An Introduction to Mobile Robotics

Who am I.

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15 years programming robots for NASA/JPL
Worked on MSL, MER, BigDog and Crusher
Expert in stereo vision and autonomous navigation
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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 itself
  - Plan a path to its goal
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

2.5 in
63.5 mm
Sensing

- Any information a robot collects about itself 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 itself

• Two types of sensors
  • Active
    - Project energy out to measure its return
  • Passive
    - Sense the natural energy around itself
Sensing 2

Passive Proprioceptive
- Thermometer
- Potentiometers
- Accelerometer

Active Proprioceptive
- Optical Encoder
- Gyroscopes

Passive Exteroceptive
- Cameras
- Contact sensors
- Compass

Active Exteroceptive
- Sonar
- Lasers
- GPS
Sensing Terms

- Dynamic range
  - Upper and lower limits of a sensor's 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
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

- Observations
  - Encoders
  - GPS
  - Inertial
  - Visual

- Predict
- Matching
- Update Belief
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
Localization 3

Kalman filtering

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

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

- 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?
Navigation 2

Configuration space

- Mobile robots operating on a flat ground have 3 DoF: $(x, y, \theta)$
- 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 traversability.
  - Expensive operations
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 the type and configuration of wheels.
  - Rolling and/or steering
  - Position relative to chassis
- Kinematic constraints come from combining all the wheels' rolling and steering constraints
  - Wheels don't like to go sideways
Wheeled Robots 2

**Standard wheel**

\[
\begin{bmatrix}
\sin(\alpha + \beta) - \cos(\alpha + \beta) (-l) \cos \beta \\
\cos(\alpha + \beta) \sin(\alpha + \beta) l \sin \beta
\end{bmatrix} R(\theta) \dot{\xi}_I - r \dot{\phi} = 0
\]

\[
\begin{bmatrix}
\cos(\alpha + \beta) \sin(\alpha + \beta) l \sin \beta
\end{bmatrix} R(\theta) \dot{\xi}_I = 0
\]


**Caster wheel**

\[
\begin{bmatrix}
\sin(\alpha + \beta) - \cos(\alpha + \beta) (-l) \cos \beta \\
\cos(\alpha + \beta) \sin(\alpha + \beta) d + l \sin \beta
\end{bmatrix} R(\theta) \dot{\xi}_I + d \ddot{\beta} = 0
\]

\[
\begin{bmatrix}
\cos(\alpha + \beta) \sin(\alpha + \beta) d + l \sin \beta
\end{bmatrix} R(\theta) \dot{\xi}_I + d \ddot{\beta} = 0
\]
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
Omni-directional drive with Maneuverability 3

- Can translate and rotate simultaneously to achieve any position and orientation
Wheeled Robots 5

- 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