6.141:
Robotics systems and science
Lecture 5: Sensing

Lecture Notes Prepared by Daniela Rus

EECS/MIT

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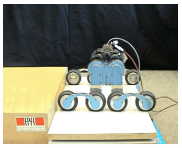
http://courses.csail.mit.edu/6.141/

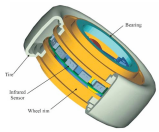
Challenge: Build a Shelter on Mars

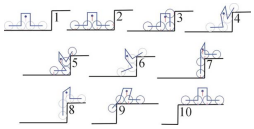
Locomotion summary

	motors	pro	con
Synchronous drive	2, one to translate, one to rotate	simple control	wheel alignment
Differential drive	2, 1 per wheel	simple	control
Car-type drive	2, one to translate, one to rotate	control	planning
Dual differential drive	2, one to drive translation and one for rotation	Translation guaranteed mechanically	gear complexity

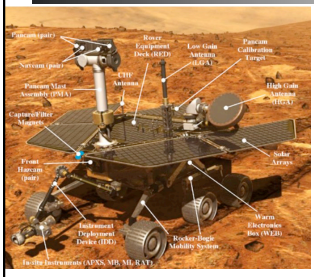
Wheeled Legs: Octobot (ETH)

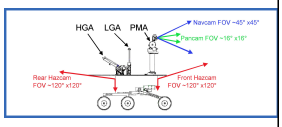






Today: sensors and perception





Outline

- What are sensors?
- Types of sensors (many examples)
- Sensor details
- Examples

What are sensors

- Sensors constitute the perceptual system of a robot
- Sensors are physical devices that measure physical quantities
- Sensors do not provide *state*
- Examples:
  - contact -> switch
  - distance -> ultrasound, radar, infra red
  - magnetic field -> compass

Examples of Sensors

- More examples:
  - light level -> photo cells, cameras
  - sound level -> microphones
  - strain -> strain gauges
  - rotation -> encoders, switch
  - temperature -> thermometer
  - gravity -> inclinometers
  - acceleration -> accelerometers
  - acceleration -> rate gyroscopes
  - flames -> UV detector

Sensor Types

- Based on energy emission:
  - Passive: received energy only
  - Active: emitted energy
- Based on data source:
  - Proprioceptive: sensing internal properties
  - Exteroceptive: sensing external properties

Sensor Types

- Based on energy emission:
  - Passive: received energy only (e.g., human vision, hearing)
  - Active: emitted energy (e.g., sonar, ladar, structured lighting, human touch)
- Based on data souce:
  - Proprioceptive: sensing internal properties (e.g., battery level, wheel encoders)
  - Exteroceptive: sensing external properties (e.g., vision, ranging)

Signal to Symbol

- Sensors provide signals
  - The bumper switch is depressed
- Acting requires state
  - Stop if we have collided with something
- Reconstruction:
  - *"Given the sensory reading I am getting, what must the world be like to make the sensor give me this reading?"*

Levels of Processing

- Determine position of switch from voltage in circuit => electronics
- Using a microphone, separate voice from noise => signal processing
- Using a camera, find people in the image and recognize "persons of interest" => computation

Perception system design

- Consider perception in context:
  - The task the robot has to perform
  - The environment it inhabits
  - The best sensors for that task
  - The best placement of sensors
  - The best way to use a sensor
- Minimalist approach:
  - Determine *sufficient* state

Example: Detecting People

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Example: Detecting People

- temperature: pyro-electric sensors detect special temperature ranges
- movement: if everything else is static or slower/faster
- color: if people wear uniquely colored clothing in your environment
- shape: now you need to do complex vision processing

Example: Measuring Distance

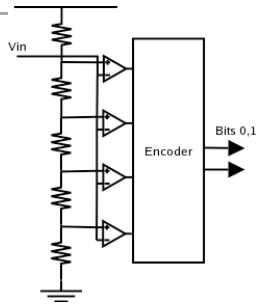
- Ultrasound sensors (sonar) give distance directly (time of flight)
- Infra red provides return signal intensity
- Two cameras (i.e., stereo) can give you distance/depth
- Use perspective projection with 1 camera
- Use structured light; overlying grid patterns on the world

Analog and Digital Signals

- Sensors may output signals in different formats:
  - Analog level (voltage or resistance)
  - Analog waveform
  - Digital level
  - Digital waveform
- Modern computers require digital inputs

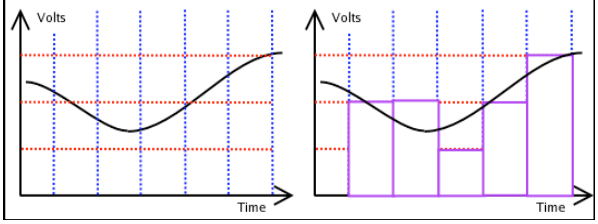
Analog to Digital Conversion

- Analog-to-digital conversion requires specialized circuit (ADC)
- Most circuits based on analog *comparators*



Sampling Rates and Resolution

- Analog waveforms are time-varying signals
- ADC will sample at some fixed frequency (x axis)
- ADC will sample at some fixed resolution (y axis)
- Nyquist criterion: sample at 2 * max frequency

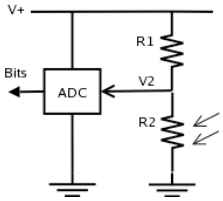


Simple Analog Sensors: Photocells for Light

- Passive sensors for measuring light intensity
- Two technologies:
  - Photoresistor: light-dependent resistor
  - Photodiode: light-dependent diode
- Photoresistor:
  - increasing light => decreasing resistance
- Photodiode (forward bias):
  - increasing light => increasing current

Photocell Circuits

- Light sensors vary current/resistance
- ADC measures voltage
- Sensor must be placed in circuit
- Ohm's Law: V = IR



Photocell Uses

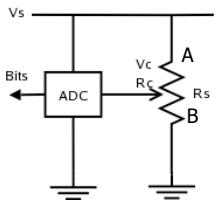
- Light sensors can measure:
  - Ambient light intensity
  - Differential intensity (two detectors)
- Light sensors should be:
  - Shielded
  - Focused
  - Oriented

Detecting Position

Potentiometer Circuit

- Pots vary resistance
- Attach wire to A; no voltage drop
- Attach wire to B: big voltage drop
- ADC measures voltage and is converted to digital value
- Uses?

Joint angle
Shaft angle
Linear travel

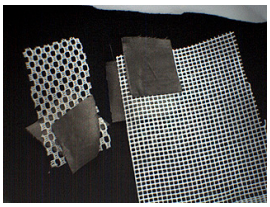


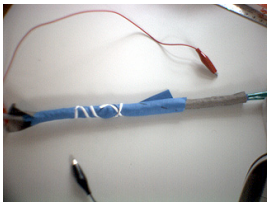
Detecting Objects

Simple Digital Sensors: Switches for Contact

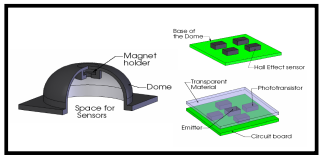
- Simplest sensor: 1-bit digital
- Minimal circuitry, processing
  - De-bounce hardware or software
- Normally open (NO):
  - Current flows when switch is pressed
- Normally closed (NC):
  - Current flows when switch is released
- Many types:
  - Press, toggle, rocker, knife
  - Reed, mercury
- Contact
  - Trigger on contact with object
- Limit
  - Trigger when joints are at end of range
- Shaft encoder
  - Count revolutions of shaft (reed)
- Orientation
  - Detect if robot is tipped over (mercury)

Skin: Electric-conductive fabric





Skin Sensor



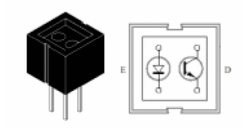
- Position of the top of the sensor gives an estimation of the force applied
- Magnetic:
  - A magnet on the dome, 4 hall effect sensors on the base
- Optical version
  - A LED and 4 photo receptors on the base

Skin

- 6 tactile sensors on the fingers and thumb
- A tactile sensor has 4 domes with 4 hall effect sensors in each dome
- Palm: 16 domes, each with 4 hall effect sensors

Simple Sensors: IR for Object Detection

- Optosensors have emitter detector pair in same package
- Reflective and break-beam configurations
- Digital and analog versions



Optosensor Uses

- Reflectance
  - Object proximity
  - Feature detection (e.g., retro reflector)
  - Bar-code reading
  - Shaft encoding
- Break-beam
  - Object presence (e.g., gripper)

Measuring Distance

How do we get distance from the measured time-of-flight?

Sound/light travels at a constant speed, which varies slightly based on ambient temperature

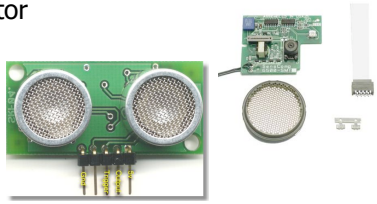
At room temperature, sound travels at 331 m/sec, or around 30 cm/msec

Ultrasound

- Ultrasound range sensing is based on the time-of-flight principle
- The emitter produces a "chirp" of sound (at very high frequency)
- Sound travels away from emitter, bounces off barrier, returns to detector
- The time elapsed is measured

Sonar sensor construction

- Some sensors have single emitter/ detector pair
- Other sensors have common emitter/ detector



Angular Resolution

- Typical sensors have 30 degree angular resolution
- Diffraction limited: wavelength is comparable to emitter size
- E.g., Polaroid transducer:
  - Frequency 50kHz
  - Wavelength 7mm
  - Sensor diameter ~ 40mm
  - Max range ~ 10m

Limitations?
How do we overcome them?

Laser range finders (ladar)

- Sonar sensors measure range using time-of-flight of *sound*
  - Sound: 330 m/sec in air
- Laser range finders measure time-of-flight of *light*
  - Light: 300,000,000 m/sec in vacuum

Scanning laser range-finders

- Scanning laser range-finder:
  - Laser range finder
  - Rotating mirror(s)
- E.g., SICK
  - 3D planar scan, 180 degree FOV
- E.g., Riegl
  - 3D volume scan, 360/80 degree FOV

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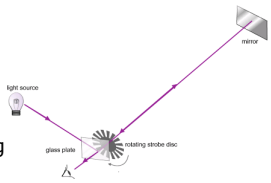
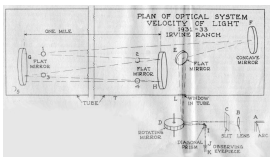
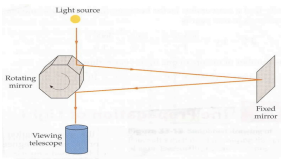


Fizeau Experiment
315,000km/s

Michaelson Experiment

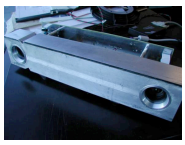




299,796 km/s +/- 4
Same principle used to measure distance
Given speed of light

Imaging Sensors

- Cameras
  - Color, texture give clues about road edges, plant and rock locations
- Stereo/LADAR
  - Provide snapshot of 3-D terrain geometry ahead of vehicle

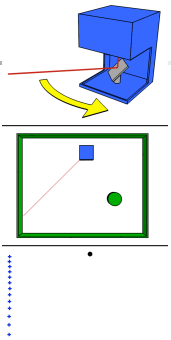


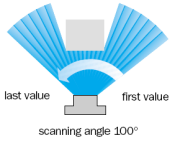
DAD's stereo camera

SICK laser ranger

LADAR

- **LA**ser **D**etection **A**nd **R**anging
  - How it works





LADAR

LMS 291-S05 2D LADAR Scanner; Cost: $3,014

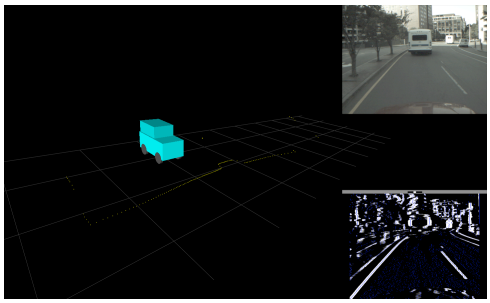
Data Specifications
- Data Interface RS 232 / RS 422 (configurable)
- Transfer Rate 9.6 / 19.2 / 38.4 / 500 kBd

Sensing Specifications
- Scanning Speed: 75 Hz
- Angular View: 100°, 180°
- Angular Resolution: 0.25° / 0 .50° / 1.00°
- Measurement Resolution 10 mm

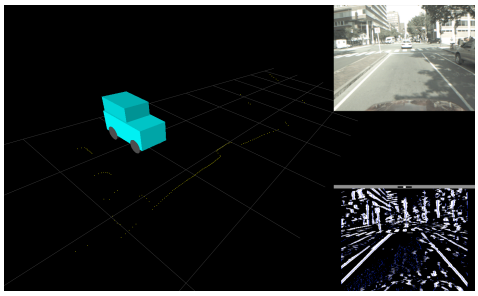
Physical Specifications
- Weight: approx. 19.8 lb
- Environment: Outdoor (Fog Correction)

Electrical Specifications
- Supply Voltage: 24 V DC ± 15%

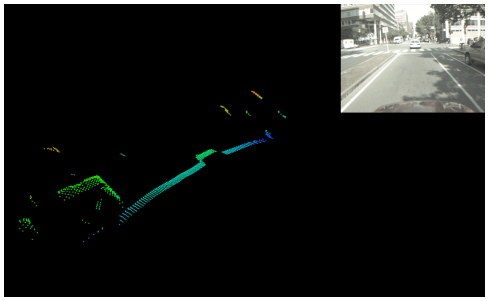
One-sweep Data



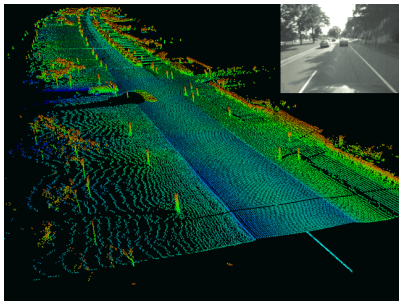
One-scan Data



Several-scan Data



Laser Processing



Ladar versus sonar

- Pros:
  - Small spot size (good angular resolution)
  - High sample rate
  - Short wavelength (fewer specular reflections)
- Cons:
  - Large/heavy
  - Complex/expensive

MIT Vehicle: Talos (Land Rover LR3)

- Approach: Perception-based navigation and planning
- Power: 6 kW gas-fueled generator
- Computation: blade cluster (40 processing cores)
- Sensing: 13 lidars, 15 radars, 5 cameras
- Planning and control: rapidly-exploring random tree (RRT), pure-pursuit
- Software: powerful new UDP messaging, visualization architecture

Detecting Location

Position Sensors

- GPS (global positioning system)
  - May provide sub-meter resolution, but can be blocked by urban landscape

courtesy of NavCom

- Vehicle attitude
  - Gyroscopes, accelerometers (IMUs) can be used to get/update compass heading, pitch, roll of vehicle