המסלול האקדמי
המכללה למינהל

Introduction to Robotics
Lesson 2 – Sensors and Actuators

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Agenda

- Mobile Robot Sensor Types
- Sensor Noise Model
- Sensors Filtering and Fusion
- Robot’s Actuators Types
- Motor Errors

Sensor

- **Sensor** – a device that measures some attribute of the world
- A sensor receives input signals (sound, light, pressure, etc.) into an analog or digital form capable of being used by a robot

Attributes of a Sensor

- Field of view (FOV)
- Range
- Accuracy
- Resolution
- Responsiveness in the target domain
- Power consumption
- Hardware reliability
- Size and weight
- Interpretation reliability
- Computational effort

Mobile Robot's Sensors

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- Contact/touch sensors: Bumpers
- Proximity sensors
  - Sonar (time of flight)
  - Radar (phase and frequency)
  - Infrared (intensity)
  - Laser range-finders (triangulation, tof, phase)
- Visual sensors: Cameras
- Internal sensors
  - Accelerometers (spring-mounted masses)
  - Gyroscopes (spinning mass, laser light)
  - Compasses, inclinometers (earth magnetic field, gravity)
- Satellite-based sensors: GPS

iRobot Roomba Sensors

Nao's Sensors

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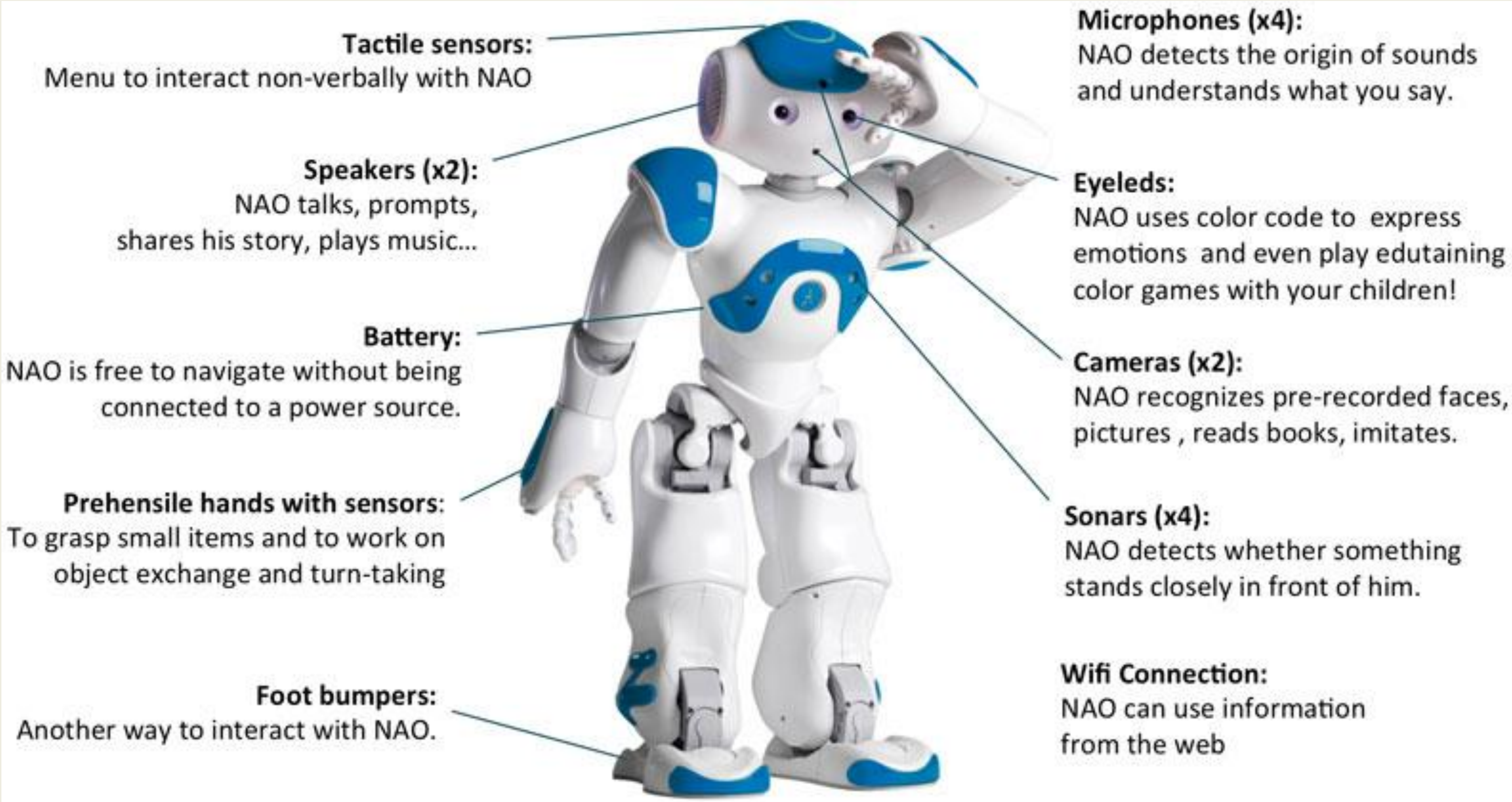

Bumpers

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- Simple touch switches that act as an “antenna” or a “feeler”
- Pros
  - Low cost
  - Simple to construct and to connect
  - Simple to operate – either the switch is active or not
  - Reliable
- Cons
  - Tactile – object must be “touched” to know it exists
  - Low range
  - Cannot acquire range data

Ranging Sensors

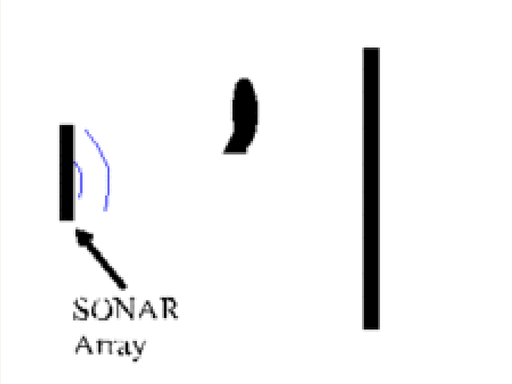
- Ranging sensors allow a robot to detect an obstacle without actually having to come into contact with it
- This can prevent possible entanglement, allow for better obstacle avoidance, and possibly allow software to distinguish between obstacles of different shapes and sizes.
- There are different methods used to allow a sensor to detect obstacles from a distance.

Sonic Sensors

- Sonic sensors use sound waves, usually ultrasonic, through a medium as their means of detection.
- The medium is typically the atmosphere or a body of water.
- A pulse of sound is emitted from some source. One or more receivers then pick up the sound wave after it has bounced off any obstacles.
- This echo is then interpreted in various ways to obtain information about an obstacle.

SONAR

- Sonic ranging sensors (SONAR) send out a pulse of sound and wait for the echo to return.
- The time it takes for the echo to return (**time of flight**) determine the distance to the obstacle.
- Sometimes an array of detectors are used to calculate the distance and shape of objects



SONAR

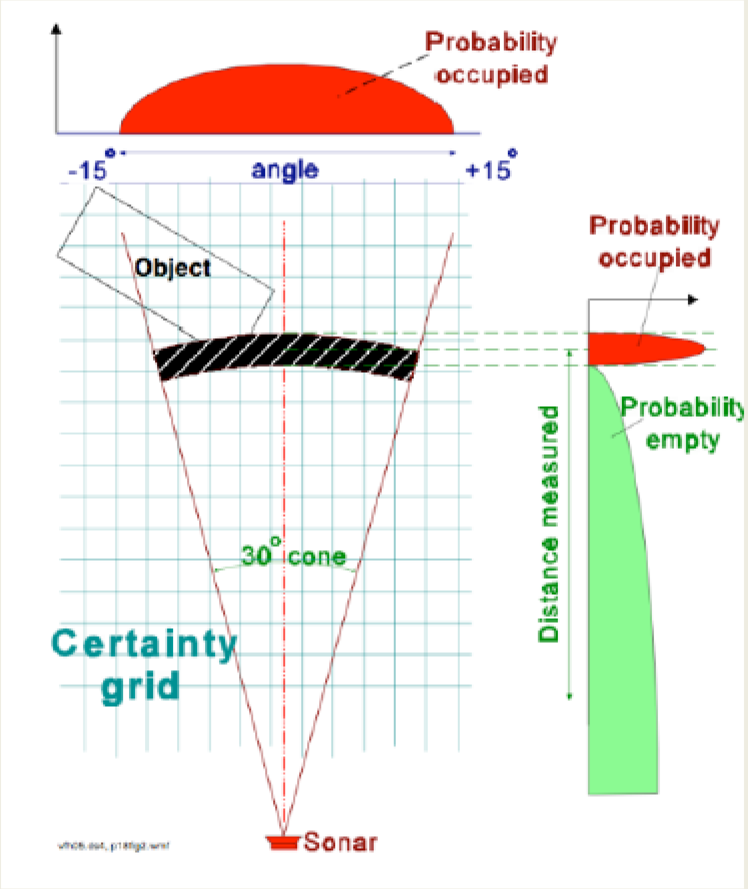
- Pros
  - Cheap
  - Easy to Use
- Cons
  - Resolution rapidly decreases with distance (limited to about 6m)
  - Dense obstacle distribution or complex surfaces can produce ghost echoes or poor echo returns

Problems with Sonar Readings

- Specular reflection
  - The wave form bounces away from the transducer
- Cross-talk
  - In a ring of sonars, sound waves from different sonars can get crossed
- Foreshortening
  - If the surface is not perpendicular to the transducer, one side of the cone will reach the object first and return a range first. Most software assumes this reading is for the right edge of the cone (30°).
- Resolution problems
  - Most desk chairs and table tops present almost no surface area to the sensor and so the robot will often not perceive their presence

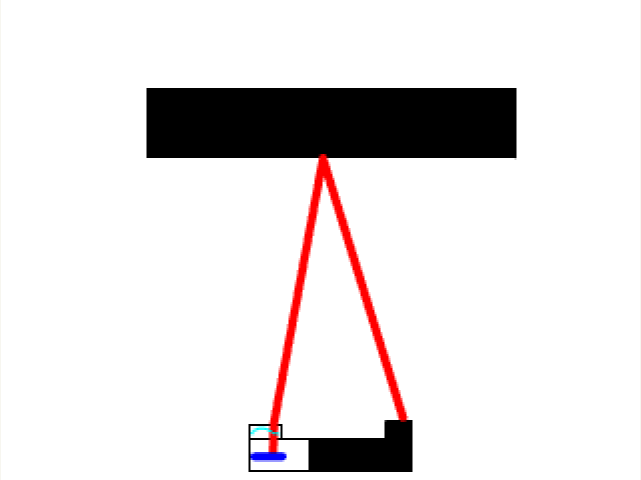
SONAR

- Obstacle could be anywhere on the arc at distance D.
- The space closer than D is likely to be free



IR Range Sensor

- IR Sensors use Infra-Red(IR) rays to emit and detect the amount of IR light that returns.
- A pulse of light is emitted and then reflected back (or not reflected at all). When the light returns it comes back at an angle that is dependent on the distance of the reflecting object.



IR Range Sensor

- Pros
  - Cheap (less than 20$)
  - Easy to build and use
  - Fast sensor response time (light travels faster than sound)
  - Less error-prone than sonars
- Cons
  - Usually short-range (<1m)
  - Can be sensitive to IR sources e.g. sun

Laser Scanners

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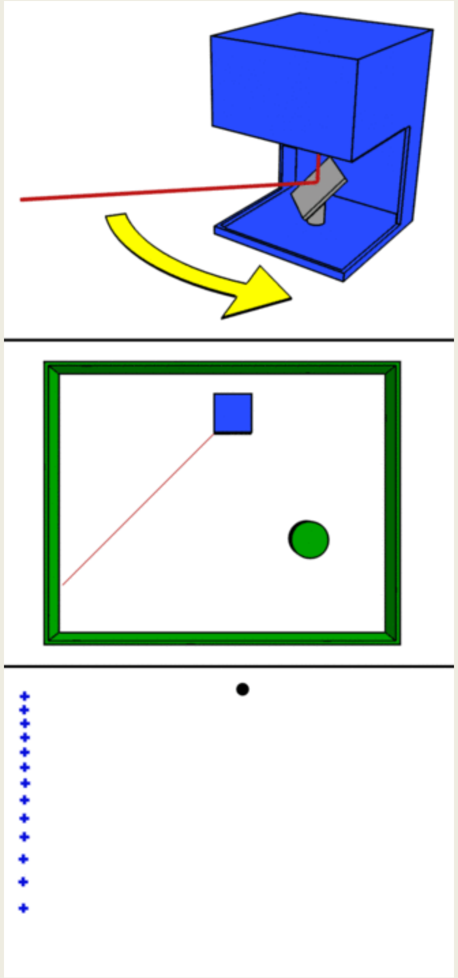
- Laser based distance sensors use the same principle as ultrasonic distance sensors, but use light instead of sound.
- They send a laser pulse in a narrow beam towards the object and measuring the time taken by the pulse to be reflected off the target and returned to the sender

LIDAR

- Light Detection and Ranging
- LiDARs actively sweep the laser beams horizontally and/or vertically so robots can map out a large area
- A basic lidar system involves a laser range finder reflected by a rotating mirror.
- The laser is scanned around the scene being digitized, gathering distance measurements at specified angle intervals.



Hokuyo Laser Sensor

- A popular laser sensor in robotics
- Wide-range (5.6m×240°)
- Accuracy(±30mm).

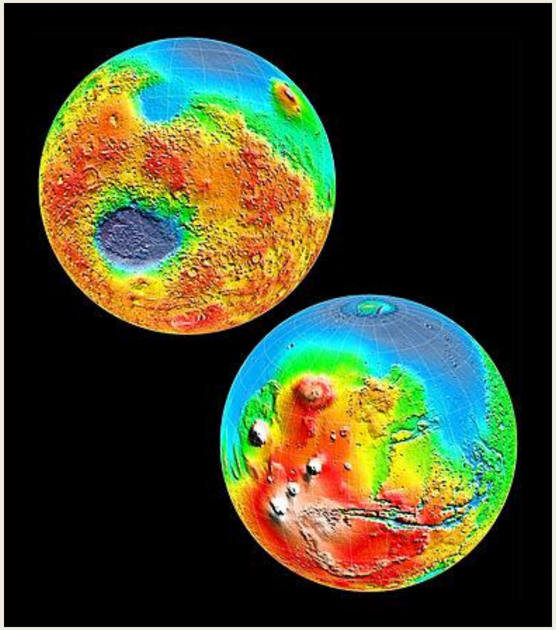
  For distance above 1m, accuracy is ±3%.
- High angular resolution (0.352°)
- Light weight (160g)
- Low-power consumption
- [Hokuyo laser-equipped Nao humanoid robot climbs some stairs]()

LIDAR in Google's Car

- Google's car holds a $70,000 LIDAR system
- The range finder mounted on the top is a Velodyne 64-beam laser.
- This laser allows the vehicle to generate a detailed 3D map of its environment.
- Velodyne Lidar Vision Sensor System

MOLA

- MOLA (the Mars Orbiting Laser Altimeter) used a LIDAR instrument in a Mars-orbiting satellite to produce a spectacularly precise global topographic survey of the red planet.
- In September 2008, the NASA Phoenix Lander used lidar to detect snow in the atmosphere of Mars



LIDAR Returns and Materials

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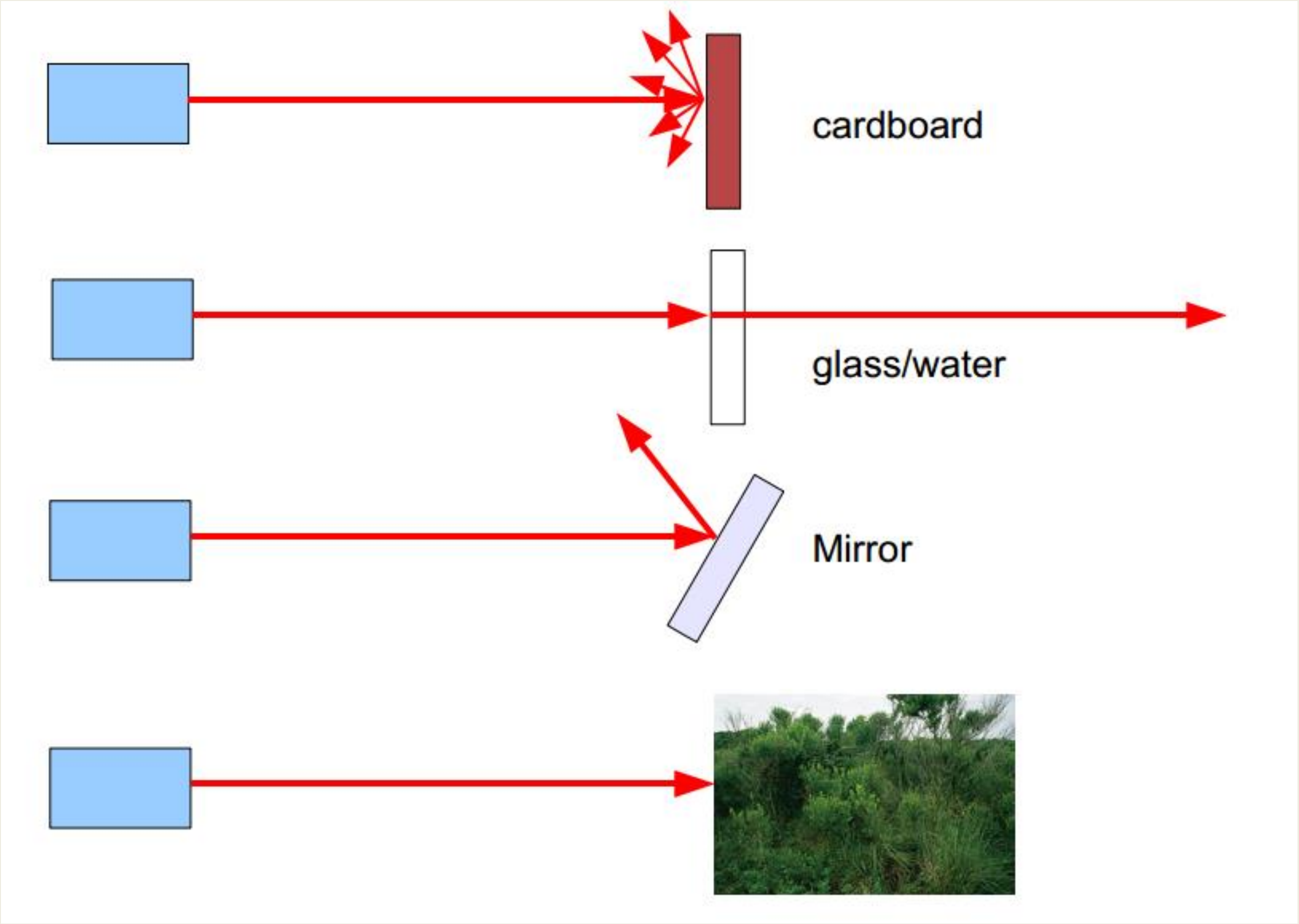


LIDAR

- Pros:
  - Narrow beam width, higher resolution
  - Not affected by temperature or vacuum
  - Greater accuracy and faster response
- Cons:
  - Costly (Hokuyo 5m-range sensor costs ~$1,200)
  - Limited in range
  - Relatively heavy
  - Works badly in poor visibility (dense refraction particles) and underwater

Robot Vision

<u>Two key steps:</u>

1. How to create an image?
2. How to extract relevant information from the image?

Vision Challenges

- Lighting changes
  - Intensity and color is a function of surface, lighting conditions, and camera optics
- Scale
  - Distance to object changes scale
- Moving from 3D to 2D creates loss of information
  - Depth, scale
- Noise

Image

- 2D array of pixels (picture elements)
- Color usually encoded using RGB

Finding Depth

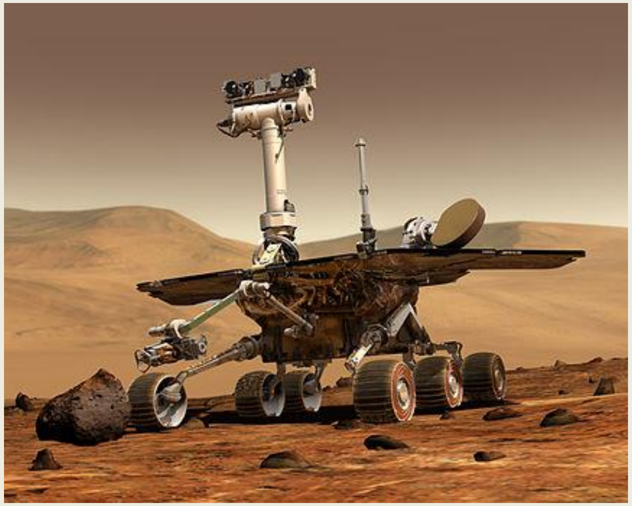
- Image collapses 3D world to 2D
  – Losing depth information
- Common solutions:
  – Stereo cameras - use multiple different images
  – RGB-D cameras

Stereo Cameras

- A stereo camera is a type of camera with two or more lenses with a separate image sensor or film frame for each lens.
- This allows the camera to simulate human binocular vision, and therefore gives it the ability to capture 3D images.
- By finding mappings of common pixel values, and calculating how far apart these common areas reside in pixel space, a rough depth map can be created

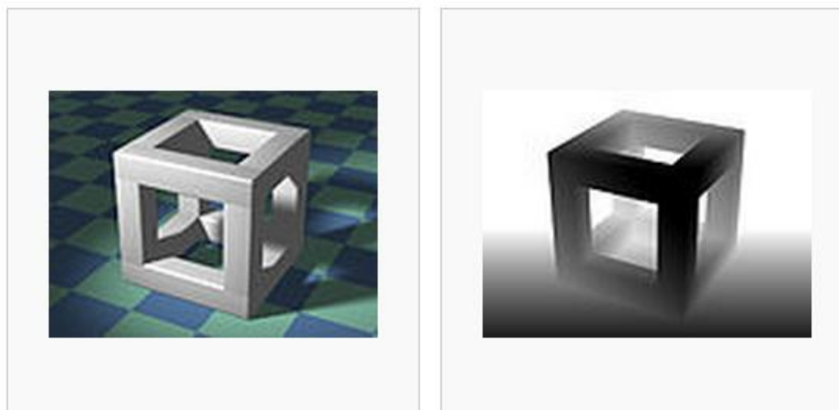
Stereo Cameras

- Mar’s Rover uses a Panoramic Camera (Pancam), a high-resolution color stereo pair of CCD cameras used to image the surface and sky of Mars.
- The cameras are located on a "camera bar" that sits on top of the mast of the rover.



Depth Map

- An image that contains information relating to the distance of the surfaces of scene objects from a viewpoint



Cubic Structure

Depth Map: Nearer is darker

Taken from wikipedia

RGB-D Cameras

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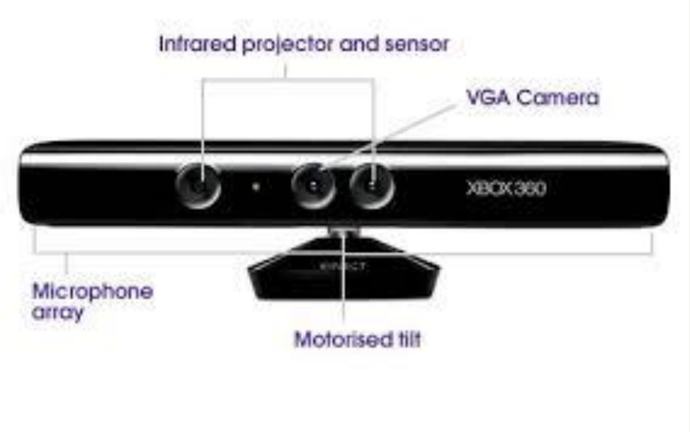
- A stereo camera is a type of camera with two or more lenses with a separate image sensor or film frame for each lens.
- This allows the camera to simulate human binocular vision, and therefore gives it the ability to capture 3D images.
- By finding mappings of common pixel values, and calculating how far apart these common areas reside in pixel space, a rough depth map can be created

Kinect



- Originally developed by Microsoft for Xbox 360.
- Combines 2 sensors to create a depth image:
  – A color VGA video camera to see the world in color
  – The depth sensor, which is an infrared projector and a monochrome CMOS sensor working together, to see objects in 3D
- Based on range camera technology developed by Israeli company called PrimeSense

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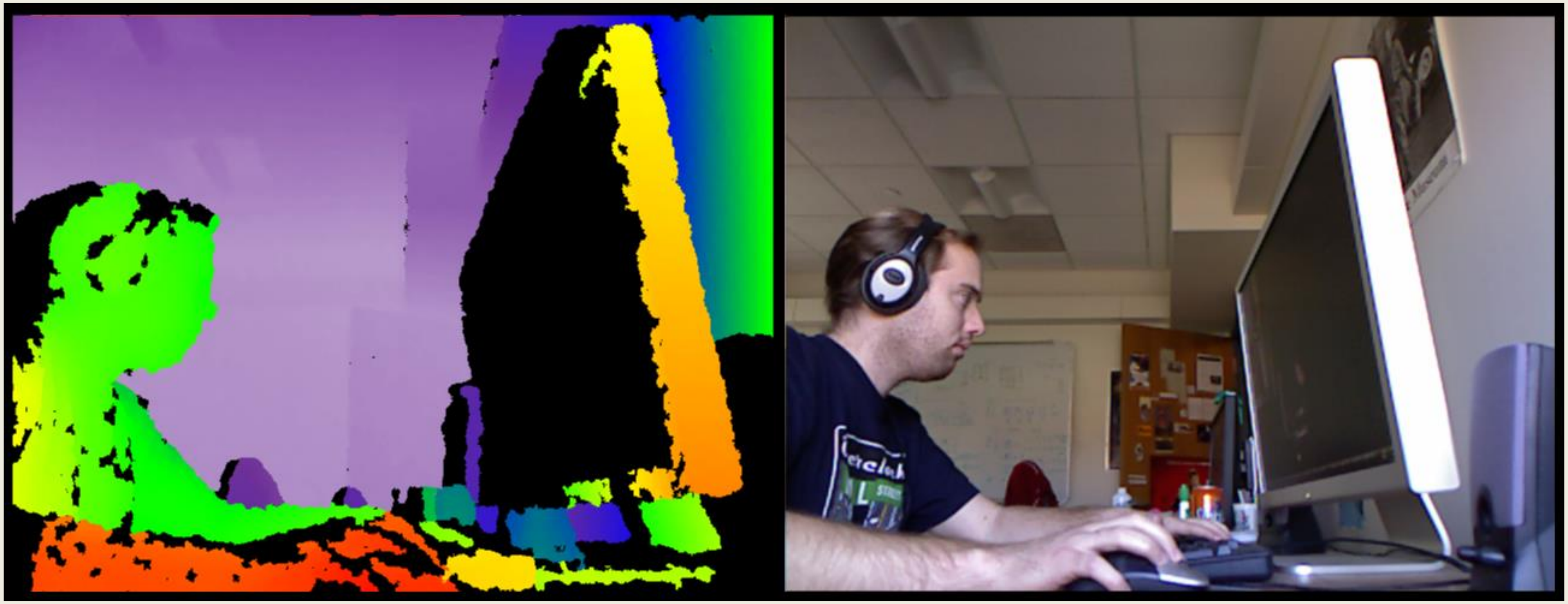
Kinect's Depth Image



Basic Computer Vision Techniques

- Filtering
  - remove noise from image
- Segmentation
  - Partition image into groups of pixels
  - Similarity can be decided based on intensity, color, pattern
- Feature detection
  - Extract interesting parts from the image
  - Edge detection, corner detection
  - For example in navigation systems it may prove useful to extract only floor lines from an image

Kernels

- In image processing, many operators are based on applying some function to the pixels within a local window.
- The **convolution operator** (kernel) is a function that we apply as a weighted average of the within-window pixels.
- For example, if the window size is 3x3 pixels, we can define the function by providing a 3x3 weight-matrix. So, at the location of every pixel in the image, we place this 3x3 matrix and perform the element-wise multiplications before summing up. This sum is deemed the output value at that location.

Kernels

- Different kernels can cause different effects

$$\begin{bmatrix}0&0&0\\0&1&0\\0&0&0\end{bmatrix} \quad \begin{bmatrix}1&0&-1\\0&0&0\\-1&0&1\end{bmatrix} \begin{bmatrix}0&1&0\\1&-4&1\\0&1&0\end{bmatrix} \begin{bmatrix}-1&-1&-1\\-1&8&-1\\-1&-1&-1\end{bmatrix} \begin{bmatrix}0&-1&0\\-1&5&-1\\0&-1&0\end{bmatrix} \quad \begin{bmatrix}1&2&1\\2&4&2\\1&2&1\end{bmatrix} \quad \begin{bmatrix}1&1&1\\1&1&1\\1&1&1\end{bmatrix}$$

original | Detect edges | sharpen | blur

- Can play in Gimp, Matlab with different kernels

Vision – The Perfect Sensor?

- Many benefits:
  - Low cost
  - Low weight
  - Low power
  - Information-dense
  - Many uses: collision avoidance, object recognition, localization and mapping, structure from motion
- **But**, making sense of vision is really hard!
  - Computationally expensive
  - A difficult AI problem

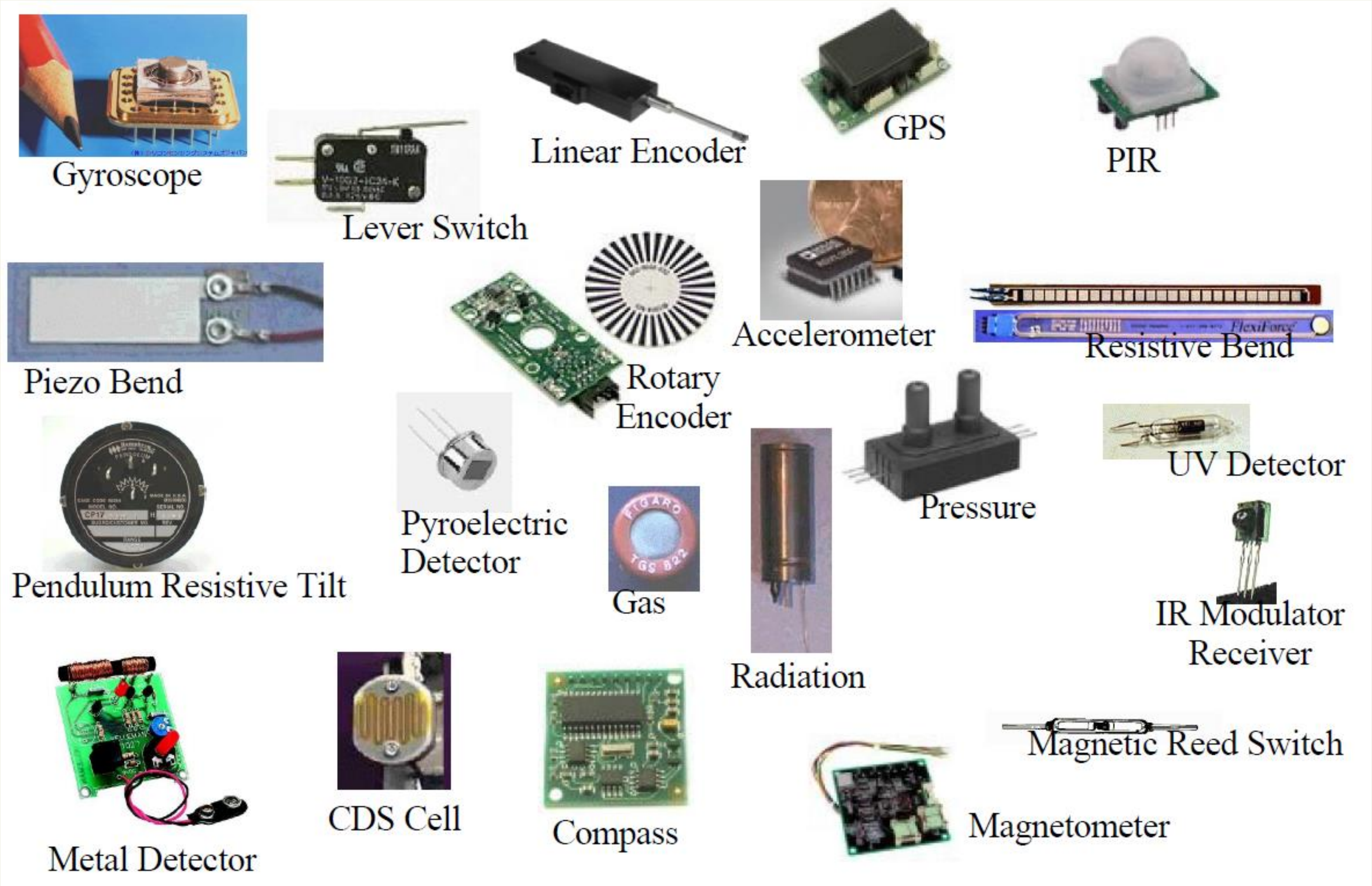
GPS

- A satellite navigation system that provides location
- Drift free, unbiased, global reference
- But, limited by line-of-sight, sensitive to vibration, multipath, cloud… inaccurate to 1m

Other Robot Sensors

- Accelerometers
  - Measure acceleration in a direction of travel
- Gyroscopes
  - Measure orientation
- Compasses
  - Measure movement direction relative to the surface of the Earth

More Sensors…



Sensor Classification

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Extereoceptive

Active
- Laser/LiDar
- Sonar
- Radar
- Structured light
- InfraRed

Passive
- Vision
- Microphone array
- Chemical sensors
- Tactile sensor

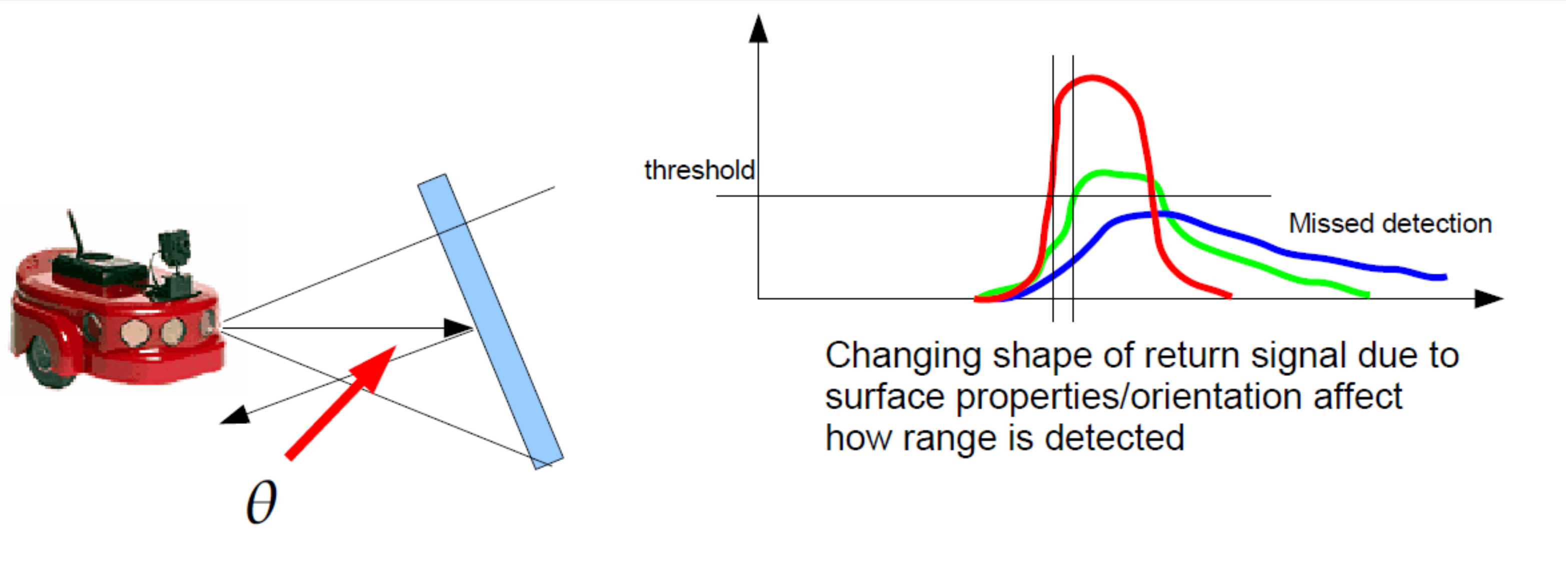
Proprioceptive
- Gyroscope
- Accelerometers
- Odometers
- Voltage sensors
- Stress/strain gauge

Sensors Noise

- Sensors are **never perfect**
  - Unmodeled effects
  - True randomness in the environment, robot, and sensing process
- Systematic errors (bias)
- Drift, jumps

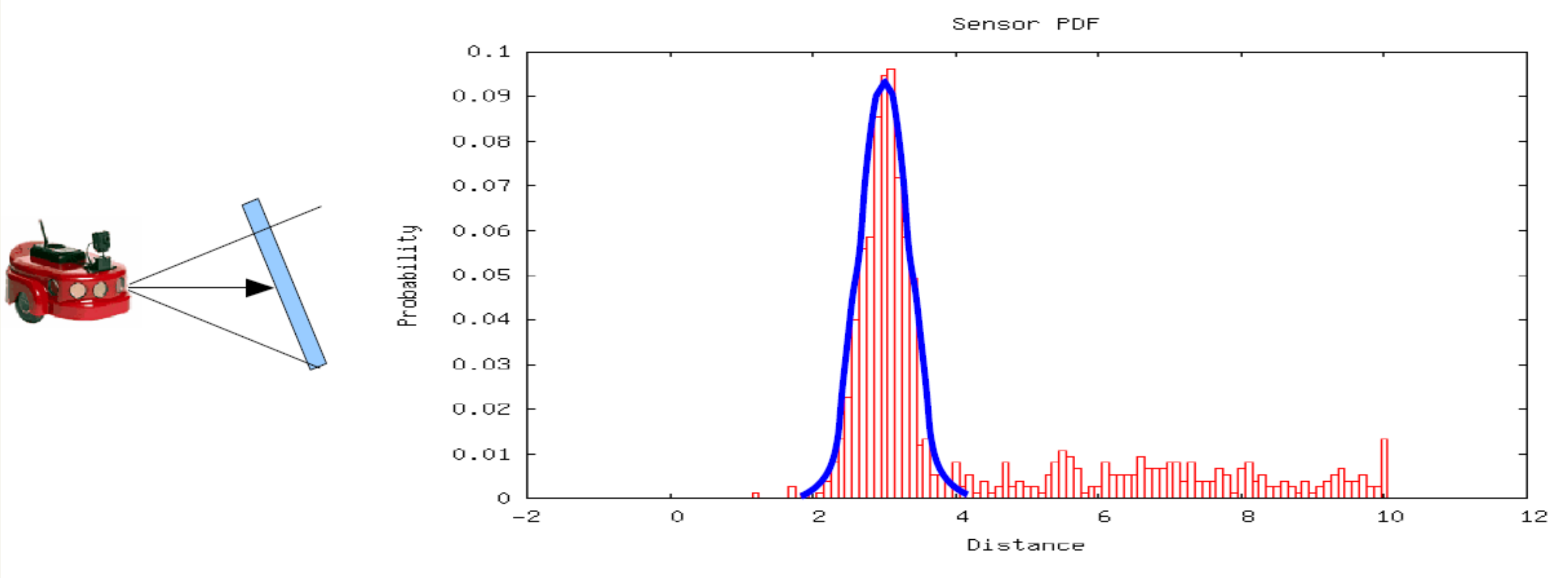
Sensor Bias

- Return may vary as a function of physical setup
  - Surface material/color, orientation, range, atmosphere



Sensor Noise Model

- Enter the world of statistics
  - Usually choose a parametric model and estimate parameters e.g. Gaussian



Sensor Filtering

- Apply some level of filtering to raw sensor data before feeding into rest of system
- Different types of filters:
  - Bayesian Filters
  - Kalman Filter
  - Particle Filter

Kalman Filter

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- Suppose we have a noisy measurement of our current state, with some estimate of variance
- If we know the system dynamics we can guess what the next state will be (with variance)
- Compare where we think we should be to where our sensors tell us we are
- Take a weighted average of the two, based on their covariance, as the new state

Pogo Stick Robot

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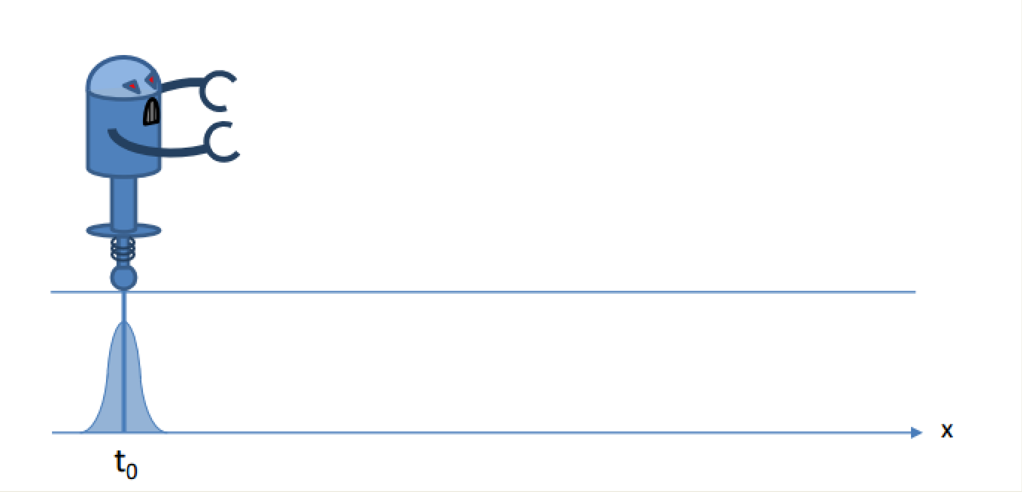
- Imagine we have a pogo stick robot
  - We know its approximate position and velocity



Pogo Stick Robot

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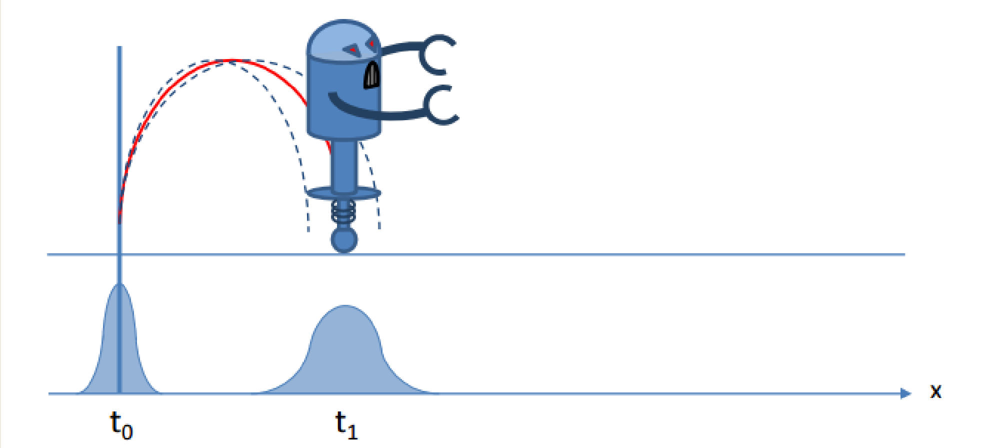
- Imagine we have a pogo stick robot
  - We know its approximate position and velocity
  - Using ballistics we can guess where it will land after each jump



Pogo Stick Robot

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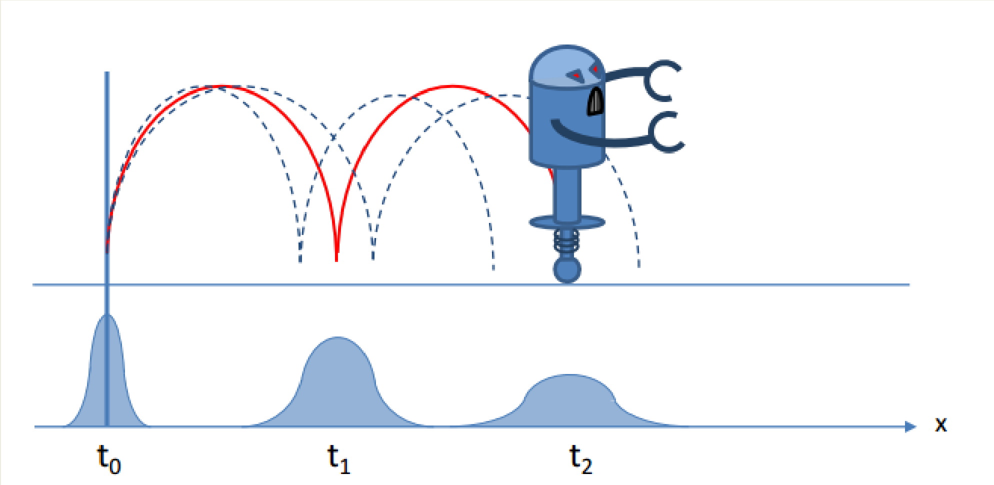
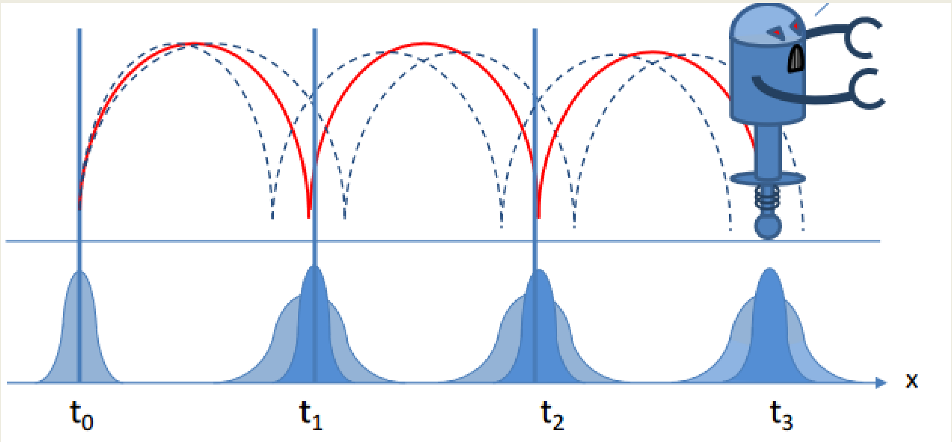
- Imagine we have a pogo stick robot
  - We know its approximate position and velocity
  - Using ballistics we can guess where it will land after each jump… becoming less certain with time



Pogo Stick Robot

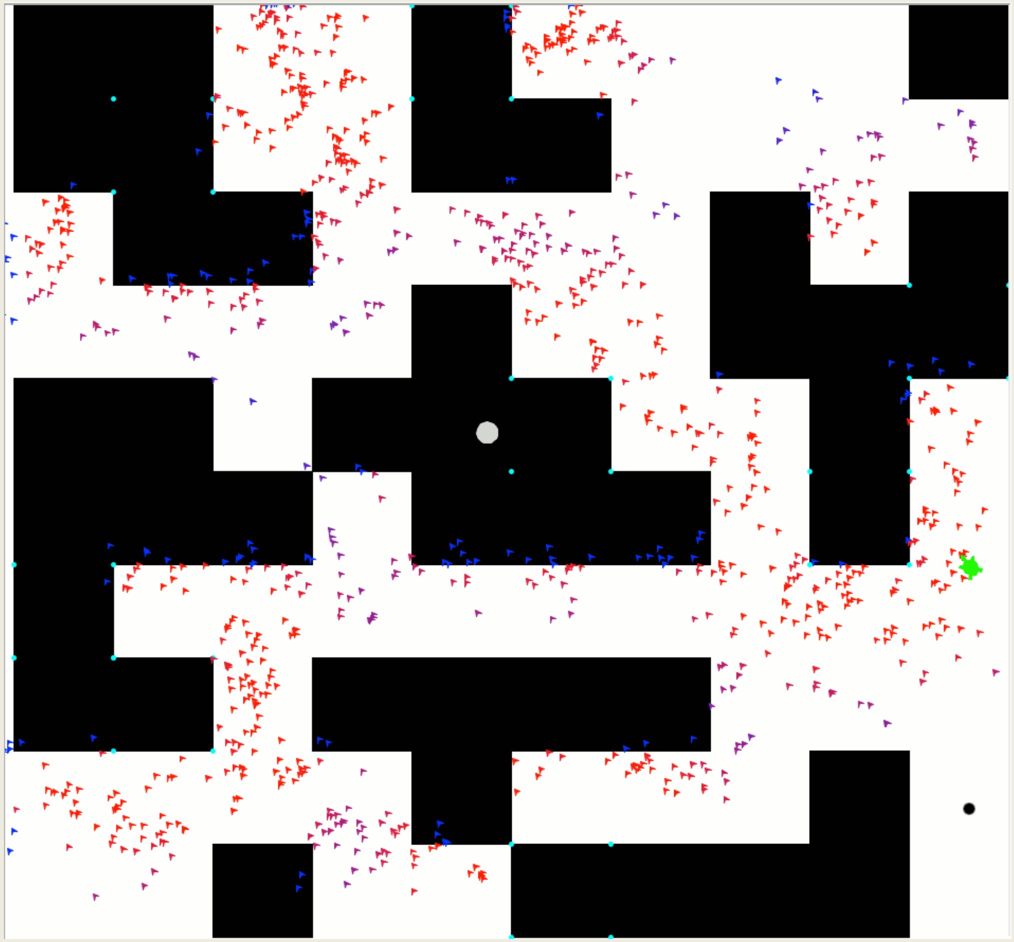
- Imagine we have a pogo stick robot
  - We know its approximate position and velocity
  - Using ballistics we can guess where it will land after each jump… becoming less certain with time
  - After each jump, we get a new measurement and we can refine our estimate



The Particle Filter

- Similar concept, but uses discretely sampled estimates of the space of possible states
  - Simulate each step in time - track the particles
  - Find out how much each subsequent measurement agrees with each particle
  - Use the ‘best’ particle as the estimate
  - – Occasionally resample around the most reliable particles

The Particle Filter



Sensor Fusion

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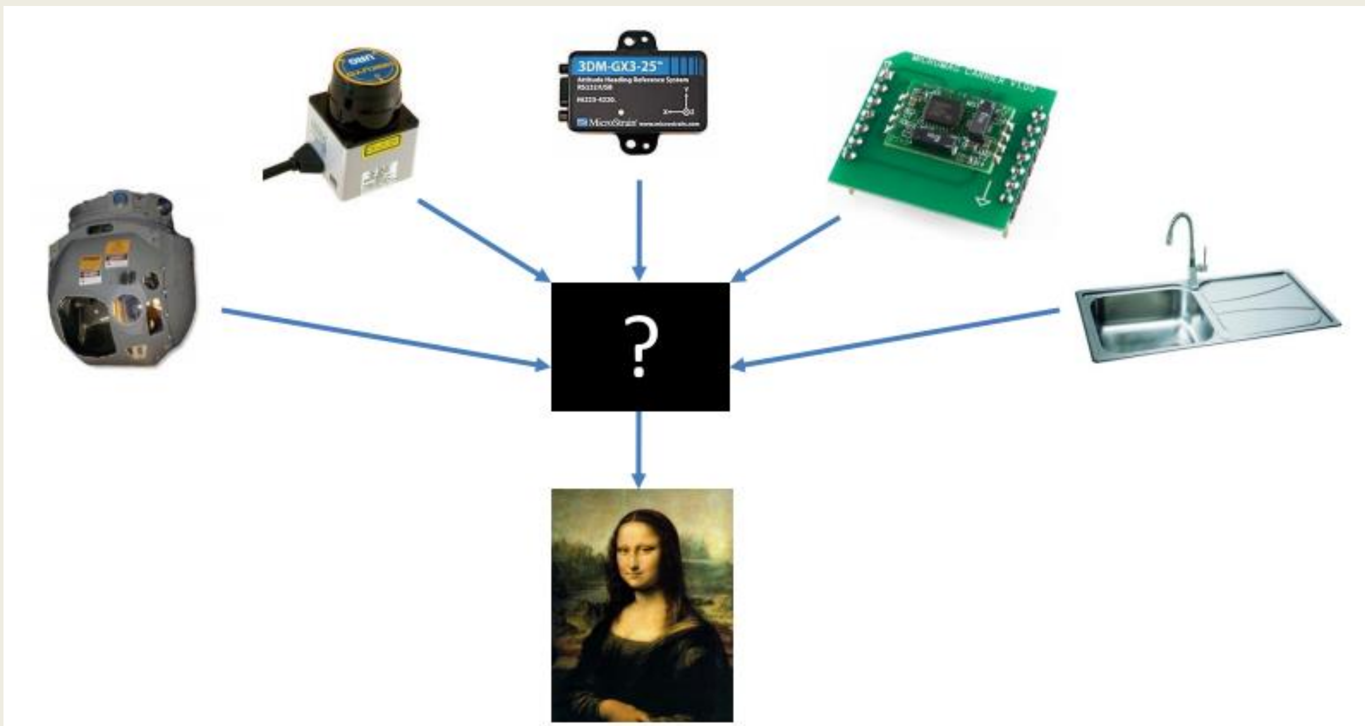
- Sensor fusion is the integration of multiple measurements from many sources



Sensor Fusion

- Redundant sensors
  - For example, lower and top sonar rings. The sonar software returns the shortest range from the two, providing a more reliable reading for low objects
- Competing sensors
  - Extracting a range image from stereo camera and from a laser range finder
- Complementary sensors
  - e.g., for urban search and rescue, a robot may search for survivors by fusing observations from a thermal sensor for body heat with a camera detecting motion.

Sensor Fusion

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- Fused measurements can be more accurate
- However, all sensors are different and all measurements are noisy – how do we resolve disagreements?
- Use stochastic methods (like Kalman filters) over multiple sensors instead of time samples
  - Every sensor has expected accuracy and variance
  - We can weight each sensor's contribution by our confidence in its measurement

Actuators

- An actuator is a type of motor for moving or controlling a mechanism or system.
- It is operated by a source of energy, such as electric current, hydraulic fluidpressure, or pneumatic pressure, and converts that energy into motion.
- Two types of robots:
  – Wheeled robots
  – Legged robots

Wheeled Robots

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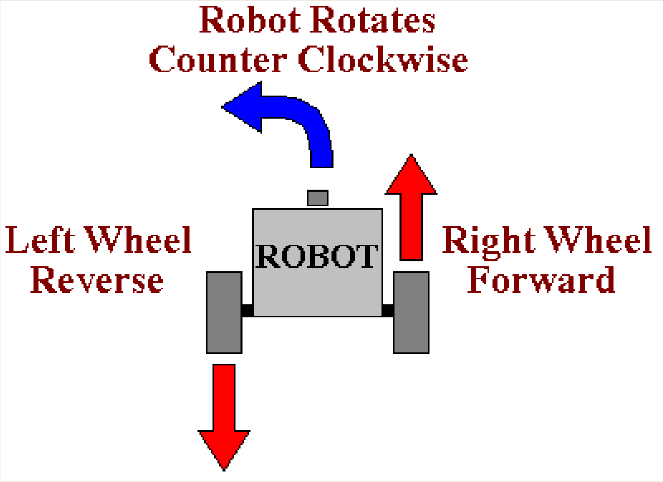
- Wheeled robots navigate around the ground using motorized wheels to propel themselves.
- Advantages of wheeled robots:
  – Easier to design and build
  – Easier to program for movement
  – More well controlled than other types of robots
  – Cheaper
- Disadvantages of wheeled robots:
  – Can not navigate well over obstacles, such as rocky terrain, sharp declines, or areas with low friction.
- Robots can have any number of wheels, but three wheels are sufficient for static and dynamic balance.
- Additional wheels can add to balance

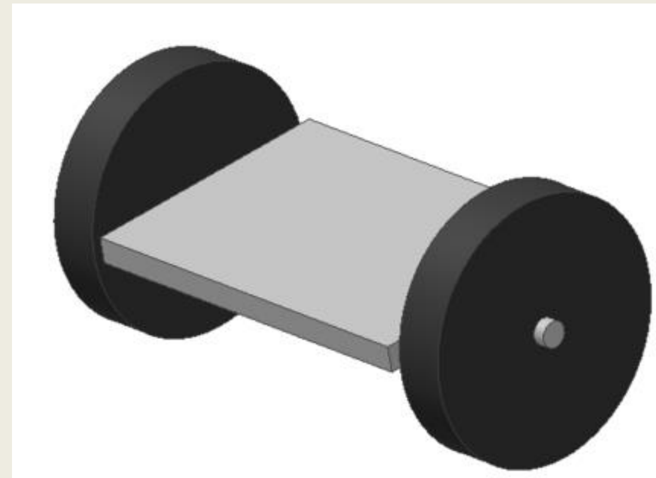
Differential Wheeled Robot

- The movement of a differential wheeled robot is based on two separately wheels placed on both sides of the robot.
- It can change its direction by varying the relative rate of rotation of its wheels and hence does not require an additional steering motion.



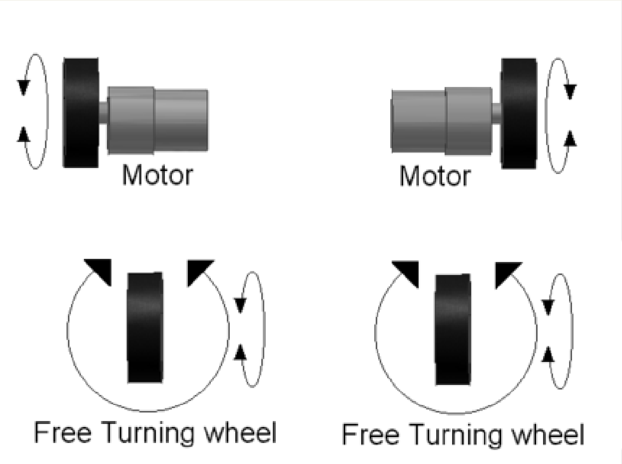
2-Wheeled Robots

- Two wheeled robots are harder to balance than other types because they must keep moving to maintain upright.
- Roombas are two-wheeled vacuum cleaners.
- They utilize a contact sensor in the front and a infrared sensor on its top.

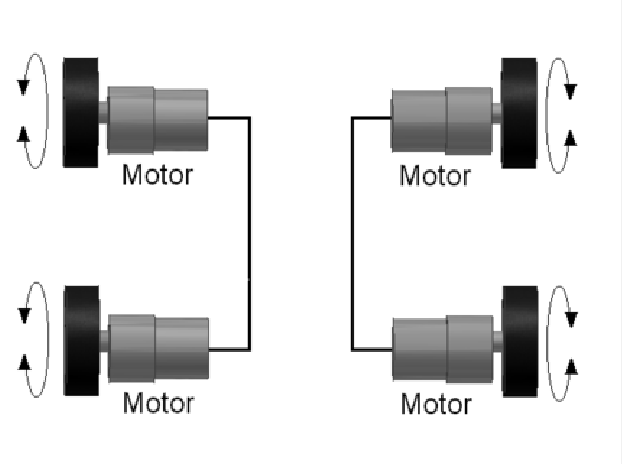


4-Wheeled Robots

- 2 powered, 2 free rotating wheels
  - Same as the Differentially steered ones above but with 2 free rotating wheels for extra balance

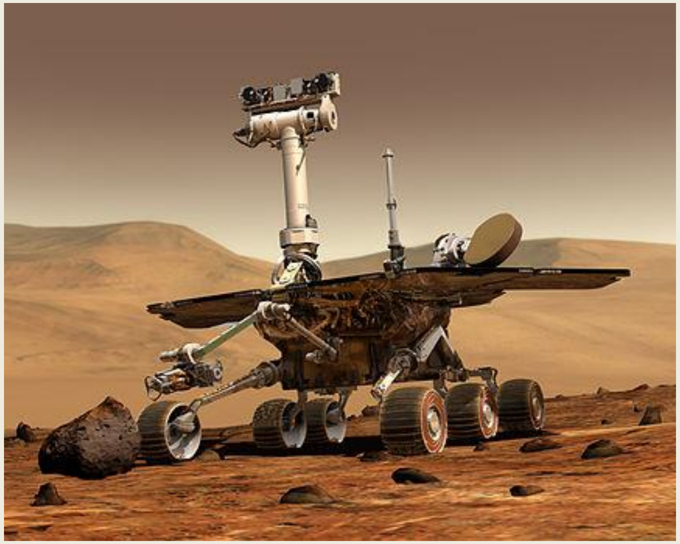


- 2-by-2 powered wheels for tank-like movement
  - Each pair (connected by a line) turn in the same direction



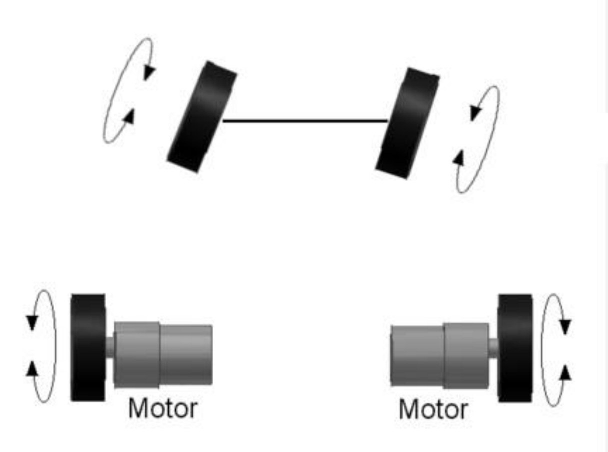
5 Or More Wheeled Robots

- For larger robots.
- Not always very practical.
- Complex design
- The Mars Rover are six wheeled robots



Car-Like Steering

- This method allows the robot to turn in the same way a car does.
- This is a far harder method to build and makes dead reckoning much harder as well.
- Advantage: need only one motor (and a servo for steering)



Omni Wheels

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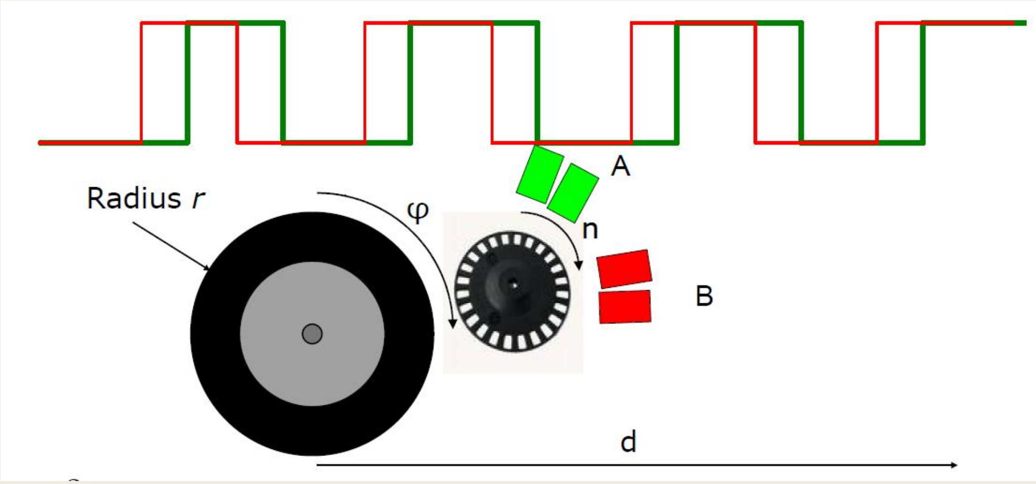
- Omni wheels are wheels with small discs around the circumference which are perpendicular to the rolling direction.
- This allows the wheels to move in two directions, and the ability to move holonomically, which means it can instantaneously move in any direction.
- Omni-wheeled robots can move in at any angle in any direction, without rotating beforehand.
- Omni Wheel Mobile Robot

Optical Encoders

- Disc to measure *rotational motion*
- Out of phase IR emitter/detector pair
  - Direction and amount of rotation from edge transitions
- The number of turns of the wheels can be used to estimate how far the robot has moved

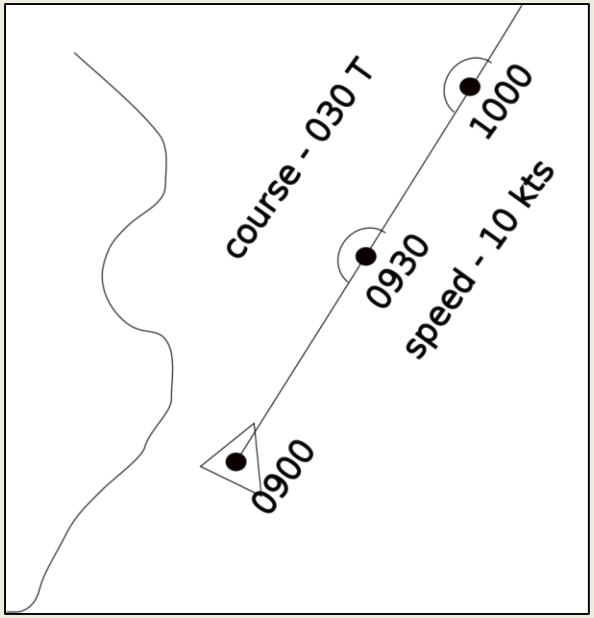


Odometry

- Odometry is the use of data from moving sensors to estimate change in position over time.
- Odometry is used by robots to estimate (not determine) their position relative to a starting location.
- This method is sensitive to errors due to the integration of velocity measurements over time to give position estimates.

Dead Reckoning

- In navigation, dead reckoning is the process of calculating one's current position by using a previously determined position (fix), and estimated speeds over elapsed time and course.
- Many mobile robots use dead reckoning navigation because of its simplicity, low cost and robustness.



Dead Reckoning

- Shaft encoders can provide only an estimate to the robot's location
  - The same robot can travel different distances for the same encoder count on different types of terrains (sidewalk, grass, etc.)
- INS (inertial navigation systems), which measure movements electronically through miniature accelerometers, provide accurate dead reckoning
  - Not suitable for mobile robots because of their cost and the constraint that motion must be smooth

Legged Robots

- Legged robots are able to:
  - Isolate their body from terrain irregularities
  - Avoid undesirable footholds
  - Regulate their stability
  - Achieve energy efficiency

Degrees of Freedom

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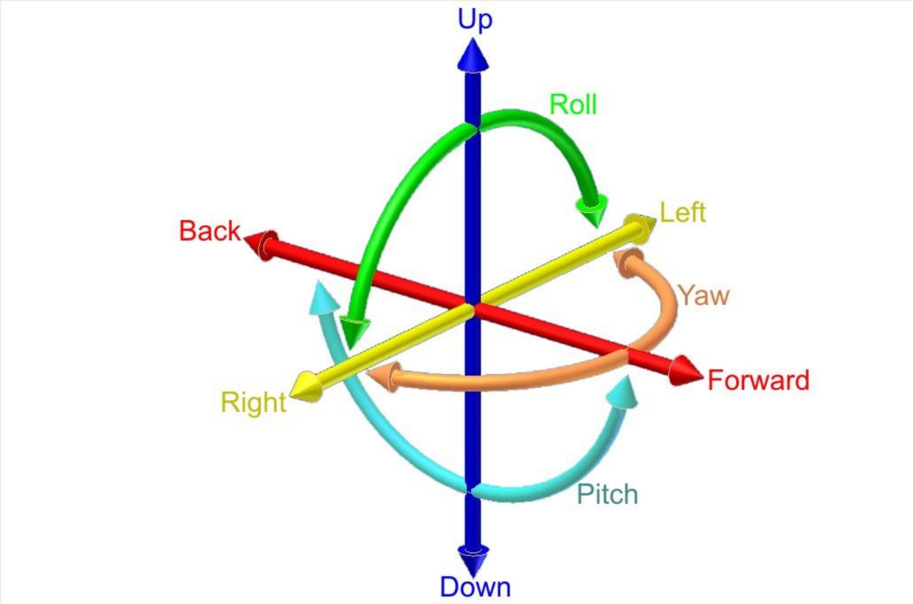
המכללה למינהל

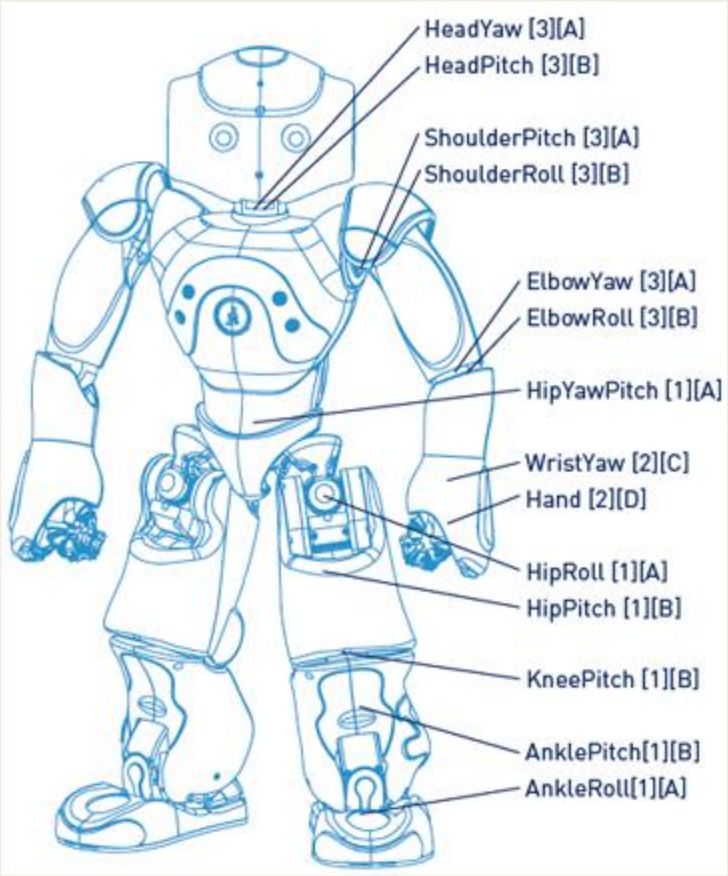
- The degree of freedom (DOF) of a mechanical system is the number of independent parameters that define its configuration.
- DOFs can be viewed as the minimum number of coordinates required to specify a configuration
- For example, an aircraft has 6 DOFs: it can move forward, sideways, and down; and it can rotate about its axes with yaw, pitch, and roll.

Degrees of Freedom



Degrees of Freedom

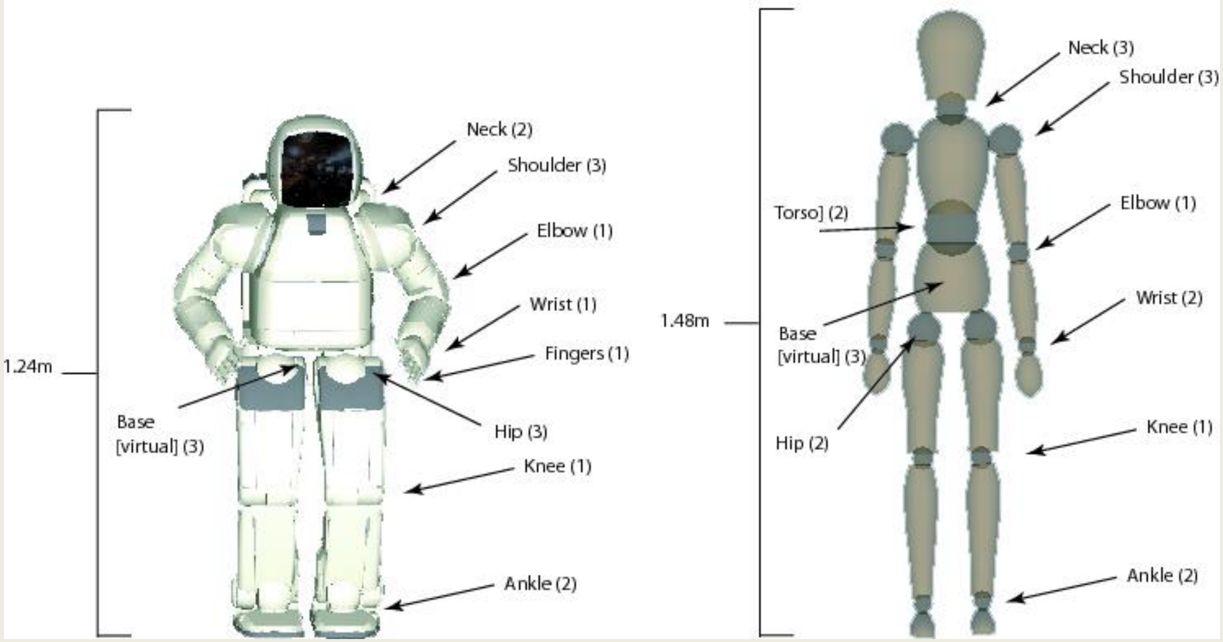
- The latest version of Nao (Nao H25) has 25 DOFs



DEGREES OF FREEDOM	
HEAD	x2 DOF
ARM (in each)	x5 DOF
PELVIS	x1 DOF
LEG (in each)	x5 DOF
HAND (in each)	x1 DOF

Degrees of Freedom

- Asimo has 57 (!) degrees of freedom
  - head: 3
  - arm: 7×2
  - hand: 13×2
  - torso: 2
  - leg: 6×2

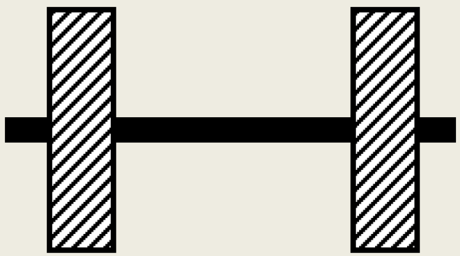


Effectors Noise

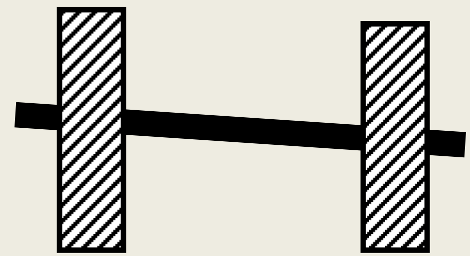
המסלול האקדמי
המכללה למינהל

- Single action may have several outcomes
- Error accumulates
  - Odometry (wheel sensors) / dead-reckoning (+ heading)
- Odometric errors
  - Misalignment of wheels, unequal floor contact, …

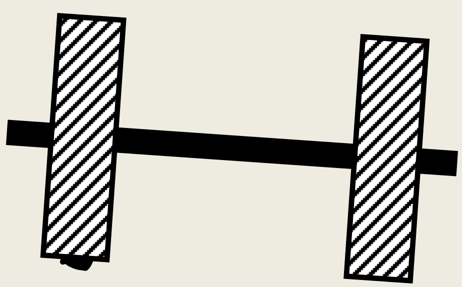
Reasons For Motion Errors



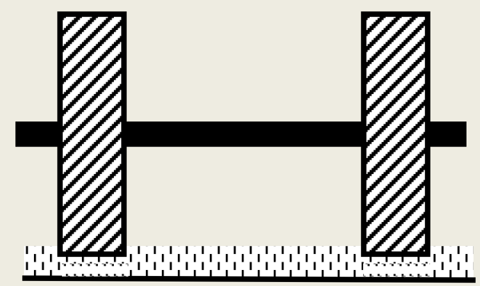
ideal case



different wheel diameters



bump



carpet

and many more …

Meet PC-Bot

- The [914 PC-BOT] is a general service robot created by White Box Robotics
- Has 5 IR sensors and bumpers
- 914 PC Bot Linux/Player Roam