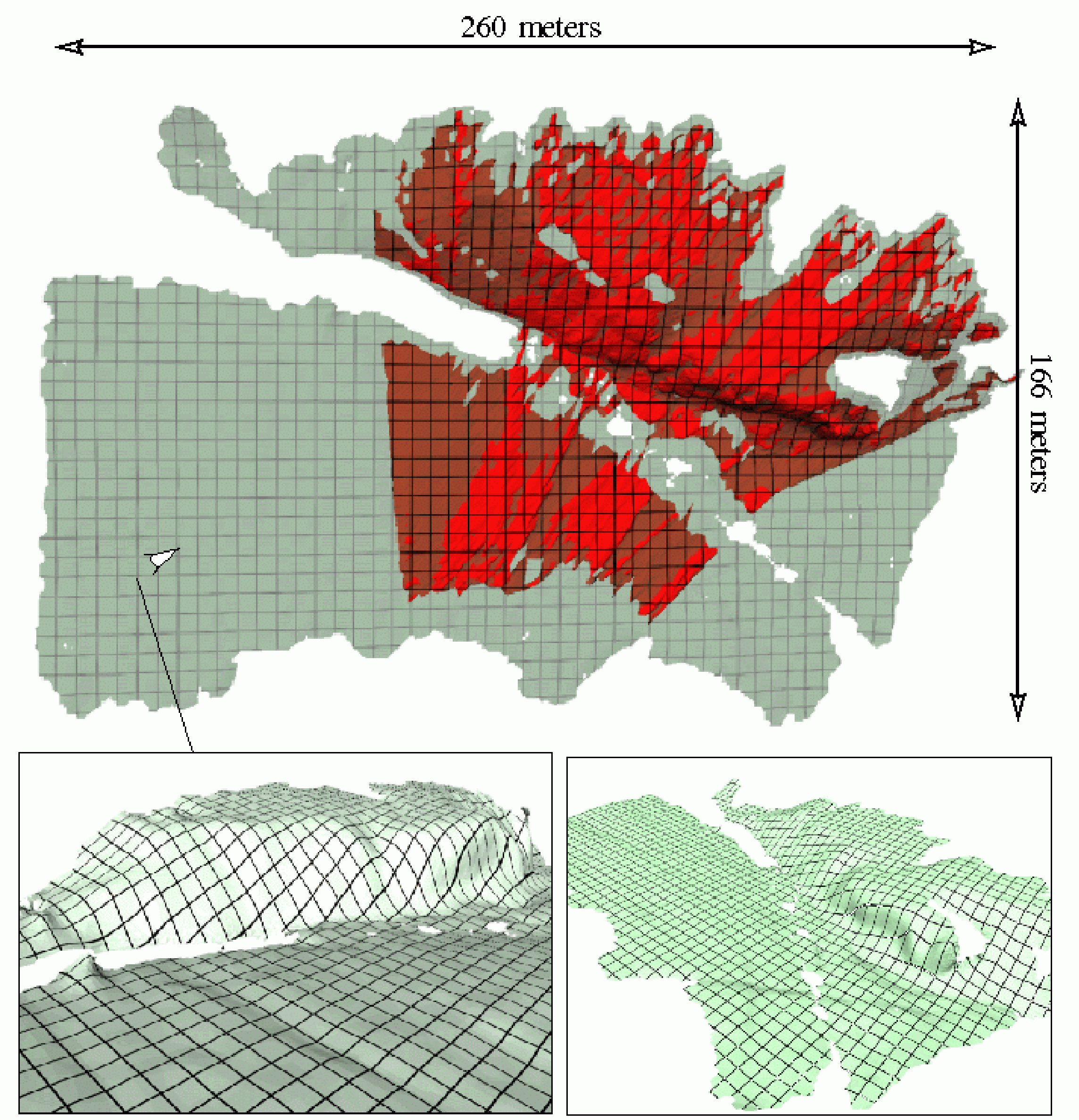


Path of the robot



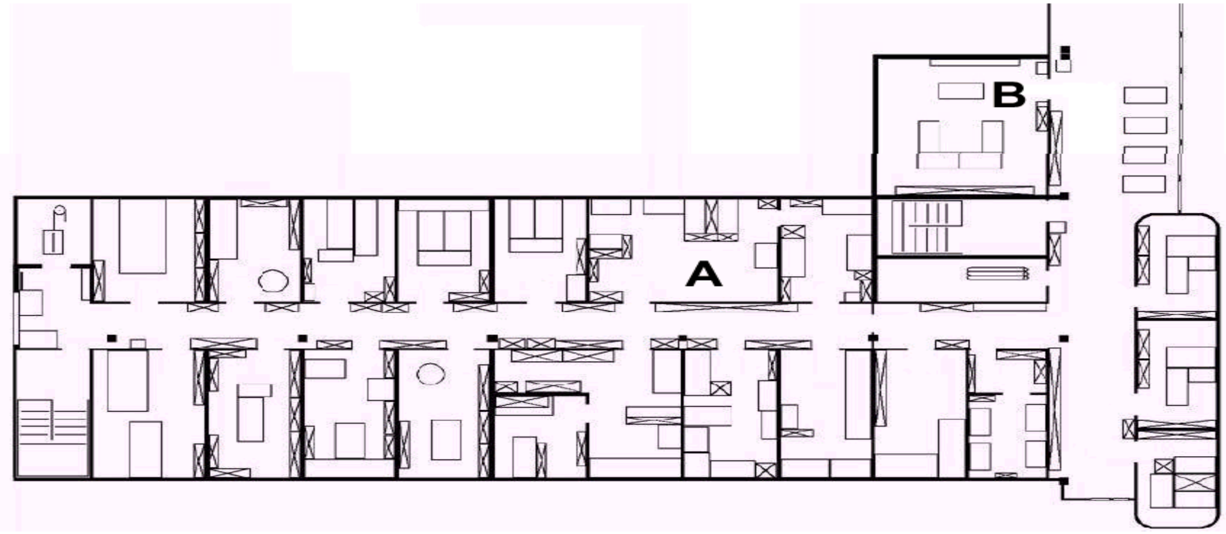
Belief states at positions 2, 3 and 4

Mapping



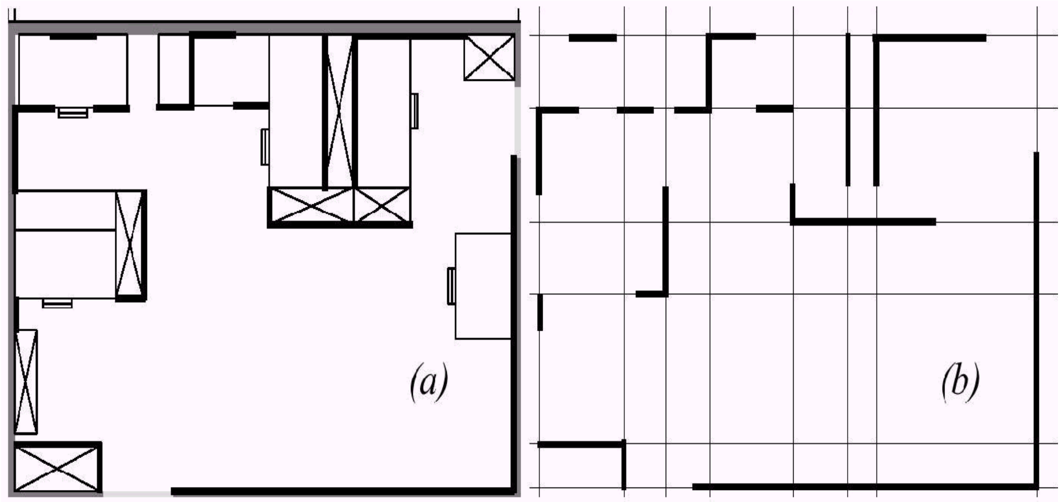
Mapping

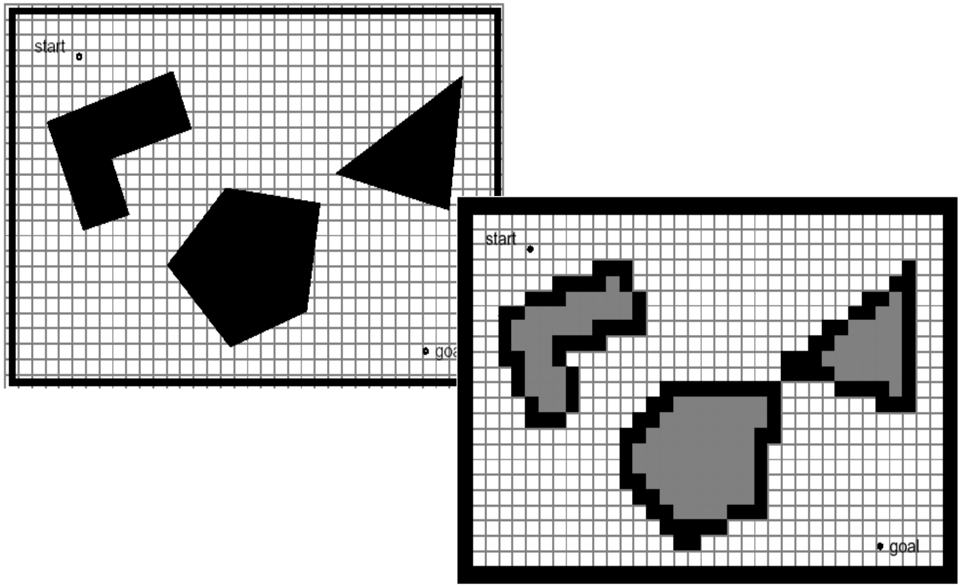
- Maps are required to help a robot get from point A to B.
- Map representations can be continuous or discrete
- Maps can be built a priori and/or dynamically



Mapping 1

- Continuous Representations
  - Maps made from line segments
  - Matching requires good line segmentation
    - Not useful in cluttered environments
  - Computationally expensive
  - Good data compression
  - Not useful outdoors
- Discrete Representations
  - Either fixed cell or adaptive cell size
  - Suffers from aliasing, insufficient resolution
    - Can narrow passages
  - Computationally more efficient
  - Usually large memory footprint





Mapping 2

Just A Priori maps

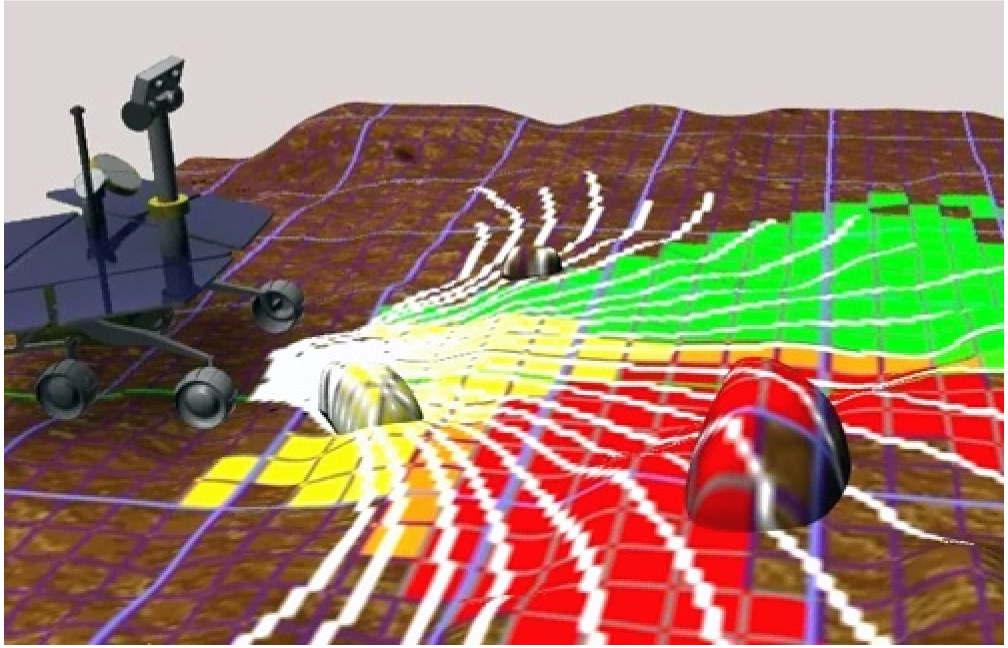
- Good for mission planning
  - Helps users specify where B is...
- Do not account for dynamic environments
  - Moving a trash can or closing a door can confuse a robot

Mapping 3

Dynamically generated maps

- Locally accuracy easier than global
- Robot exploration techniques used to keep relative positions of environment
- Can be used with A Priori maps to improve localization
- Loop closure
- SLAM

Navigation



Navigation

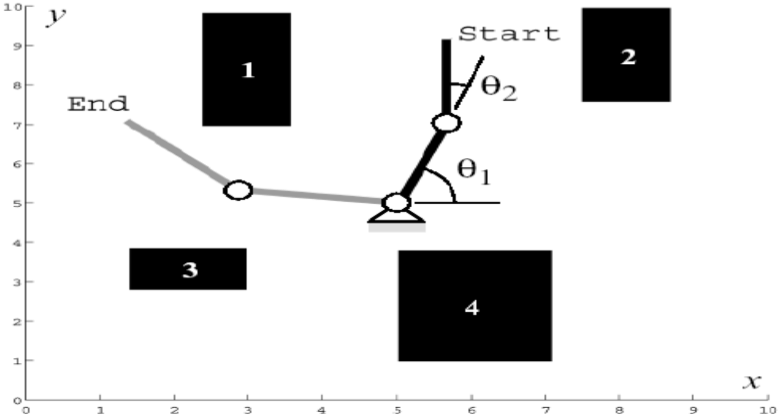
Given a map, now get from point A to B

- A Priori maps a good start
- Local vs Global
  - Local path planning with obstacle detection and avoidance helps us to do it safely
  - Global path planning helps us get from A to B

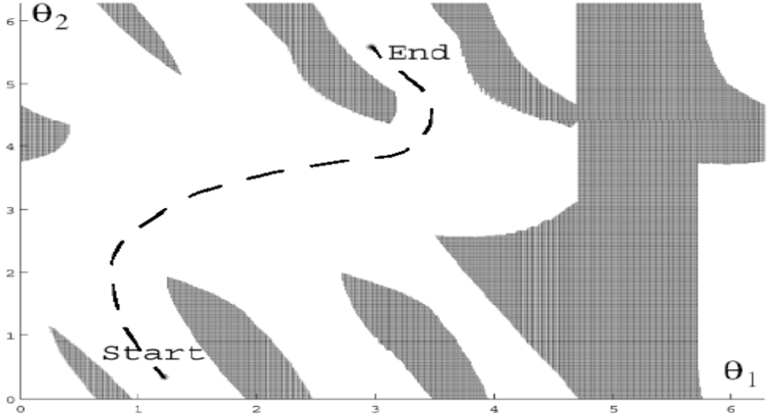
Navigation 1

Global path planning

- Find a path from A to B in the robots configuration space.
  - What is the configuration space of a mobile robot?



Work Space



Configuration Space: the dimension of this space is equal to the Degrees of Freedom (DoF) of the robot

Navigation 2

Configuration space

- Mobile robots operating on a flat ground have 3 DoF: (x, y, θ)
- To simplify the world, we often reduce the robot to a point = DoF: (x,y)
  - Then we need to grow the obstacles by the shape of the robot in its orientation
- If not simplified, a model of the robot is convolved with the map to determine traversablity.
  - Expensive operations

Navigation 3

- Many global navigation strategies exist
- Discrete maps
- Graph based strategies
- EM
- D *

Navigation 4

Obstacle detection

- Detect obstacles in our sensor or map data and place in the map
- Sensor measurements are analyzed for hazardous regions
  - Hazards can include barriers, slope, roughness etc

Navigation 5

Obstacle Avoidance

- Path planning is required to avoid hitting obstacles in the map
- Similar to global path planning except more dynamic

Play video of MER Navigation

Kinematics and Mobility

Kinematics and Mobility

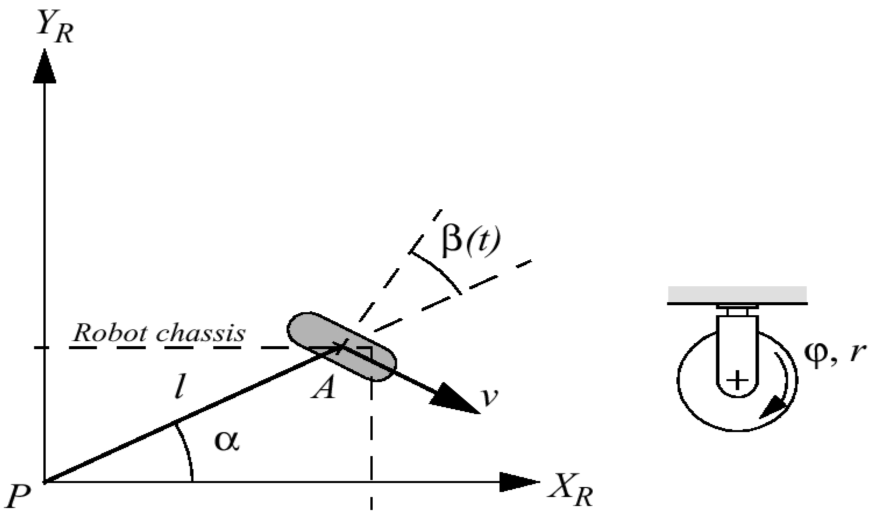
- Robots can roll, walk, fly or swim.
- Wheels offer excellent power/performance in locally planer environments
- Legs offer excellent mobility in rough environments at the cost of power.
- Flying and swimming increases sensing and navigation complexity.

Wheeled Robots 1

- Kinematic parameters come from type and configuration of wheels.
  - Rolling and/or steering
  - Position relative to chassis
- Kinematic constrains come from combining all the wheels rolling and steering constrains
  - Wheels don't like to go sideways

Wheeled Robots 2

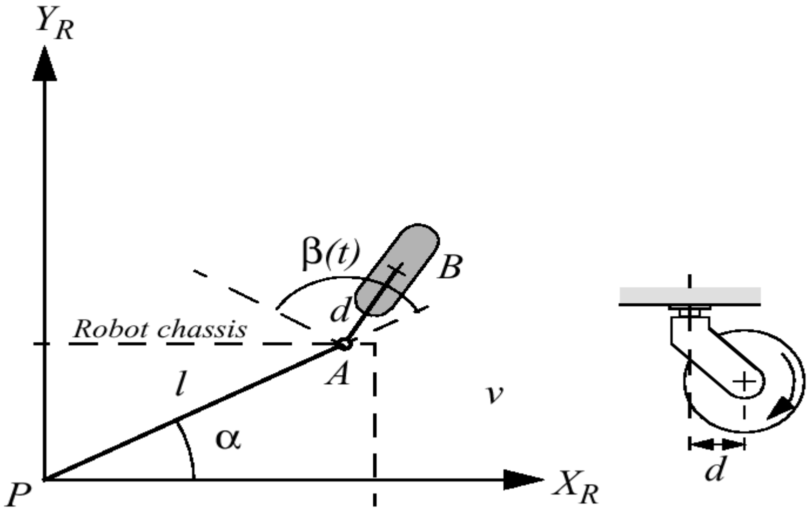
Standard wheel



$$\left[\sin(\alpha+\beta)\ \ -\cos(\alpha+\beta)\ \ (-l)\cos\beta\right] R(\theta)\dot{\xi}_I - r\dot{\varphi} = 0$$

$$\left[\cos(\alpha+\beta)\ \ \sin(\alpha+\beta)\ \ l\sin\beta\right] R(\theta)\dot{\xi}_I = 0$$

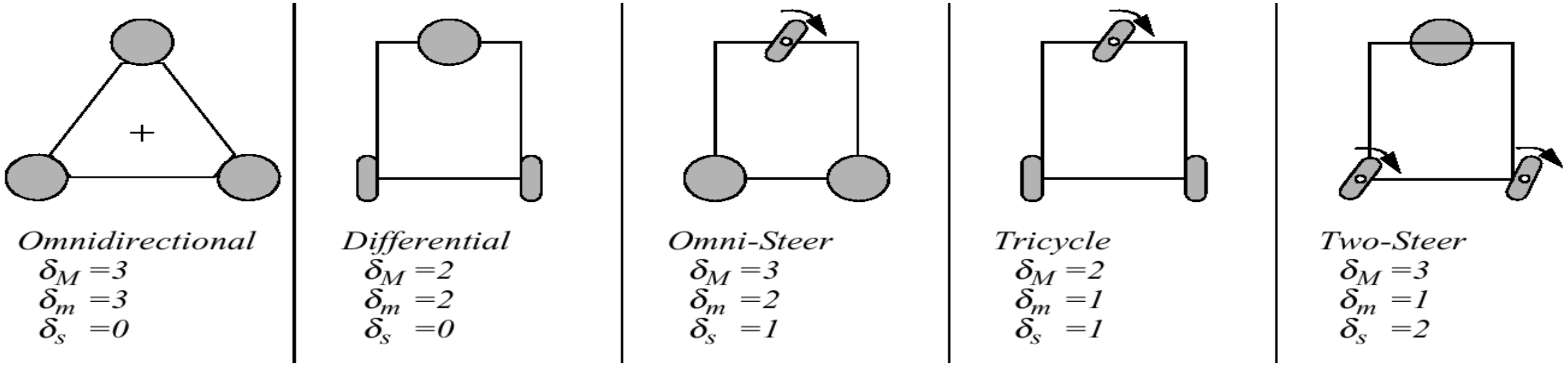
Caster wheel



$$\left[\sin(\alpha+\beta)\ \ -\cos(\alpha+\beta)\ \ (-l)\cos\beta\right] R(\theta)\dot{\xi}_I - r\dot{\varphi} = 0$$

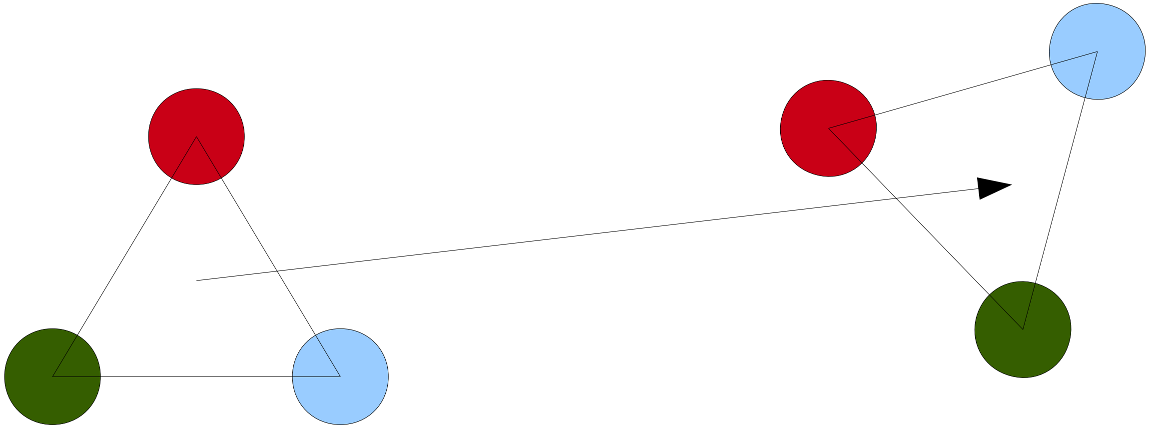
$$\left[\cos(\alpha+\beta)\ \ \sin(\alpha+\beta)\ \ d + l\sin\beta\right] R(\theta)\dot{\xi}_I + d\dot{\beta} = 0$$

Wheeled Robots 3



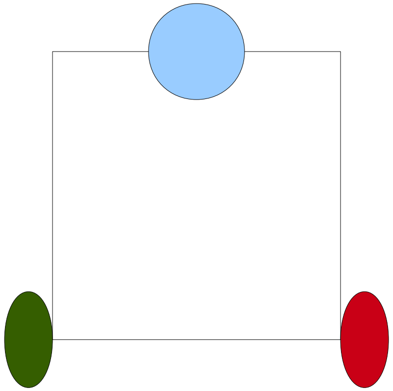
- Maneuverability = mobility + steerability
  - Instantaneous Center of Rotation (3 = plane, 2 is line)
  - The mobility available based on the sliding constraints plus additional freedom contributed by the steering

Wheeled Robots 4

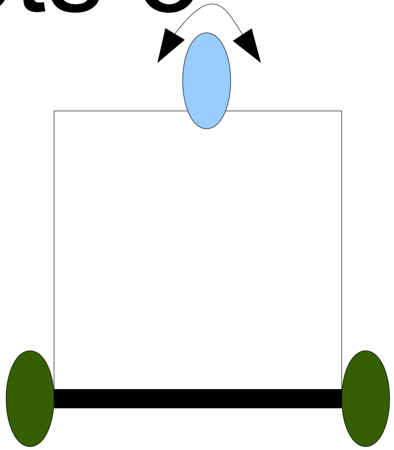


- Omni-directional drive with Maneuverability 3
  - Can translate and rotate simultaneously to achieve any position and orientation

Wheeled Robots 5



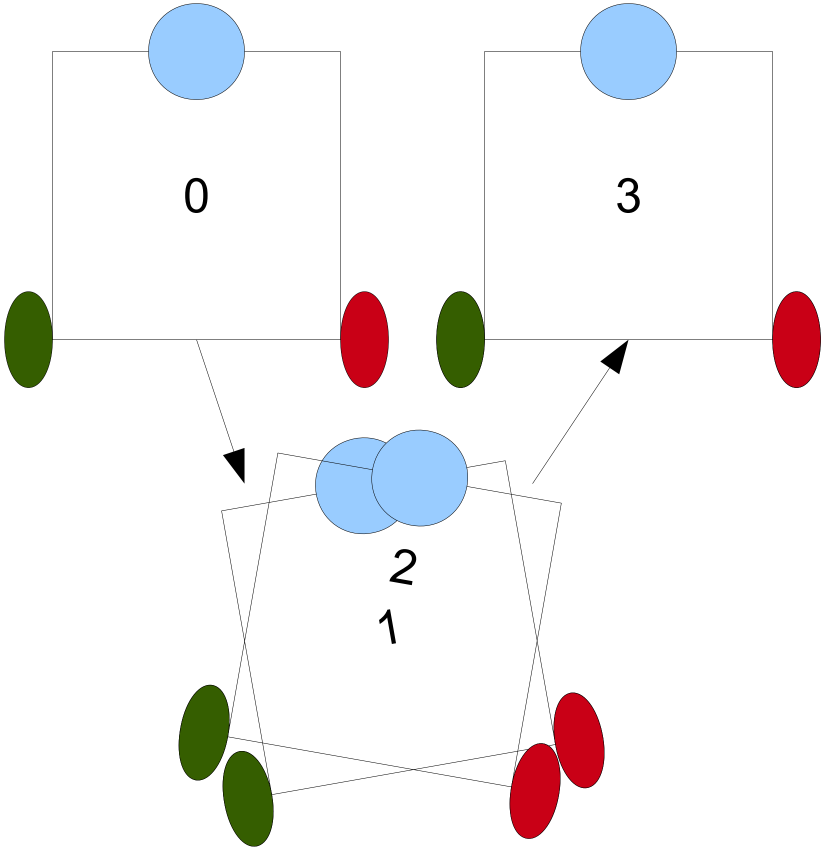
Differential Drive

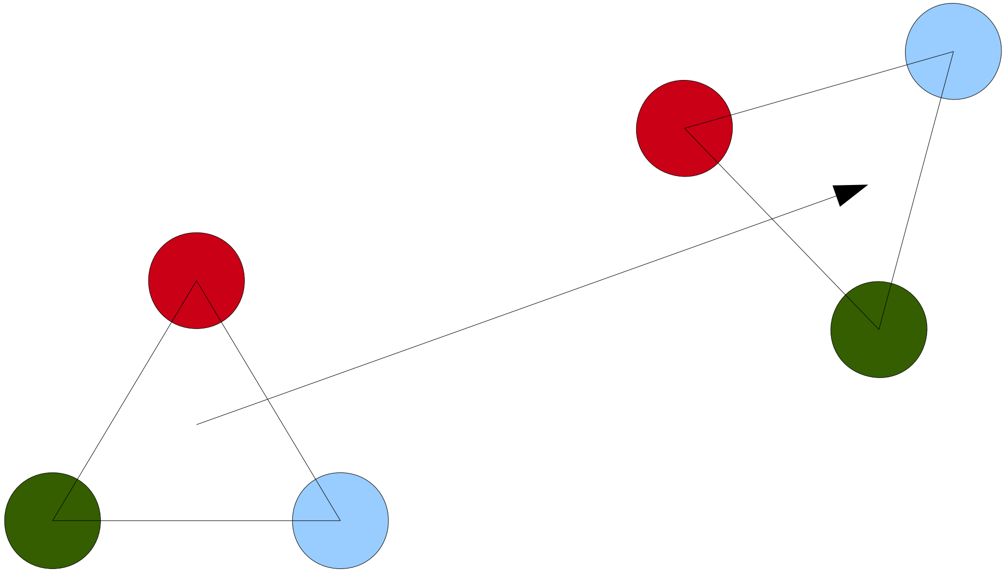


Tricycle

- Differential Drive and Tricycle both have a degree of maneuverability 2
  - Differential drive has mobility 2 as each wheel can rotate independently along a common axis but no steerable actuators
  - Tricycle has mobility 1 as both wheels rotate together on a common axle and 1 degree of steerability.
  - Both designs must change pose before being able to achieve any position

Wheeled Robots 6





- Noholonomic configurations
  - Robot must use transition states to achieve any state in it's state space
  - Example: Bicycle, Car

- Holonomic configurations
  - Robot can directly achieve any state in their state space directly.
  - Examples: Omni-Steer, Helicopter

For more Reading

- Introduction to Autonomous Mobile Robots

  By Roland Siegwart

Robot Videos

- BigDog and PETMAN
- Crusher
- MER
- MSL
- QuadRotors ETH