UMSL
Mathematics & Computer Science

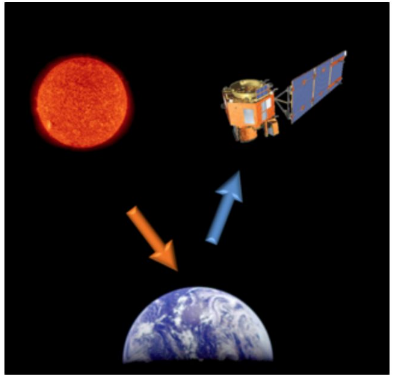
25. Robotics

25.2.1 Sensors

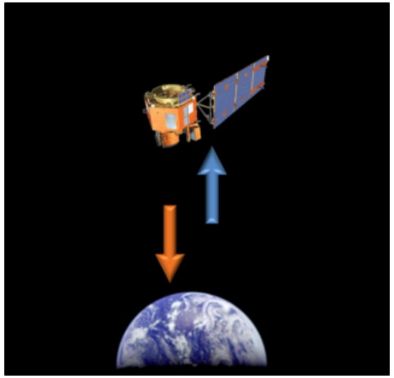
- Sensors are the perceptual interface between robot and environment
- Sensors may be categorized as:
  - (a) Active
    - Read & Write to the environment
  - (b) Passive
    - Only read the environment
- Sensors also may be categorized as:
  - (a) Range finders
    - Range finders determine location of objects in the environment
  - (b) Location sensors
    - Location sensors find the robot's location in the environment (own location)
  - (c) Proprioceptive sensors
    - Proprioceptive sensors inform the robot of its own motion (for example, odometer)

25.2.1 Active vs Passive Sensors

- Passive sensors (such as cameras) capture signals that are generated by other sources in the environment
    - They are true observers of the environment
- Active sensors, such as sonar, send energy into the environment
    - They rely on the fact that this energy is reflected back to the sensor
    - They usually provide more information than passive sensors, but at the expense of increased power consumption and with a **danger of interference when multiple active sensors are used at the same time**



Passive sensor



Active sensor

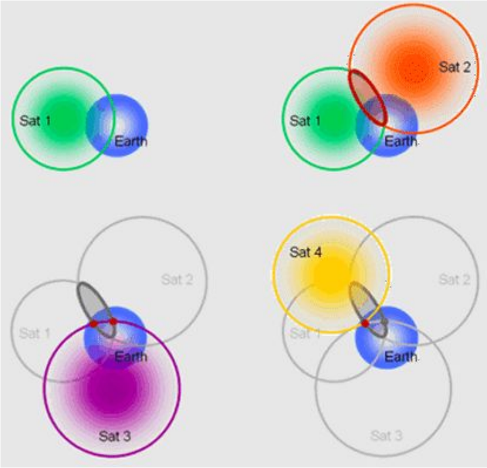
25.2.1 Location Sensors - Global Positioning System

When we are using GPS (in our phones), what information do we transmit?

- GPS measures the distance to satellites that emit pulsed signals
  - there are 31 satellites in orbit, transmitting signals on multiple frequencies
- Each GPS satellite continuously broadcasts a navigation message
  - All satellites broadcast at the same two frequencies - 1.6 GHz and 1.2 GHz (FM is ~100 MHz)
  - The message contain information such as week number and the time within the week
  - GPS must demodulate the message from each satellite for 18 to 30 seconds
  - Need an unobstructed line of sight to four or more GPS satellites
  - By triangulating signals from multiple satellites, GPS receivers can determine their absolute location on Earth to within a few meters
- GPS does not work indoors (unlike cell phone signals) or underwater
  - Margins of operation is less than 10 to 20 dB & Higher frequencies are worse for propagation

Why does GPS positioning require four satellites?

- You need four satellites because each data from one satellite put you in a sphere around the satellite. By computing the intersections you can narrow the possibilities to a single point
    - Two satellites intersection places you on a circle. (all points possible)
    - Three satellites intersection places you on two possible points.
    - The last satellite give you the exact location.
    - You can avoid using four satellite if you already know the altitude, for example when you drive, you can use the ground level as the last intersection. But you can't possibly do this in a plane, since you are not bound to the ground.



25.2.1 Range Finders

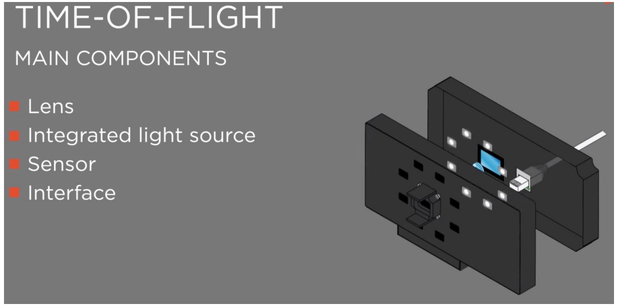
- Range finders are sensors that measure the distance to nearby objects
  - Sonar sensors
  - Stereo vision
  - Optical range finders
    - Time of flight cameras (for close objects, say detecting human hand)
    - Scanning lidars (for objects within, say 100m)
  - Radar
- Most ground robots today are equipped with optical range finders and scanning lidars

25.2.1 Sonar sensors and Stereo vision

- Sonar sensors emit directional sound waves, which are reflected by objects, with some of the sound making it back into the sensor
  - The time and intensity of the returning signal indicates the distance to nearby objects
  - Sonar is the technology of choice for autonomous underwater vehicles
  - Examples: dolphins, bats, human echo-location (Daniel Kish's story)
- Stereo vision relies on multiple cameras to image the environment from slightly different viewpoints
  - analyzes the resulting parallax in these images to compute the range of surrounding objects
- For mobile ground robots, sonar and stereo vision are now rarely used, because they are not reliably accurate

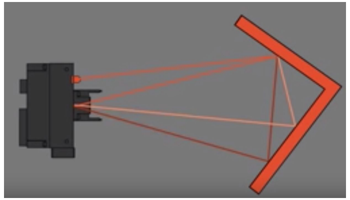
25.2.1 Time of Flight Cameras

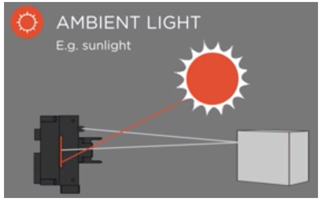
- Just like sonar sensors, optical range sensors emit active signals (light) and measure the time until a reflection of this signal arrives back at the sensor
- The Time of Flight (ToF) cameras are a widely used example
    - Example: Kinect for Xbox One (released on November 22, 2013) uses a wide-angle time-of-flight camera; it processes 2 gigabits of data per second to read its environment
- Features
    - Captures full 3D at once (no need to take various pictures and assemble them to form a 3D model
    - The artificial illumination may be provided by a laser or by an LED

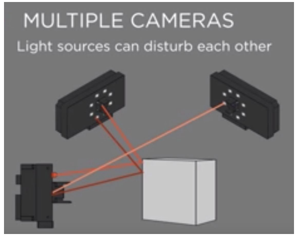


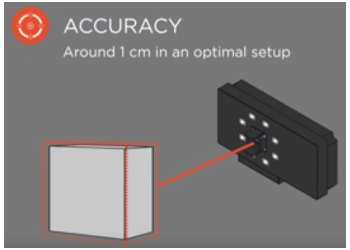
25.2.1 Time of Flight Cameras

- Applications
  - Logistics - box packing, moving packages inside a warehouse, scanning and labelling items, autonomous vehicles in warehouses
  - Factory automation - find, pick, and mount objects
  - Medical - check patient monitoring and positioning
- Disadvantages
  - Multiple reflections produced by corners and concave shapes create noises
  - High intensity ambient light confuses the sensors
  - Lights from multiple cameras can disturb each other
  - Accuracy is only around 1 cm in optimal setup









25.2.1 Scanning Lidars

- Lidars (Light detection and ranging) measure distance to a target by illuminating the target with pulsed laser light
  - and measuring the reflected pulses with a sensor
- Lidars tend to provide longer ranges than time of flight cameras, and tend to perform better in bright daylight (than ToFs)
- 600–1000 nm lasers are most common for many applications
  - Maximum power is limited by the need to make them eye-safe (in applications that operate around people)
- Disadvantages
  - Computational requirement for data processing
  - It is an active sensor
  - Do not scan the full scene at once (need to scan)

This lidar may be used to scan buildings, rock formations, etc., to produce a 3-D model. The lidar can aim its laser beam in a wide range: its head rotates horizontally; a mirror tilts vertically. The laser beam is used to measure the distance to the first object on its path.

25.2.1 Scanning Lidars - Applications

- Agriculture - Lidar can create a topographical map of the fields and reveal slopes and sun exposure of the farm-land; and help determine where to apply costly fertilizer
- Autonomous vehicles may use lidar for obstacle detection and avoidance to navigate safely through environments, using rotating laser beams
  - Five lidar units (produced by the German company Sick AG) were used for short range detection on Stanley, the autonomous car that won the 2005 DARPA Grand Challenge
- Lidar speed guns are used by the police to measure the speed of vehicles for speed limit enforcement purposes

Tesla & Google Disagree About LIDAR — Which Is Right?

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July 29th, 2016 by **Michael Barnard**

Tesla rather **famously** has **chosen not to** use LIDAR as one of the sensors on its cars to assist with **its autonomous features**, at least so far. **Google uses LIDAR** as one of its dominant sensors and insists it's necessary. With the recent **fatality** in a Tesla that was operating under Autopilot, Tesla's choice is under **attack**. Assessing the competing claims requires understanding the strengths, weaknesses, and compromises inherent in the different sensor types.

25.2.1 Radars

- Radar is the sensor of choice for unmanned aerial vehicles
- Radar sensors can measure distances of multiple kilometers
- If a surface can reflect light, radar can spot it

Toyota Safety Sense

Dynamic Radar Cruise Control

This high-tech cruise control uses radar behind the Toyota badge plus a camera on the windshield designed to adjust your speed, helping you maintain a preset distance from the car in front of you. [32]

25.2.2 Effectors

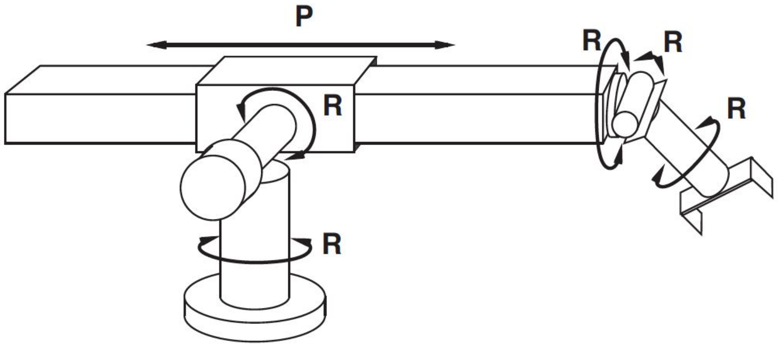
- Effectors are the means by which robots move and change the shape of their bodies
  - Understanding **degree of freedom (DOF)** is a key to understand the design of effectors
- We count one degree of freedom for each independent direction in which a robot, or one of its effectors, can move
  - For example, a rigid mobile robot such as an Autonomous Underwater Vehicle has six degrees of freedom, three for its (x, y, z) location in space and three for its angular orientation. How?
  - These six degrees define the pose of the robot; the dynamic state of a robot includes these six plus an additional six dimensions for the rate of change of each kinematic dimension, that is, their velocities (total 12 DOFs)

25.2.2 Additional Degrees of Freedom Within a Robot

- The elbow of a human arm possesses _______ degree of freedom
  - It can flex the upper arm towards or away, and can rotate right or left

- The wrist has _______ degrees of freedom
- Six degrees of freedom are required to place an object, such as a hand, at a particular point in a particular orientation

Six degrees of freedom, created by **five revolute joints** that generate rotational motion and **one prismatic joint** that generates sliding motion



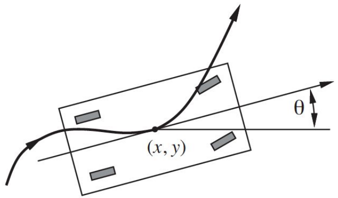
SIX Degrees of Freedom for which part?

25.2.2 Additional Degrees of Freedom Within a Robot

- The human arm as a whole has more than six degrees of freedom. How?
    - Put your hand on the table and notice that you still have the freedom to rotate your elbow without changing the configuration of your hand
- Manipulators that have extra degrees of freedom **are easier to control** than robots with only the minimum number of DOFs
- Many industrial manipulators therefore have seven DOFs, not six
    - Industrial manipulators are stationary in nature (they don't move like cars)

25.2.2 DOFs in Mobile Robots

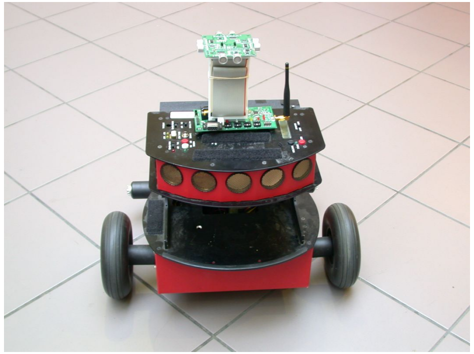
- For mobile robots, the DOFs are not necessarily the same as the number of actuated elements - How?
  - What is the DOF for a “typical” car?
    - It can move forward or backward, and it can turn - giving it _____ DOFs
  - A car’s kinematic configuration is three-dimensional
    - on an open flat surface, one can easily maneuver a car to any (x, y) point, **in any orientation**
  - **Thus, the car has three effective degrees of freedom but two controllable degrees of freedom**



- We say a robot is **nonholonomic** if it has more effective DOFs than controllable DOFs and **holonomic** if the two numbers are the same
  - Holonomic robots are easier to control—it would be much easier to park a car that could move sideways as well as forward and backward—but holonomic robots are also mechanically more complex

25.6 Moving

- Deterministic path planning algorithms can produce path plans
    - these algorithms assume that the robot can simply follow any path that the algorithm produces
    - In the real world, this is not the case
    - Robots have inertia and cannot execute arbitrary paths except at arbitrarily slow speeds
- Three techniques for robot moving
    - Potential-field control
    - Reactive control
    - Reinforcement learning control



25.6.2 Potential-field Control

- Define an attractive force that pulls the robot towards its goal configuration and a repellent potential field that pushes the robot away from obstacles
  - Then move the robot in a direction that minimizes the total energy
- Potential-field control is great for local robot motion

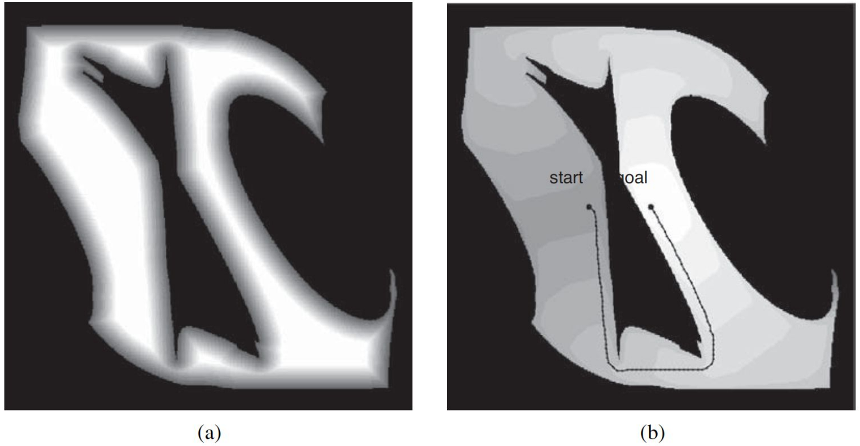
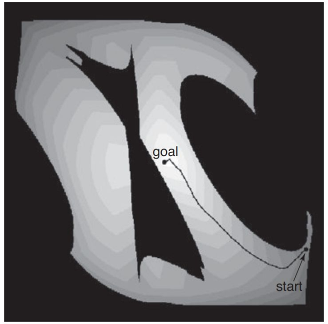


Figure 25.17 (a) A repelling potential field pushes the robot away from obstacles. (b) Path found by simultaneously minimizing path length and the potential.

25.6.2 Limitations of Potential-field Control

- Moving based on the potential-field is similar to searching using only the “physical distance heuristic” in the greedy best-first search algorithm
    - Performing hill climbing in the potential field can lead to the robot being trapped in local minima
- Additional Limitation
    - The forces they generate depend only on the obstacle and robot positions, not on the robot’s velocity
    - Thus, potential field control is really a kinematic method and may fail if the robot is moving quickly
- Potential-field control is great for local robot motion.. But sometimes we need global planning



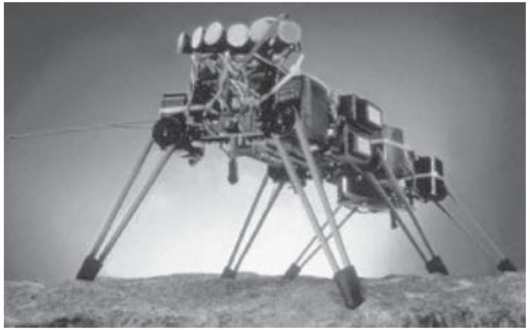
(a)

(b)

Figure 25.23 Potential field control. The robot ascends a potential field composed of repelling forces asserted from the obstacles and an attracting force that corresponds to the goal configuration. (a) Successful path. (b) Local optimum.

25.6.3 Reactive Control

- Sometimes the model of the environment may not be available
    - Especially in complex or remote environments, such as the surface of Mars
    - In such cases, a reflex agent architecture using reactive control is more appropriate
- Example - A legged robot that attempts to lift a leg over an obstacle
    - Rule for the robot
        - (a) lift the leg a small height “h” and move it forward, and
        - (b) if the leg encounters an obstacle, move it back and start again at a higher height



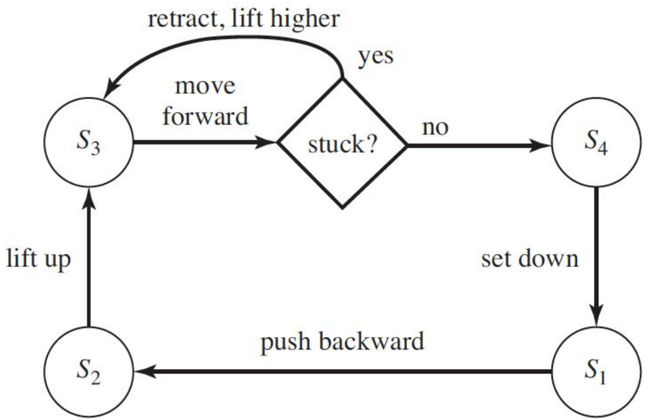
[Genghis - A hexapod robot]()

The robot’s sensors are inadequate to obtain models of the terrain for path planning. Moreover, even if we added sufficiently accurate sensors, **the twelve degrees of freedom (two for each leg) would render the resulting path planning problem computationally intractable**

25.6.3 Reactive Control

- On rugged terrain, obstacles may prevent a leg from swinging forward
    - A simple control rule: when a leg's forward motion is blocked, simply retract it, lift it higher, and try again
- Variants of this simple feedback-driven controller have been found to generate remarkably robust walking patterns, capable of maneuvering the robot over rugged terrain

An augmented finite state machine (AFSM) for the control of a single leg. Notice that this AFSM reacts to sensor feedback: if a leg is stuck during the forward swinging phase, it will be lifted increasingly higher



25.6.4 Reinforcement Learning Control

- Reinforcement learning for Policy Search
  - The idea is to keep twiddling the policy as long as its performance improves, then stop
  - A policy π is a function that maps states to actions
  - We are interested primarily in parameterized representations of π that have far fewer parameters than there are states in the state space
  - It could be a nonlinear function such as a recurrent neural network
- RL has solved challenging robotics problems for which no solution existed
- Example of acrobatic autonomous helicopter flight

  - autonomous flip of a small RC (radio-controlled) helicopter
  - Only the most experienced of human pilots are able to perform it
  - RL using only a few minutes of computation, learned to safely execute a flip every time
- Reinforcement learning in action

Summary

- Sensors can be classified as active or passive, OR as range finders, location sensors, or proprioceptive sensors
- Time of flight sensors are best for close 3D modeling, Lidars are better for slightly farther sensing such as for self-driving vehicles, and Radars are more suitable for much long-distance sensing such as for unmanned aerial vehicles
- Holonomic robots are easier to control are mechanically more complex
- Potential-field control and reactive control are use (almost) the opposite strategies for robot movement
- Reinforcement learning does end-to-end mapping between sensors and actions by searching the optimal policies