Robot Sensing and Sensors

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Brief Review
(Mobot Locomotion)

ICR of wheeled mobile robot

- Instantaneous center of rotation (ICR)
  - A cross point of all axes of the wheels

Degree of Mobility

- Degree of mobility
  - The degree of freedom of the robot motion
  - Fixed arc motion (Only one ICR)
  - Fully free motion (ICR can be located at any position)

Degree of Steerability

- Degree of steerability
  - The number of centered orientable wheels that can be steered independently in order to steer the robot
  - No centered orientable wheels
  - One centered orientable wheel
  - Two mutually dependent centered orientable wheels
  - Two mutually independent centered orientable wheels

Degree of Maneuverability

- The overall degrees of freedom that a robot can manipulate:
  \[ \delta_M = \delta_s + \delta_t \]

Examples of robot types (degree of mobility, degree of steerability)
Degree of Maneuverability

\[ \delta_M = \delta_m + \delta_s \]

Mobile Robot Locomotion

Locomotion: the process of causing a robot to move

- Differential Drive
- Tricycle
- Synchronous Drive
- Ackerman Steering
- Swedish Wheel
- Omni-directional

Differential Drive

Property: At each time instant, the left and right wheels must follow a trajectory that moves around the ICC at the same angular rate \( \omega \), i.e.,

\[
\begin{align*}
V_L &= r w_L \\
V_K &= r w_K \\
\omega &= V_x - V_y \\
&= \frac{V_x + V_y}{2}
\end{align*}
\]

- Kinematic equation
- Nonholonomic Constraint

\[
\begin{bmatrix}
\sin \theta \\
\cos \theta
\end{bmatrix}
= \begin{bmatrix}
\sin \theta - \cos \theta \\
\cos \theta + \sin \theta
\end{bmatrix}
\]

Tricycle

- Steering and power are provided through the front wheel
- Control variables:
  - Angular velocity of steering wheel \( w_s(t) \)
  - Steering direction \( \omega(t) \)
  - Linear velocity of steering wheel \( v_s(t) \)
  - Angular velocity of the moving frame \( \omega(t) \)

Tricycle

Kinematics model in the world frame

--- Posture kinematics model
Synchronous Drive

- All the wheels turn in unison
  - All wheels point in the same direction and turn at the same rate
  - Two independent motors, one rolls all wheels forward, one rotates them for turning
- Control variables (independent)
  - $v(t)$, $\omega(t)$

Ackerman Steering (Car Drive)

- The Ackerman Steering equation:
  \[
  \frac{\cot \theta_i - \cot \theta_o}{\cot \theta} = \frac{d}{l}
  \]
  \[
  \cot \theta_o = \frac{\cos \theta}{\sin \theta}
  \]

Car-like Robot

Driving type: Rear wheel drive, front wheel steering

- $R = u_i \tan \varphi$
- $\frac{\dot{R}}{l} = \frac{\dot{\theta}}{\tan \varphi} = u_i$

Rear wheel drive car model:

- $\dot{x} = u_i \cos \theta$
- $\dot{y} = u_i \sin \theta$
- $\dot{\theta} = \frac{u_i}{l} \tan \varphi$
- $\dot{\varphi} = u_2$

Non-holonomic constraint:

- $x \sin \theta - y \cos \theta = 0$

Robot Sensing and Sensors

References


Some websites

- [http://www.omega.com](http://www.omega.com) (sensors + hand-helds)
- [http://www.extech.com](http://www.extech.com) (hand-helds)
- [http://www.agilent.com](http://www.agilent.com) (instruments, enormous)
- [http://www.keithley.com](http://www.keithley.com) (instruments, big)
- [http://www.tegam.com](http://www.tegam.com) (instruments, small)
- [http://www.edsci.com](http://www.edsci.com) (optics++)
- [http://www.pacific.net/~brooke/Sensors.html](http://www.pacific.net/~brooke/Sensors.html) (comprehensive listing of sensors etc. and links)
What is Sensing?

- Collect information about the world
- Sensor - an electrical/mechanical/chemical device that maps an environmental attribute to a quantitative measurement
- Each sensor is based on a transduction principle - conversion of energy from one form to another

Human sensing and organs

- Vision: eyes (optics, light)
- Hearing: ears (acoustics, sound)
- Touch: skin (mechanics, heat)
- Odor: nose (vapor-phase chemistry)
- Taste: tongue (liquid-phase chemistry)

Extended ranges and modalities

- Vision outside the RGB spectrum
  - Infrared Camera, see at night
- Active vision
  - Radar and optical (laser) range measurement
- Hearing outside the 20 Hz – 20 kHz range
  - Ultrasonic range measurement
- Chemical analysis beyond taste and smell
- Radiation: α, β, γ-rays, neutrons, etc

Transduction to electronics

- Thermistor: temperature-to-resistance
- Electrochemical: chemistry-to-voltage
- Photocurrent: light intensity-to-current
- Pyroelectric: thermal radiation-to-voltage
- Humidity: humidity-to-capacitance
- Length (LVDT: Linear variable differential transformers): position-to-inductance
- Microphone: sound pressure-to-<anything>

Sensor Fusion and Integration

- Human: One organ ⇨ one sense?
  - Not necessarily
    - Balance: ears
    - Touch: tongue
    - Temperature: skin
- Robot:
  - Sensor fusion:
    - Combine readings from several sensors into a (uniform) data structure
  - Sensor integration:
    - Use information from several sensors to do something useful

Sensor Fusion

- One sensor is (usually) not enough
  - Real sensors are noisy
  - Limited Accuracy
  - Unreliable - Failure/redundancy
  - Limited point of view of the environment
    - Return an incomplete description of the environment
  - The sensor of choice may be expensive - might be cheaper to combine two inexpensive sensors
**General Processing**

- Sensor → Preprocessing
- Sensor → Preprocessing
- Sensor → Preprocessing
- Sensor → Preprocessing
- Fusion → Interpretation

**Preprocessing**

- Colloquially - ‘cleanup’ the sensor readings before using them
- Noise reduction - filtering
- Re-calibration
- ‘Basic’ stuff - e.g. edge detection in vision
- Usually unique to each sensor
- Change (transform) data representation

**Sensor/Data Fusion**

- Combine data from different sources
  - measurements from different sensors
  - measurements from different positions
  - measurements from different times
- Often a mathematical technique that takes into account uncertainties in data sources
  - Discrete Bayesian methods
  - Neural networks
  - Kalman filtering
- Produces a merged data set (as though there was one ‘virtual sensor’)

**Interpretation**

- Task specific
- Often modeled as a best fit problem given some a priori knowledge about the environment
- Tricky

**Classification of Sensors**

- Proprioception (Internal state) v.s. Exteroception (external state)
  - measure values internally to the system (robot), e.g. battery level, wheel position, joint angle, etc
  - observation of environments, objects
- Active v.s. Passive
  - emitting energy into the environment, e.g., radar, sonar
  - passively receive energy to make observation, e.g., camera
- Contact v.s. non-contact
- Visual v.s. non-visual
  - vision-based sensing, image processing, video camera

**Proprioceptive Sensors**

- Encoders, Potentiometers
  - measure angle of turn via change in resistance or by counting optical pulses
- Gyroscopes
  - measure rate of change of angles
  - fiber-optic (newer, better), magnetic (older)
- Compass
  - measure which way is north
- GPS: measure location relative to globe
### Touch Sensors

- Whiskers, bumpers etc.
  - mechanical contact leads to
    - closing/opening of a switch
    - change in resistance of some element
    - change in capacitance of some element
    - change in spring tension
    - ...

### Sensors Based on Sound

- **SONAR: Sound Navigation and Ranging**
  - bounce sound off of objects
  - measure time for reflection to be heard - gives a range measurement
  - measure change in frequency - gives the relative speed of the object (Doppler effect)
  - bats and dolphins use it with amazing results
  - robots use it w/ less than amazing results

### Sensors Based on EM Spectrum

- Radio and Microwave
  - **RADAR:** Radio Detection and Ranging
  - Microwave radar: insensitive to clouds
- Coherent light
  - all photons have same phase and wavelength
  - **LASER:** Light Amplification by Stimulated Emission of Radiation
  - **LASER RADAR:** LADAR - accurate ranging

### Electromagnetic Spectrum

- Visible Spectrum
  - 700 nm
  - 400 nm

### Sensors Based on EM Spectrum

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  - **LASER RADAR:** LADAR - accurate ranging

### Sensors Based on EM Spectrum

- **Light sensitive**
  - eyes, cameras, photocells etc.
  - Operating principle
    - **CCD:** charge coupled devices
    - photoelectric effect
- **IR sensitive**
  - **Local Proximity Sensing**
    - Infrared LEDs (cheap, active sensing)
    - usually low resolution - normally used for presence/absence of obstacles rather than ranging, operate over small range
  - Sense heat differences and construct images
    - Human detection sensors
    - night vision application
Sensors Used in Robot

- Resistive sensors
  - bend sensors, potentiometer, resistive photocells, ...
- Tactile sensors
  - contact switch, bumpers...
- Infrared sensors
  - Reflective, proximity, distance sensors...
- Ultrasonic Distance Sensor
- Inertial Sensors (measure the second derivatives of position)
  - Accelerometer, Gyroscope,
- Orientation Sensors
  - Compass, Inclinometer
- Laser range sensors
- Vision, GPS, ...

Resistive Sensors
Resistive Sensors

Bend Sensors
- Resistance = 10k to 35k
- As the strip is bent, resistance increases

Potentiometers
- Can be used as position sensors for sliding mechanisms or rotating shafts
- Easy to find, easy to mount

Light Sensor (Photocell)
- Good for detecting direction/presence of light
- Non-linear resistance
- Slow response to light changes

Inputs for Resistive Sensors

Voltage divider:
You have two resistors, one is fixed and the other varies, as well as a constant voltage

\[ V_{\text{sense}} = \frac{R_1}{R_1 + R_2} V \]

Digital I/O

Comparator:
If voltage at + is greater than at -, digital high out

Infrared Sensors

• Intensity based infrared
  - Reflective sensors
  - Easy to implement
  - Susceptible to ambient light

• Modulated Infrared
  - Proximity sensors
  - Requires modulated IR signal
  - Insensitive to ambient light

• Infrared Ranging
  - Distance sensors
  - Short-range distance measurement
  - Impervious to ambient light, color and reflectivity of object

IR Reflective Sensors

• Reflective Sensor:
  - Emitter IR LED + detector photodiode/phototransistor
  - Phototransistor: the more light reaching the phototransistor, the more current passes through it
  - A beam of light is reflected off a surface and into a detector
  - Light usually in infrared spectrum, IR light is invisible

• Applications:
  - Object detection,
  - Line following, Wall tracking
  - Optical encoder (Break-Beam sensor)

• Drawbacks:
  - Susceptible to ambient lighting
  - Provide sheath to insulate the device from outside infringement
  - Susceptible to reflectivity of objects
  - Susceptible to the distance between sensor and the object
Modulated Infrared

- Modulation and Demodulation
  - Flashing a light source at a particular frequency
  - Demodulator is tuned to the specific frequency of light flashes (32kHz~45kHz)
  - Flashes of light can be detected even if they are very week
  - Less susceptible to ambient lighting and reflectivity of objects
  - Used in most IR remote control units, proximity sensors

IR Proximity Sensors

- Proximity Sensors:
  - Requires a modulated IR LED, a detector module with built-in modulation decoder
  - Current through the IR LED should be limited: adding a series resistor in LED driver circuit
  - Detection range: varies with different objects (shiny white card vs. dull black object)
  - Insensitive to ambient light

IR Distance Sensors

- Basic principle of operation:
  - IR emitter + focusing lens + position-sensitive detector

  Location of the spot on the detector corresponds to the distance to the target surface, Optics to covert horizontal distance to vertical distance

Basic Navigation Techniques

- Relative Positioning (called *Dead-reckoning*)
  - Information required: incremental (internal)
    - Velocity
    - heading
  - With this technique the position can be updated with respect to a starting point
  - Problems: unbounded accumulation error

- Absolute Positioning
  - Information Required: absolute (external)
    - Absolute references (wall, corner, landmark)
  - Methods
    - Magnetic Compasses (absolute heading, earth’s magnetic field)
    - Active Beacons
    - Global Positioning Systems (GPS)
    - Landmark Navigation (absolute references: wall, corner, artificial landmark)
    - Map-based navigation

Dead Reckoning

- Cause of unbounded accumulation error:
  - Systematic Errors:
    a) Unequal wheel diameters
    b) Average of both wheel diameters differs from nominal diameter
    c) Misalignment of wheels
    d) Limited encoder resolution, sampling rate, …

  - Nonsystematic Errors:
    a) Travel over uneven floors
    b) Travel over unexpected objects on the floor
    c) Wheel-slipage due to: slippery floors; over-acceleration, fast turning (skidding), non-point wheel contact with the floor
Sensors used in navigation

- **Dead Reckoning**
  - Odometry (monitoring the wheel revolution to compute the offset from a known starting position)
  - Encoders,
  - Potentiometer,
  - Tachometer, …
- **Inertial Sensors** (measure the second derivative of position)
  - Gyroscopes,
  - Accelerometer, …
- **External Sensors**
  - Compass
  - Ultrasonic
  - Laser range sensors
  - Radar
  - Vision
  - Global Positioning System (GPS)

Motor Encoder

Incremental Optical Encoders

- Relative position
  - Calibration?
  - Direction?
  - Resolution?

Incremental Optical Encoders

Quiz 1:
If there are 100 lines in the grating, what is the smallest detectable change in motor-shaft angle?

Quiz 2:
How could you augment a grating-based (relative) encoder in order to detect the direction of rotation?

Incremental Optical Encoders

- Incremental Encoder:
  - It generates pulses proportional to the rotation speed of the shaft.
  - Direction can also be indicated with a two phase encoder:
Incremental Optical Encoders

- Incremental Encoder:

![Incremental Encoder Diagram](image)

Absolute Optical Encoders

- Used when loss of reference is not possible.
- Gray codes: only one bit changes at a time (less uncertainty).
- The information is transferred in parallel form (many wires are necessary).

<table>
<thead>
<tr>
<th>Binary</th>
<th>Gray Code</th>
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</thead>
<tbody>
<tr>
<td>000</td>
<td>000</td>
</tr>
<tr>
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<td>001</td>
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<tr>
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<td>111</td>
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<td>110</td>
<td>101</td>
</tr>
<tr>
<td>111</td>
<td>100</td>
</tr>
</tbody>
</table>

Absolute Optical Encoder Diagram

Other Odometry Sensors

- Resolver
  - It has two stator windings positioned at 90 degrees. The output voltage is proportional to the sine or cosine function of the rotor’s angle. The rotor is made up of a third winding, winding C.

- Potentiometer
  - Varying resistance

Range Finder

- Time of Flight
  - The measured pulses typically come from ultrasonic, RF, and optical energy sources.
  - \( D = v \times t \)
  - \( D \) = round-trip distance
  - \( v \) = speed of wave propagation
  - \( t \) = elapsed time
  - Sound = 0.3 meters/msec
  - RF/light = 0.3 meters/ns (Very difficult to measure short distances 1-100 meters)

- Range Finder (Ultrasonic, Laser)

Range Finder Diagram

Ultrasonic Sensors

- Basic principle of operation:
  - Emit a quick burst of ultrasound (50kHz), (human hearing: 20Hz to 20kHz)
  - Measure the elapsed time until the receiver indicates that an echo is detected.
  - Determine how far away the nearest object is from the sensor

- \( D = v \times t \)
  - \( D \) = round-trip distance
  - \( v \) = speed of propagation (340 m/s)
  - \( t \) = elapsed time

Bat, dolphin, …
Ultrasonic Sensors

- Ranging is accurate but bearing has a 30 degree uncertainty. The object can be located anywhere in the arc.
- Typical ranges are of the order of several centimeters to 30 meters.
- Another problem is the propagation time. The ultrasonic signal will take 200 msec to travel 60 meters. (30 meters roundtrip @ 340 m/s)

Polaroid Ultrasonic Sensors

- It was developed for an automatic camera focusing system
- Range: 6 inches to 35 feet

Transducer Ringing:
- Transmitter + receiver @ 50 KHz
- Residual vibrations or ringing may be interpreted as the echo signal
- Blanking signal to block any return signals for the first 2.38 ms after transmission

http://www.acroname.com/robotics/info/articles/sonar/sonar.html

Operation with Polaroid Ultrasonic

- The Electronic board supplied has the following I/O
  - INIT: trigger the sensor, (16 pulses are transmitted)
  - BLANKING: goes high to avoid detection of own signal
  - ECHO: echo was detected.
  - BHN: goes high to end the blanking (reduce blanking time < 2.38 ms)
  - BLNK: to be generated if multiple echo is required

Ultrasonic Sensors

- Applications:
  - Distance Measurement
  - Mapping: Rotating proximity scans (maps the proximity of objects surrounding the robot)

Scanning at an angle of 15º apart can achieve best results

Noise Issues

Laser Ranger Finder

- Range 2-500 meters
- Resolution: 10 mm
- Field of view: 100 - 180 degrees
- Angular resolution: 0.25 degrees
- Scan time: 13 - 40 msec.
- These lasers are more immune to Dust and Fog

http://www.sick.de/de/products/categories/safety/
Inertial Sensors

- **Gyroscopes**
  - Measure the rate of rotation independent of the coordinate frame
  - Common applications:
    - Heading sensors, Full Inertial Navigation systems (INS)
- **Accelerometers**
  - Measure accelerations with respect to an inertial frame
  - Common applications:
    - Tilt sensor in static applications, Vibration Analysis, Full INS Systems

Accelerometers

- They measure the inertia force generated when a mass is affected by a change in velocity.
- This force may change
  - The tension of a string
  - The deflection of a beam
  - The vibrating frequency of a mass

Accelerometer

- Main elements of an accelerometer:
  1. Mass
  2. Suspension mechanism
  3. Sensing element

High quality accelerometers include a servo loop to improve the linearity of the sensor.

Gyroscopes

- These devices return a signal proportional to the rotational velocity.
- There is a large variety of gyroscopes that are based on different principles

Global Positioning System (GPS)

24 satellites (+ several spares)

- broadcast time, identity, orbital parameters (latitude, longitude, altitude)

Noise Issues

- Real sensors are noisy
- Origins: natural phenomena + less-than-ideal engineering
- Consequences: limited accuracy and precision of measurements
- Filtering:
  - software: averaging, signal processing algorithm
  - hardware tricky: capacitor
Thank you!

Homework 6 posted on the web
Due date: Nov. 22, 2005
Next class: Robot Motion Planning