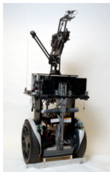


6.141: Robotics Systems and Science
Technical Lecture 2
Introduction to
Robot Control Architectures
and
Sensing

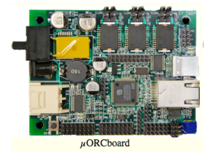
Lecture Notes Prepared by
Una-May O'Reilly
CSAIL/MIT
Spring 2010

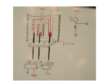
http://courses.csail.mit.edu/6.141/
Challenge: Build a Shelter on Mars

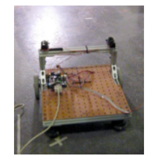


# Lecture 2

- You will learn about the high level design of the control software for the hardware you saw in lab 1
- You will learn about sensors and sensing
- Outcome: ready to work on lab 2
  - Building a reactive robot that moves in response to light







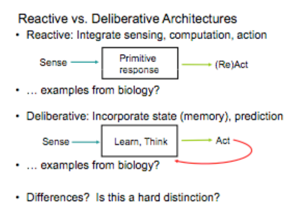
# Lecture Outline

- Control architectures
  - Reactive to deliberate spectrum
  - Consider the rss robot
  - Sense-model-plan-act
  - Behaviour-based
- Sensors
  - Definition, properties
  - Bottom-up from signal to simple analog or digital sensor
  - Examples introduced in terms of information a mobile robot might need



# Reactive and Deliberative Intelligence and Behavior

- Recap from Lecture 1
- There is a spectrum of "design solutions" for behavior
  - They all link sensing the world to acting in the world through a physical device (robot!)
- As robot behavioural competence increases,
  - Software design of this control architecture becomes more complicated in structure, decomposed and more complex abstractions.
- Specialization for different "kinds" of robots
  - Health service robots, humanoids, mobile autonomous
  - Mission sets priorities, perspective
- Depends on sensing and acting components,
- Depends on environment we anticipate the robot inhabiting



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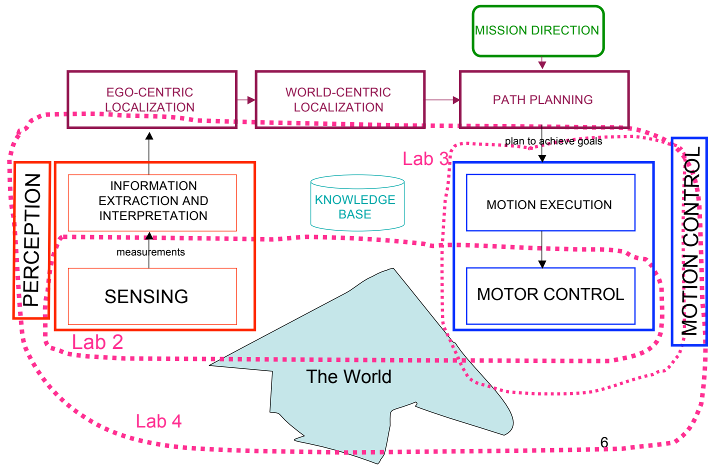
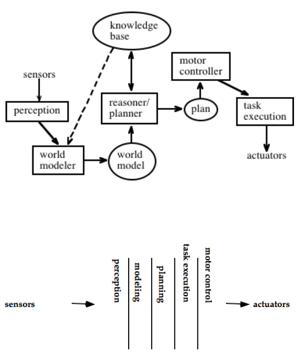
# A Mobile Robot Control Architecture






# Behavior-Based Control Architecture



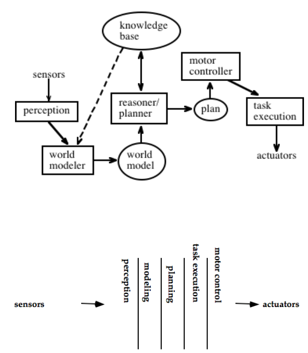

Horizontal decomposition

Sense-Model-Plan-Act

Design Choices
-How much memory to keep,
-How much internal state to represent
-Unified or distributed representation(s) of the world
Design Philosophy:
rational agent like “us”
vs
creature intelligence
Practicality
handling complexity
mission requirements

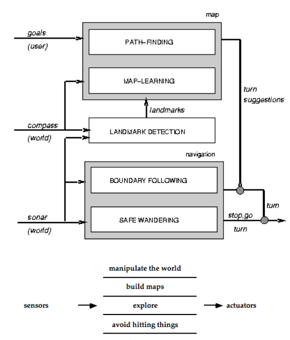


# Behavior-Based Control Architecture




Horizontal decomposition

Sense-Model-Plan-Act




Vertical decomposition

Behavioral Layering

# If we are going to react, what triggers the reaction?…sensor!

- What might a mobile robot need to know?
  - Where am I? local reference frame
  - What's out there? Obstacles, walls
  - Where have I been? History of position
- Other: Depends on the mission
  - We assume the mission perspective
  - Not the "whatever comes naturally" creature perspective
- Sensor functions
  - report distance wheels have traveled — proprieception
  - report changes in internal state — proprieception
    - tilted? Over-heating? Low battery?
  - report about structure in the world (external state) — exteroception
    - touch objects -contact or non-contact



# What is a Sensor?

Sensor model

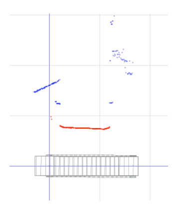
- Sensors are physical devices that measure physical quantities
  - R=f(e) or dR/dt =f'(e)
- From robot design perspective:
  - inverse problem: extracting state from R
  - << a sensor doesn't provide state >>
  - This problem is ill-posed
    - More than one solution (or none!)
      - We have to bring context and outside information to bear
    - Pragmatic deduction of state
  - Sensor can be unstable
    - Occurs outside operating spec envelope
    - Continuous changes in environment are not mapped to smooth changes in the measurement range



# Sensors

Sensor Characterization
- Dynamic range
  - largest possible signal divided by the smallest possible signal it can generate.
- Resolution
  - smallest change it can detect in the quantity that it is measuring
- Sensivity:
  - how much the sensor's output changes when the measured quantity changes
- Noise:
  - a random deviation of the signal that varies in time
- System or random error

The REALITY
- Real sensors are noisy
- A sensor can't give you the complete picture





# Sensor Selection

- Issues taken into consideration
  - Computational expense
  - Physical properties - Power, weight, mounting,
  - Speed of data reporting /operation
  - Robustness in environment condition tolerance
  - Cost
  - Error rate

# Examples of Sensors

Measurement -> sensor

- Contact -> switch
- Distance -> ultrasound, radar, infra-red
- 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



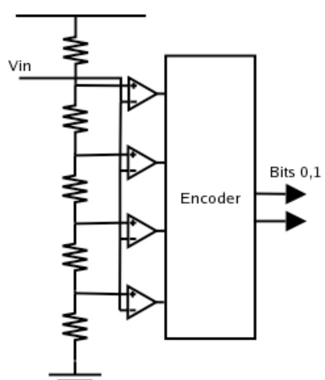
# Analog and Digital Signals

- 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

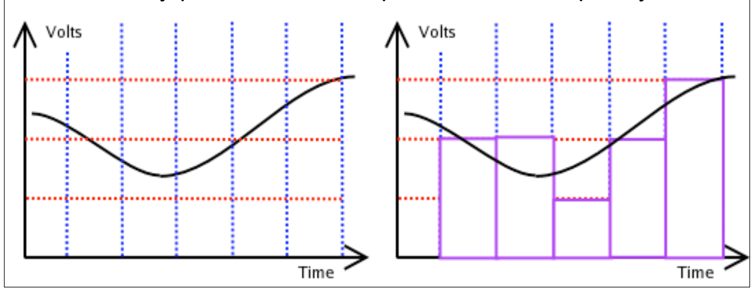
- Analog-to-digital conversion requires specialized circuit (ADC)
- Most circuits based on analog *comparators*



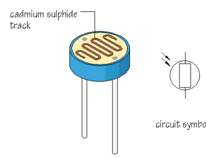



# Sampling Rates and Resolution

- 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

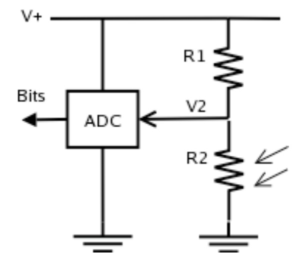



- Passive sensors for measuring light intensity
- Two technologies:
  - Photoresistor: light-dependent resistor
  - Photodiode: light-dependent diode
- Photoresistor:
  - Cadmium sulfide
  - increasing light => decreasing resistance
- Photodiode (forward bias):
  - increasing light => increasing current



# 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



# 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

# Switch Uses

- 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)



# Mobile Robot Sensors Classified by Information they Return

- INTERNAL STATE:
  - tilted? inclinometer
  - Differential properties, eg acceleration
  - Wheel shaft rotations, eg encoders - Lecture 4
- POSITION: Where is robot with respect to…?
  - World coordinate system -- Absolute terms - Compass, GPS
  - Local frame of reference - ego-centric terms, 'pose'
- ENVIRONMENT PROPERTIES: What's out there?
  - Obstacles? Perimeter sensors…camera
  - People? Pyroelectric sensors…camera
  - Objects of interest: camera
- RANGE: How far away is something?
  - Ultra-sound
  - Laser Range Finder

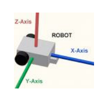


# Internal Sensing



# Internal Sensors - Accelerometers

- Vehicle attitude via inertial sensors
- Gyroscopes can be used to determine pitch, roll of vehicle
- Accelerometer: spring-mounted mass whose displacement under acceleration can be measured
  - F=ma and F=kx^2
  - a=kx^2/m
  - Usually 3 are placed orthogonally (IMU)
  - Factor out local gravity vector in direction and magnitude
  - Tilt angle=arcsin(m/1g)




- Battery level (voltage sensor)
- Heat - thermometer

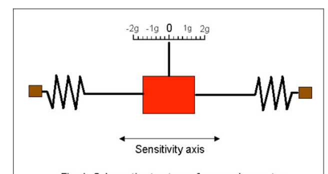
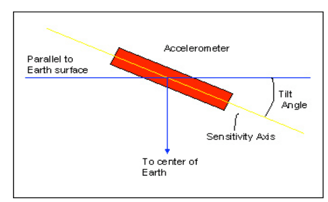


Fig. 1. Schematic structure of an accelerometer

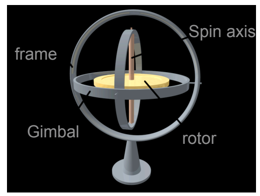



www.rotoview.com/accelerometer.htm

# Internal Sensors- Gyros

- Gyroscopes can be used to determine pitch, roll of vehicle
- Spinning mass suspended in a gimball
- Spins: standard definition of angular momentum of particle about origin, angular momentum is conserved
- Precession:
  - Resistance to change in orientation
  - Can be measured as a force
  - Spinning device actually rotates





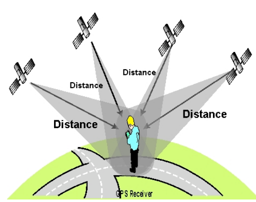



# Detecting Position



# Global Position

- GPS (global positioning system)
- May provide sub-meter resolution, but can be blocked by urban landscape
- 24 satellites placed in orbit
- Works in any weather condition, anywhere, 24/7
- 2 orbits/day and radio tx to Earth for time differencing
- Receivers triangulate signals
  - from at least 3 satellites - longitude, latitude, tracking
  - 4: altitude also
  - Lock on with 12 parallel channels

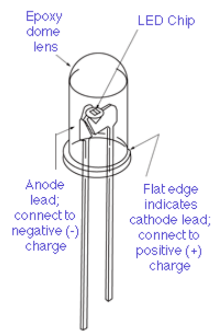






# Detecting Objects

## Proximity Sensors: Optosensors

- *Active* sensors with emitter-detector pairs (in single package)
- Emitters are light emitting diodes (LEDs)
- Detectors are photodiodes or phototransistors
- Emitter/detector have matched wavelengths, usually in IR
- Measuring reflected intensity
  - Light objects appear closer than reality, dark objects can be missed
- Or, break beam
- Finicky: calibrate and test required





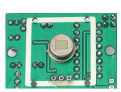

## Detecting People

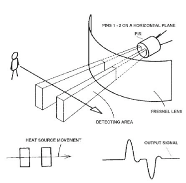
- temperature: pyro-electric sensors detect special temperature ranges and report change directionally
- movement: if everything else is static or slower/faster
- color: if people wear uniquely colored clothing in your environment
- shape: now you need to do complex vision processing

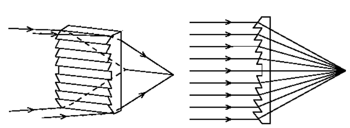


## Pyroelectric sensors

- PIR motion sensor is a pyro-electric IR sensor with Fresnel lens
- The Fresnel lens condenses light, providing a larger range of IR to the sensor.





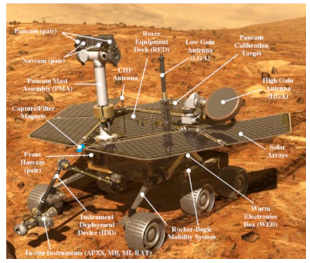


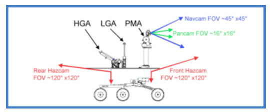


## Range Sensing

# Measuring Distance

- Infra red provides range detection via position sensitive detector
- Two cameras (i.e., stereo) can give you distance/depth
- Use structured light; overlying grid patterns on the world
- Ultrasound sensors (sonar) give distance directly (time of flight)
- Laser range finders
  - Time of flight, triangulation, phase shift




There's more than one way to skin a cat!



# Distance from Time of Flight

- 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

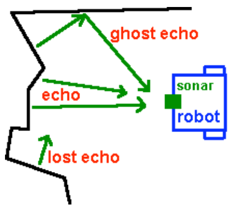


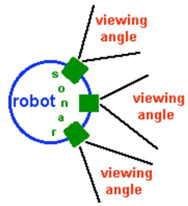
# Sonar: Angular Resolution

- 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?

# Sonar Issues





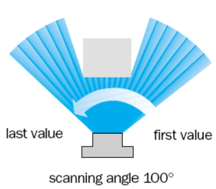

# Laser range finders (ladar)

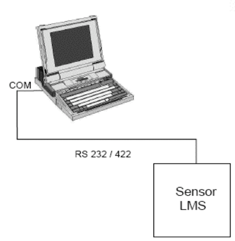
- Laser Detection and Ranging
- Aka LIDAR (Light Detection And Ranging)
- Sonar sensors measure range using time-of-flight of *sound*
  - Sound: 330 m/sec in air
- Laser range finders measure time-of-flight of *light*
  - Light: 300,000,000 m/sec in vacuum



# How LADAR Works

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



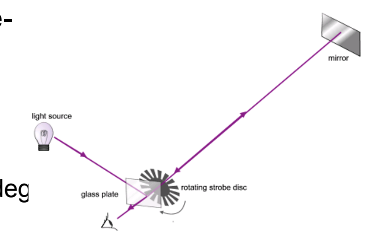







# Scanning laser range-finders

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




Fizeau Experiment
315,000km/s

## LMS 291-S05 2D LADAR Scanner; Cos $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

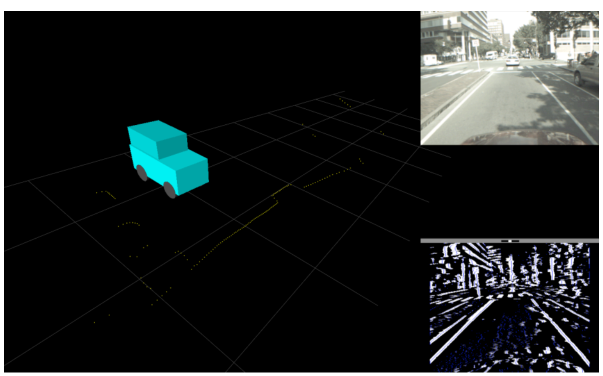
Physical Specifications
- Weight: approx. 19.8 lb
- Environment: Outdoor (Fog Correction)

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

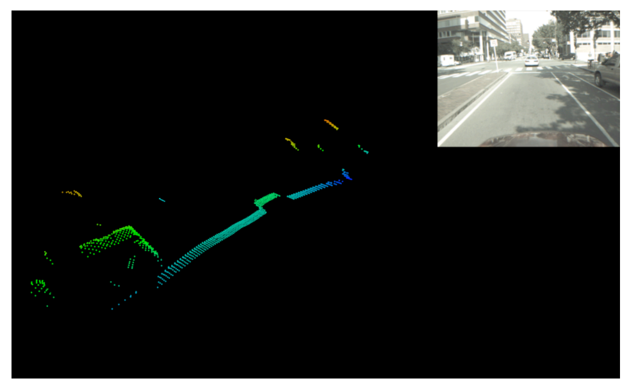


## Mounting a SICK on Talos

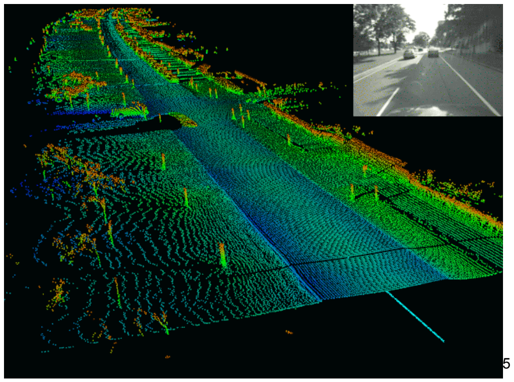

## One-scan Data



## Several-scan Data



## Laser Processing Full Image EG





## Ladar versus sonar

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