Lecture 4
Sensors and Actuators

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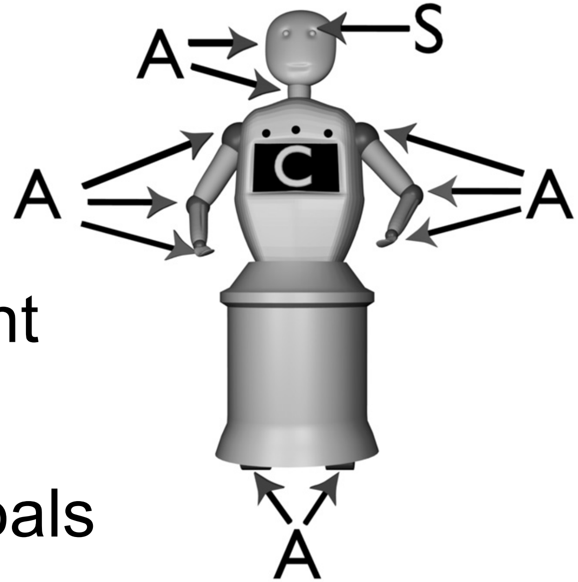
Content

- Robot Components
- Actuators and Effectors
  - Active vs Passive effectors
  - DOF Degrees of Freedom
  - Soft robotics and embodied intelligence
- Types of Actuators

- Sensors
  - States and sensors uncertainty
  - Perception theories
  - Simple, Sonar, Lidar, Cameras

Robot Components

- *A robot is an autonomous system which exists in the **physical world**, can **sense** its environment, and can **act** on it to achieve some goals (Mataric)*



- Physical body (*embodied*) in the world
- **S**ensors, to sense/perceive its environment
- **E**ffectors and actuators, to take actions
- **C**ontroller, to be autonomous and have goals

Actuators, Effectors and Action

Effectors and Actuators

- **Effector**
  - Any device that has an effect on the environment
  - Humans/animals: legs, arms, fingers, wings, flippers
  - Robots: legs, wheels, arms, fingers, grippers
- **Actuator**
  - Mechanism enabling effector to execute movement
  - Humans/animals: muscles and tendons
  - Robots: electric motors, hydraulic/pneumatic cylinders, temperature/chemically sensitive materials
- An effector needs at least one actuator

Joint and Degrees Of Freedoms (DOF)

- Joint: An actuator connecting two body parts
  - A joint can have more than one DOF

Degree Of Freedom (DOF)

Degrees of Freedom (DOF) is the dimension in which a movement can be produced in 3D

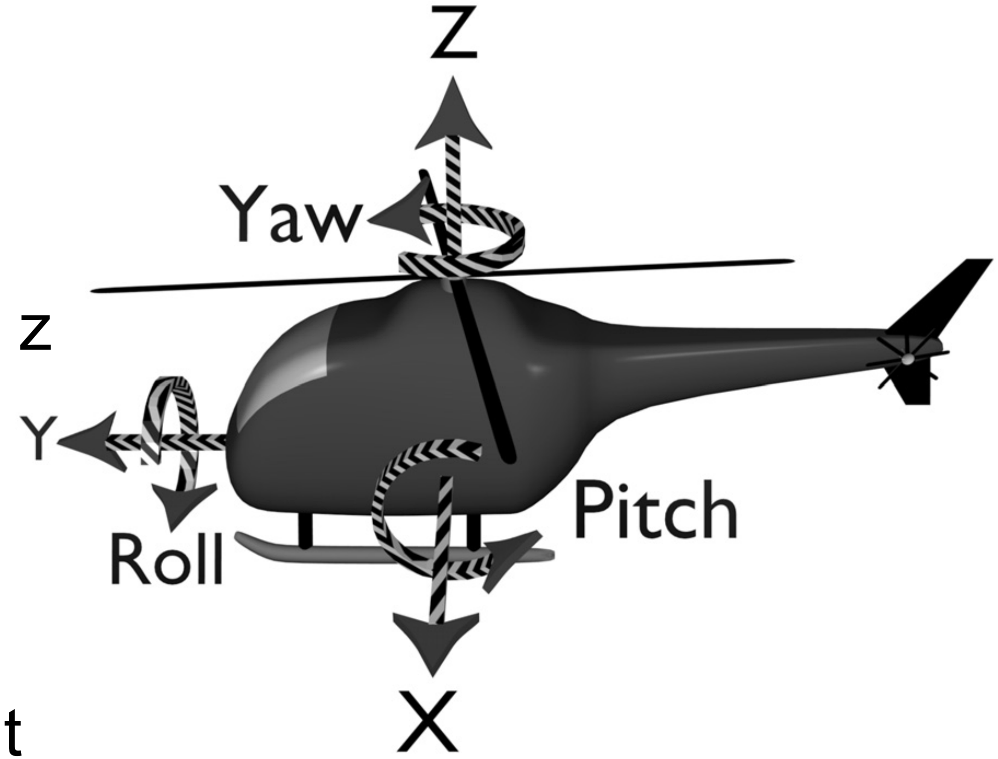
- minimum number of coordinates to completely specify the motion of a mechanical system

6 DOFs for freely attached body in 3D space

- **Translational** DOF (translate/move without rotation):
  - x, y, z
- **Rotational** DOF:
  - Roll, Pitch, Yaw

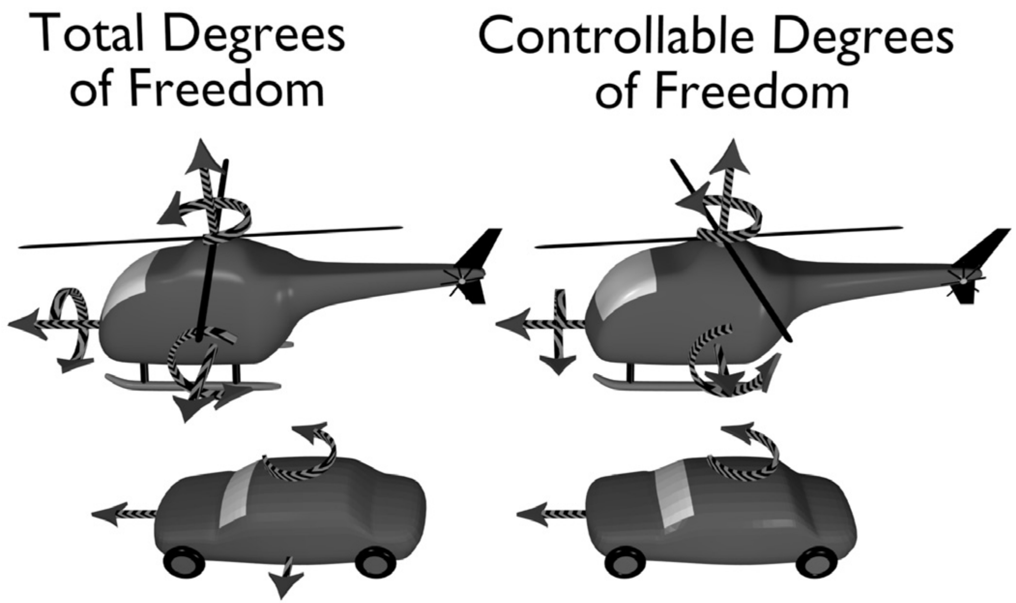
Degree Of Freedom (DOF)

- **Translational** DOF:
  - Move sideways x
  - Move up/down y
  - Move forward/backward z
- **Rotational** DOF:
  - *Roll* from side to side
  - *Pitch* up and down
  - *Yaw* (turning) left or right



Degree Of Freedom (DOF)

- Total DOF vs. Controllable DOFs
  - uncontrollable DOF create problems for the controller in that they make movement more complicated



Degree Of Freedom (DOF)

- Total DOF vs. Controllable DOFs
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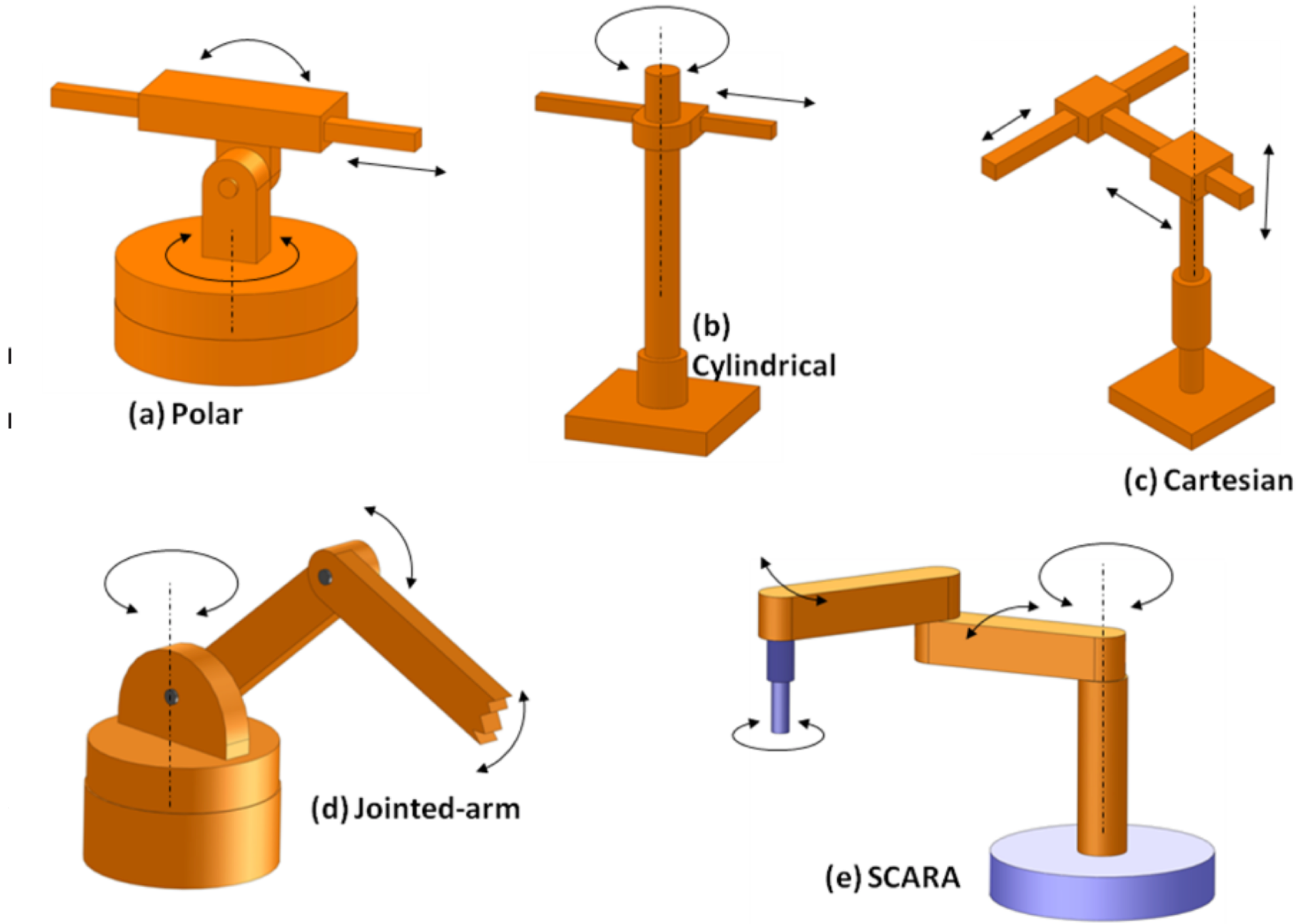
- T.DOF/C.DOF ratio
  - *Holonomic* C.DOF = T.DOF (e.g. helicopter)
  - *Non-holonomic* C.DOF < T.DOF (e.g. car)
  - *Redundant* C.DOF > T.DOF (e.g. arm)

Redundant DOF: Human Arm

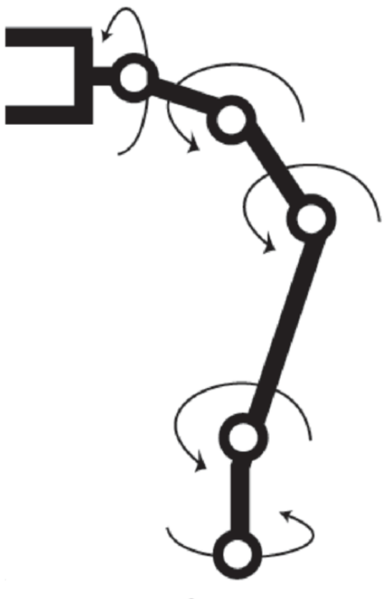
- 7 DOFs for human arm (not including the hand)
  - 3 shoulder (up-down, side-to-side, rotation about the axis of the arm)
  - 1 elbow (open-close)
  - 3 wrist (up-down, side-to-side, again rotation)
- Note…
  - Shoulder: based on a ball-and-socket joint
  - Wrist: rotational DOF from the muscles and ligaments in the forearm.

Redundant DOF: Robot Arms



Redundant DOF: Robot Arms

- Examples
  - MOVEMASTER: 5 DOFs (five joints, each with single rotational DOF)
  - Puma 560: 6 DOFs (with revolute joints)



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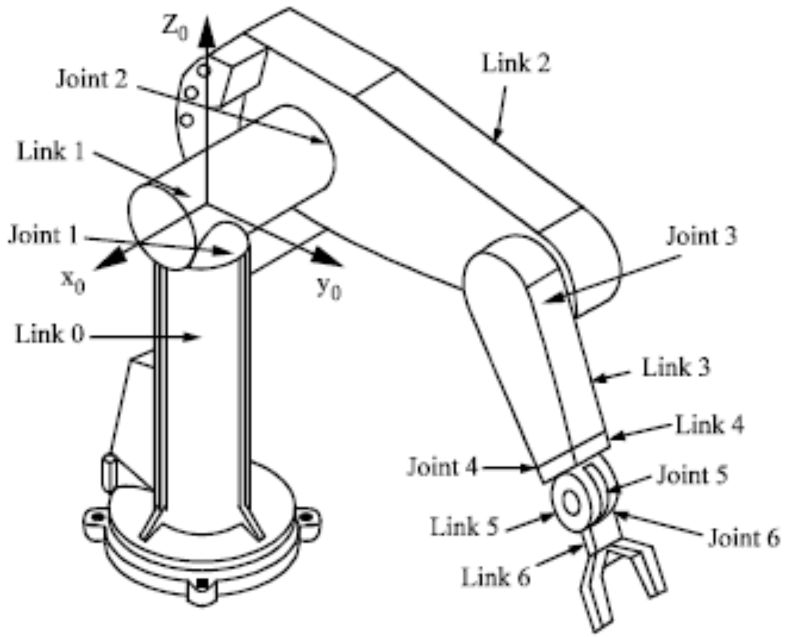
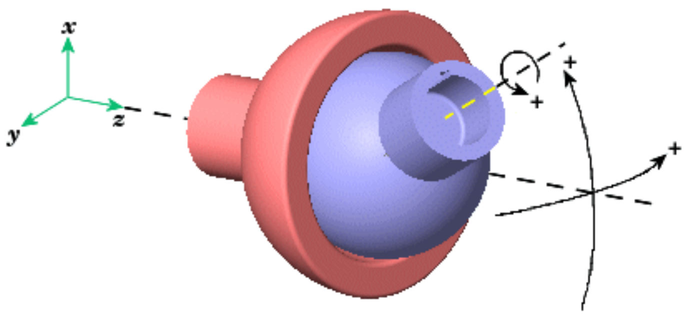


Chouraqui & Benyettou (2009)

Joint and Degree Of Freedoms (DOF)

- Joint: An actuator connecting two body parts
  - A joint can have more than one DOF
  - A separate actuator is needed for each DOF
  - But new motors allow more than one DOF



Multi-DOF Soft Actuator
(Piltan et al. 2016)

Omniwheel
(Rotacaster)

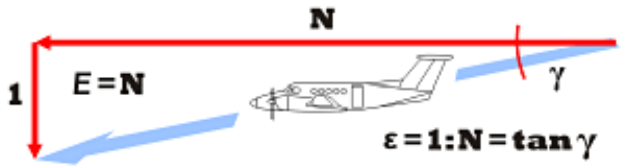
Multi-DOF Soft Actuator
(K. Galloway)

Active and Passive Actuation

- **(Active) Actuator**: uses energy to provide power to move the effector to a desired position
  - **Stiff effector**: predetermined position/trajectory
  - **Compliant actuator**: software/hardware mechanism to respond to external force, by stopping its motor → safe human-robot interaction
- **Passive effector**: uses passive actuation mechanisms exploiting the body-environment physics interaction (no/minimal energy needed)

Passive Effectors in Nature?

Alsomitra macrocarpa
twitter.com



Wikipedia/Google

Active and Passive Actuation

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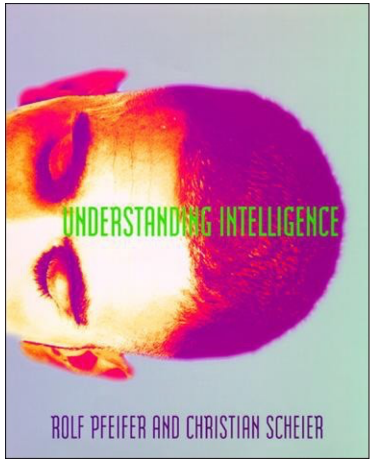
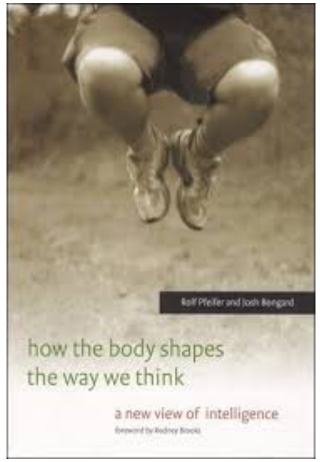
- **Passive effector**: uses passive actuation mechanisms exploiting the body-environment physics interaction (no/minimal energy needed)
  - e.g. shape of body/effector (e.g. glider wings)
  - e.g. passive joints (e.g. leg and gravity/slope to walk)

History of Robotics: Theories & Approaches

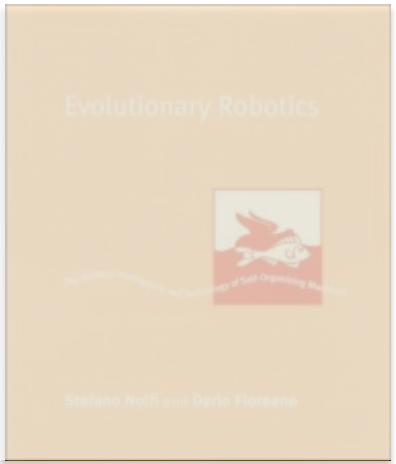
– Brooks's Behaviour-Based Robotics (1991/1998)

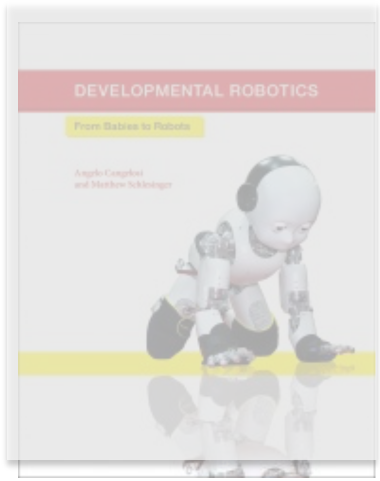
– **Pfeifer's Embodied Intelligence (1999/2006)**



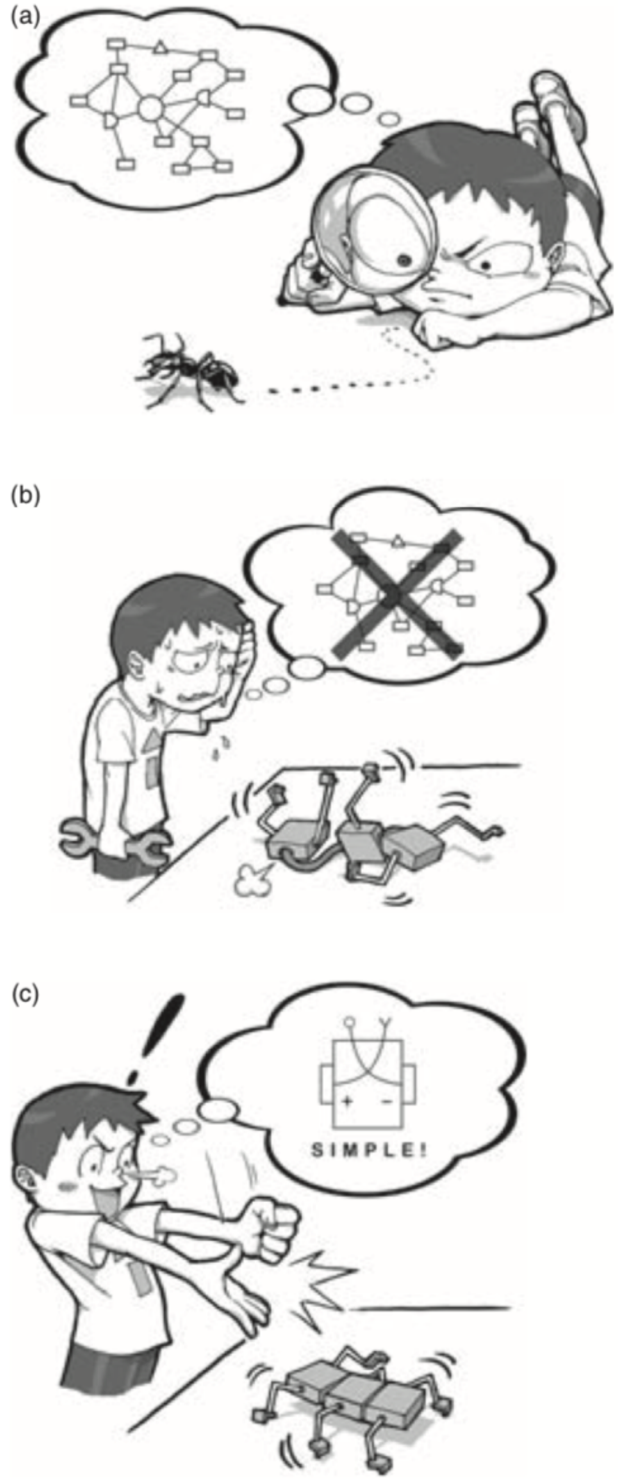


– Evolutionary Robotics (1986/2002)
Developmental Robotics (2000/2015)





Embodied Intelligence (Pfeifer)



Embodied Intelligence (Pfeifer)

(a)

(b)

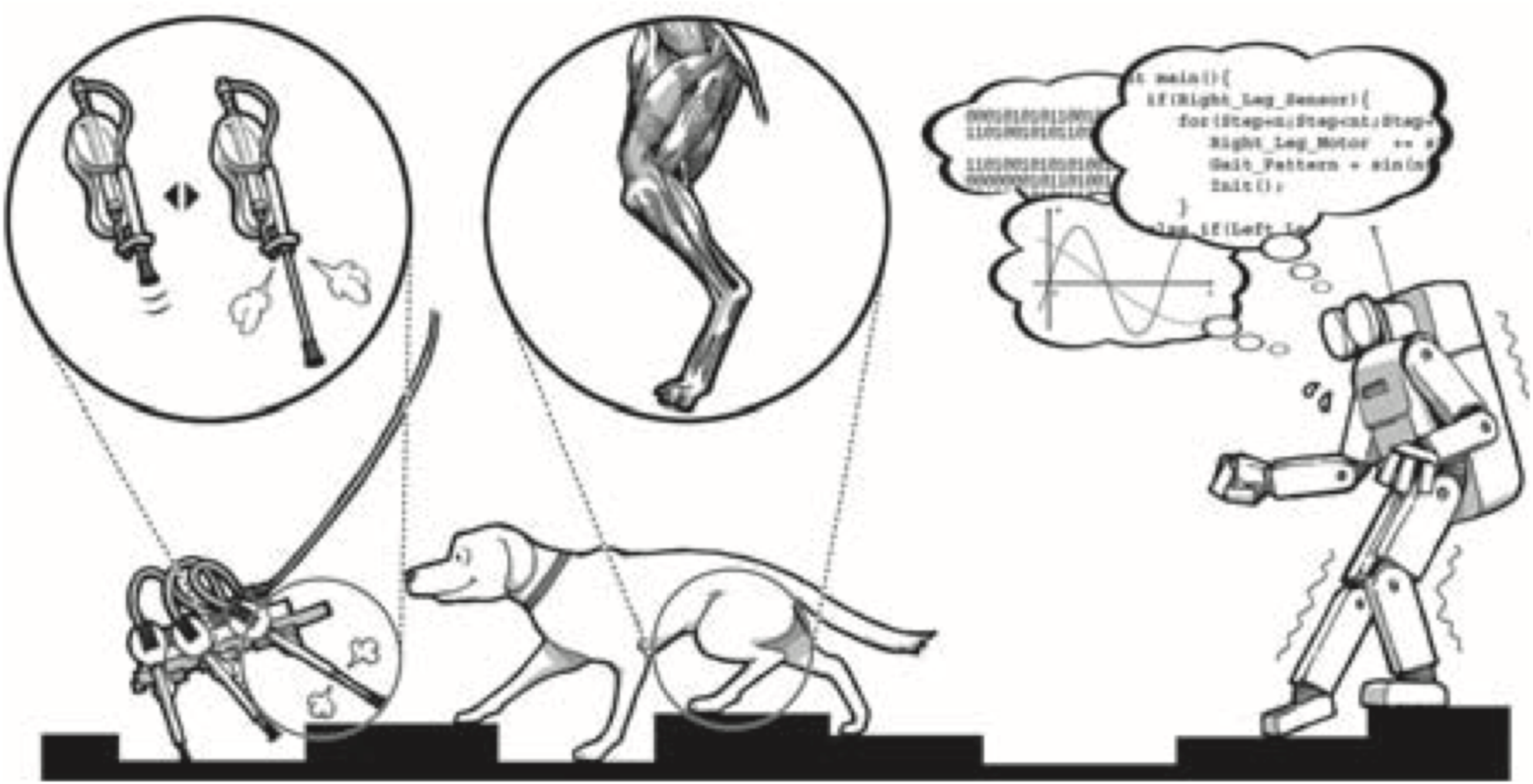
Bongard & Pfeifer (2006)

Embodied Intelligence & Morphological Computation

- Embodied intelligence in nature
  - Many animal/human body structures and systems **exploit passive and compliant effectors**
  - Exploitation of the **body-environment interaction** for effective actuation
- Embodied intelligence in robotics
  - Inspiration from biological systems to develop low energy consumption robots, with passive or hybrid passive-active actuators (Pfeifer & Bongard, 2007)
  - ecological balance: relation between morphology, materials and (brain) control

Bongard & Pfeifer (2006)

Embodied Intelligence & Morphological Computation



Bongard & Pfeifer (2006)

Embodied Intelligence & Morphological Computation

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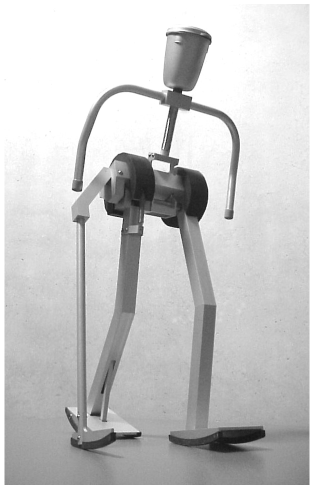
  - **Ecological balance**: relation between morphology, materials and (brain) control

Bongard & Pfeifer (2006)

Passive Dynamic Walkers

- Passive Dynamic Walker (Collins et al., 2005; McGeer ‘ Wisse)
  - exploits gravity and structure of two legs with flexible knees, without the need of applying energy



https://www.youtube.com/watch?v=wMlDT17C_Vs

McGeer

Collins

Types of Actuator

Actuator	Description	Notes
Electric Motors	Rotating motors producing movement due to electric current	Pros: simple, affordable, common Cons: produce heat, not very energy efficient Main types: DC motors, Geared DC motors, Servo motors, Stepper motors
Hydraulics	Actuators producing movement due to changes in fluid pressure	Pros: for powerful, precise movements Cons: large, dangerous, risk of leaking Main types: Pistons
Pneumatics	Actuators producing movement due to changes in air pressure	Pros: for powerful movements, quick and accurate response, passive dynamics Cons: dangerous, noisy, risk of leaking Main types: McKibben muscles
Reactive materials	Materials producing small movement (shrinking/elongation) due to reaction to light, or chemical substances or temperature	Pros: suitable for micro-robots, linear actuators Cons: only for small/weak movements; chemical risks Main Types: Photo-reactive materials, Chemically-reactive materials, Thermally-reactive materials

*Electric Motor Actuators

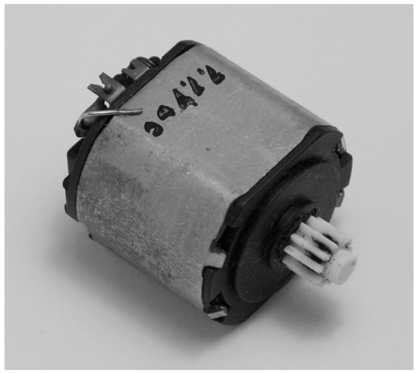
- Used extensively in robotics
  - affordable, require relatively low energy consumption, based on the standard engineering
- Four main types of electric motors in robotics:
  1. DC Motors
  2. Geared DC Motors
  3. Servo Motors
  4. Stepper Motors
- Rotational mechanism for 1-3
  - rotational motors transform energy into motion of a shaft

*Electric Motors Control

- Two main parameters of rotational motors
  - **Torque**: rotational force produced at a given distance
  - **Speed**: the rotational velocity (revolutions per minutes/seconds: rpm/rps)
- Motor control mechanisms for robot joints:
  - **Position control**: Controller drives the motor to reach a target position. If an obstacle/force are applied, the controller will react to this (stiffness) and produce a counter force to keep the desired position
  - **Torque control**: the motor aims to keep a target torque, ignoring the actual position of the shaft

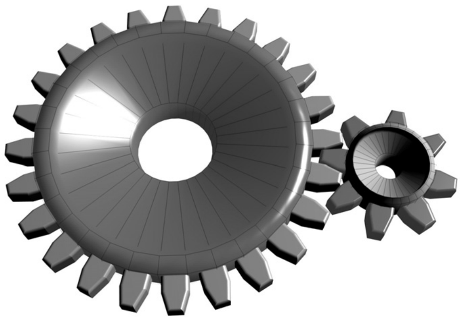
*Electric Motors: Types

- **DC Motors (Direct-Current Motors)**
  - The most commonly used type of actuator in robotics.
  - Convert electric energy into rotating movements
  - **Voltage modulation** causes rotations of different speeds (rotational velocity) and torques (force)
  - Typically high speed (3000-9000 rpm) and low torque (but robots need high rotational force and low speed)

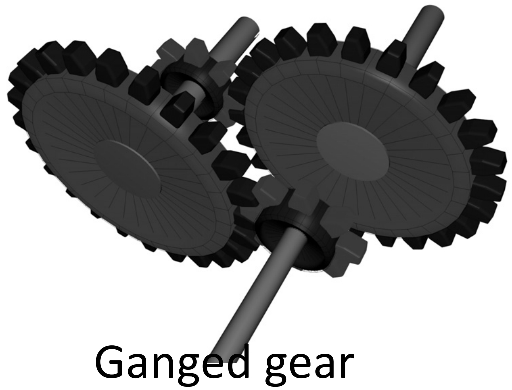


*Electric Motors: Types

- **Geared DC Motors**
  - Gear mechanism that converts the speed and torque of the rotating shaft into slower/stronger movements
    - Combining different gears to change the force and torque output of motors
    - When a small gear drives a large one, torque is increased and speed is decreased.
    - “Ganged” gears to to multiply their effect



Example of a 3:1 gear reduction



Ganged gear

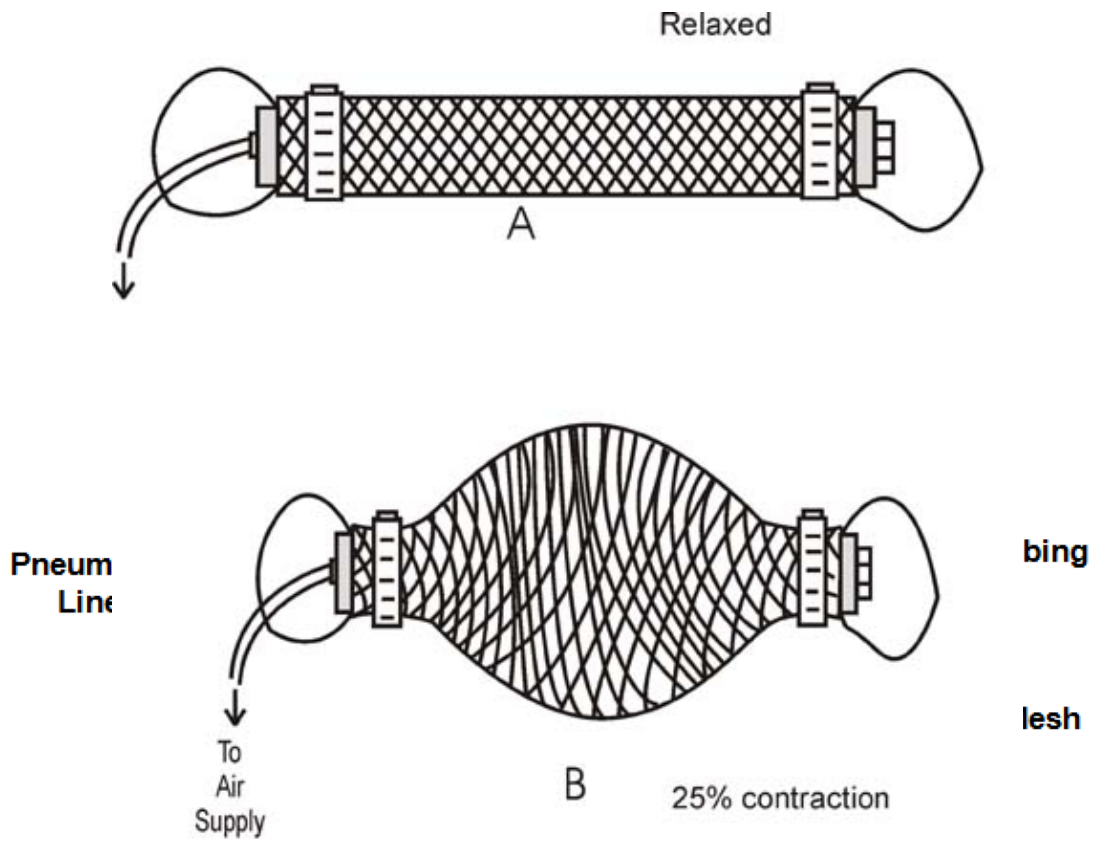
*Electric Motors: Types

- **Servo Motors (aka Servos)**
  - Rotate the shaft to a specific angular position
  - Combines (i) DC motor, (ii) electronics component to turn the shaft to target position, (iii) potentiometer to sense the current position of the shaft
  - feedback signals to calculate error and adjust position
  - Increasingly used in robotics due to higher precision
  - **PID control** algorithm
- **Stepper Motor**
  - Rotate in specified “steps”, or degrees of rotation, to move the actuator to a desired angular position

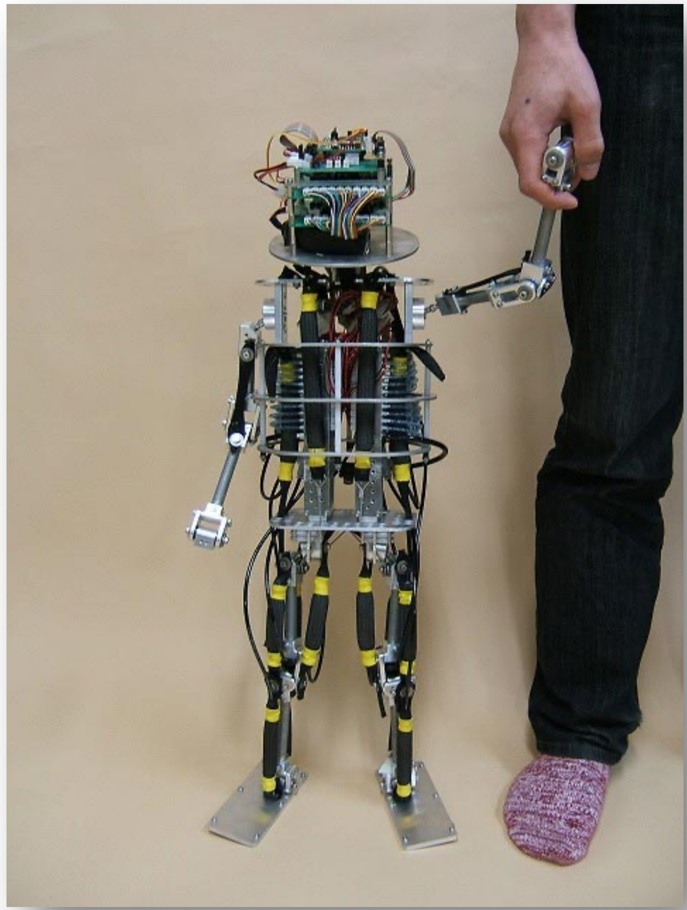
*Hydraulic and Pneumatic Actuators

- Linear actuators where water/air pressure in a tube causes a linear shrinking or elongation
- Can apply **strong force** → common in industrial robotics (but noisy, bulky, dangerous, likeage)
  - Noisy! Big dog video
- **Hydraulic** actuators: offer a high level of precision for the target position
- **Pneumatic** actuators: can model the dynamics of muscles (McKibben pneumatic) (soft robots)

*Pneumatic: McKibben air muscles



When muscle is pressurized (B), it can contract up to about 75% of it's relaxed length



Narioka & Hosoda 2008

softroboticstoolkit.com/book/pneumatic-artificial-muscles

*Reactive Material Actuators

- Variety of special materials, e.g. fabric or polymers and chemical compounds
- **Small movement** (shrinking/elongation) as a reaction to
  - light (photo-reactive)
  - chemical substances, and acidic/alkaline solutions (chemically-reactive)
  - temperature (thermally-reactive)
  - electric charges when pressed (Piezoelectric/crystals)
- Suitable for soft robots

www.researchgate.net/publication/4677426_Electroactive_Polymers_as_Artificial_Muscles

Robotics Sensors

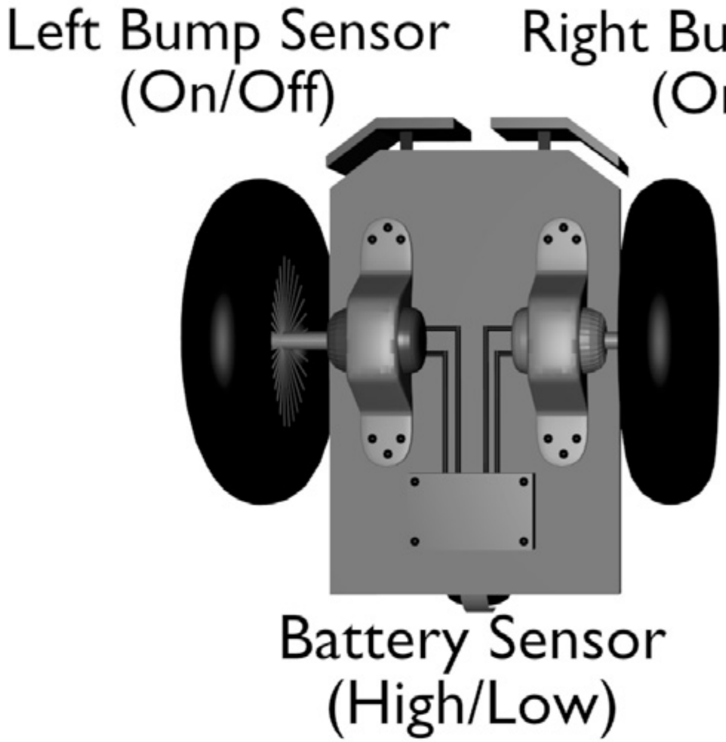
Sensors and Perception

Sensors and Perception

- **Sensor**: physical devices to measure physical quantities
  - Internal (proprioception): battery, motor (motor force, wheel odometry)
  - External (exteroception): vision, distance, tactile, olphactory, geospatial (Cameras, sonars, lasers, switches, skin)
- **State (state space)**: all possible values or variations of a sensor
  - Discrete or continuous (cf. Reinforcement Learning)
- **Representation**: model of the world

Mataric (2007)

Sensors and Perception



Battery	Left Bump	Right Bump
high	on	on
high	on	off
high	off	on
high	off	off
low	on	on
low	on	off
low	off	on
low	off	off

State = (Internal State) + (External State)
= (Battery Sensor) +
(Left Bump + Right Bump)

Mataric (2007)

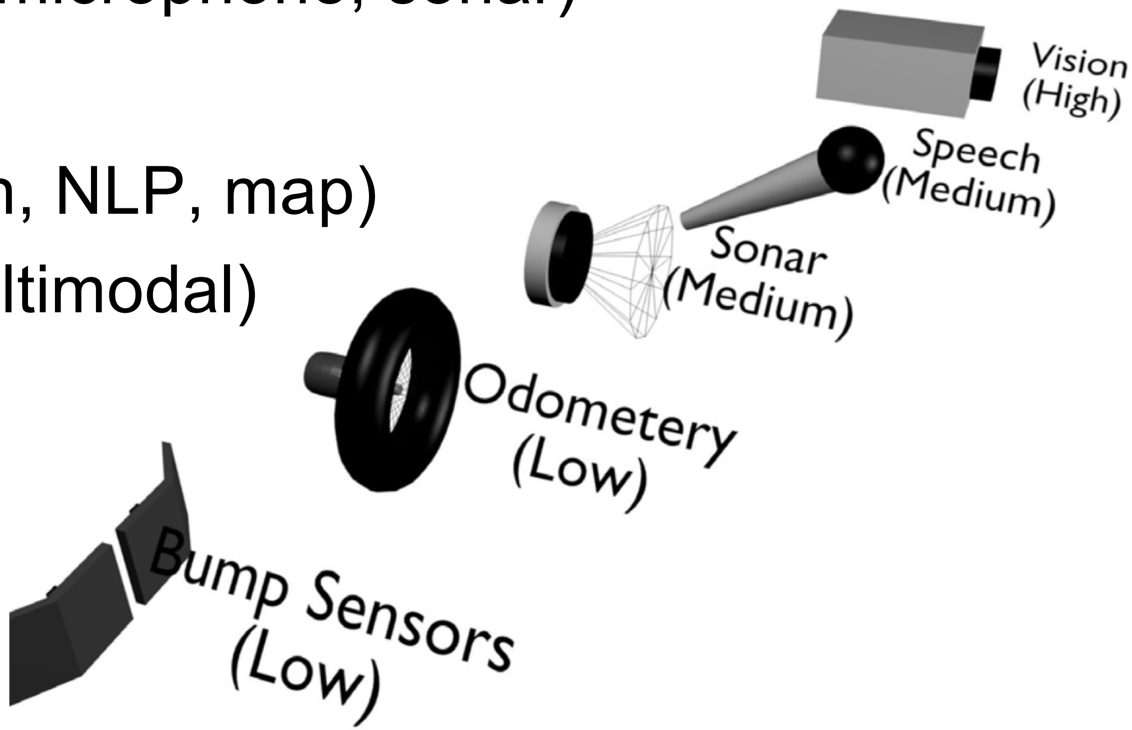
Sensor Uncertainty

- Uncertainty: robot's inability to be certain about the state of itself and its environment
  - Sensor noise and errors
  - Sensor limitations
  - Sensor calibration
  - Effector and actuator noise and errors
  - Hidden and partially observable states
  - Lack of prior knowledge about environment, or dynamic and changing environment

Mataric (2007)

Levels of sensory processing

- Low:
  - Electronics (bump sensor, odometry)
- Medium
  - Signal processing (microphone, sonar)
- High
  - Computation (vision, NLP, map)
  - Sensors fusion (multimodal)

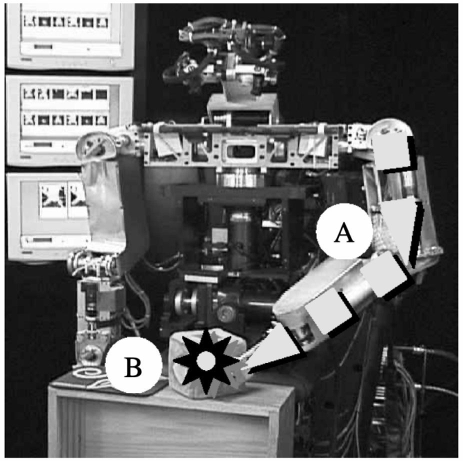


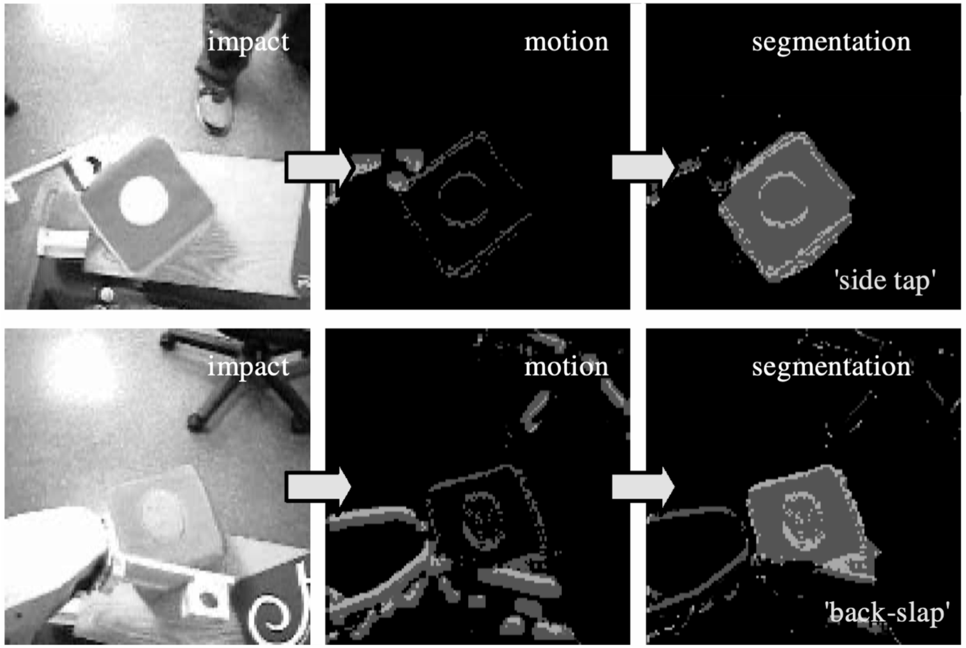
Perception theories

- Passive vision
  - Bottom-up image-processing approach (Marr 1982)
- Active vision
  - Use knowledge about task to look for particular stimuli
  - Humans: Land et al. (1999): "*the eye-movement has the frenetic appearance of a movie that has been greatly speeded up*"
  - Computer vision: fovea directed to different locations within the visual field (Aloimonos et al. 1997)
  - Robots: for navigation/map, for object recognition/manipulation (Chen et al. 2011)

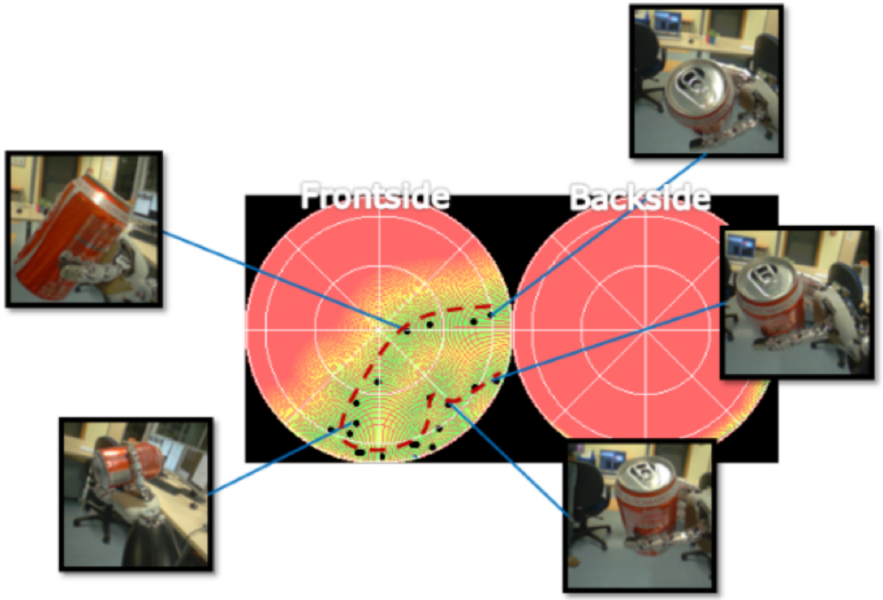
Findlay & Gilchrist (2003). Active Vision, The Psychology of Looking and Seeing. Oxford U Press
Chen et al. (2011). Active vision in robotic systems: A survey. *Intl J Robotics Research*, *30*(11)

Active vision in robots





Fitzpatrick, P., & Metta, G. (2003). Grounding vision through experimental manipulation.



Browatzki et al. (2012). Active object recognition on a humanoid robot.

Types of Sensors

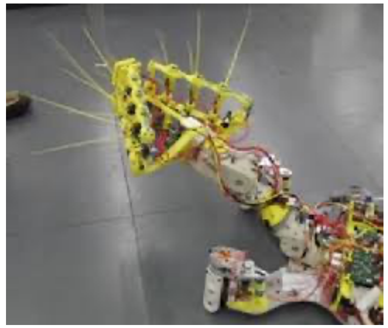
Sensors	Devices	Notes
Vision (Light)	Photocell	For intensity of light
	1D camera	For perception of horizontal direction
	2D B&W or color camera	Full visual processing sensing; Computational intensive but information rich
Sound	Microphone	Full audio processing sensing; Computational intensive but information rich
Distance and proximity	Ultrasonic (Sonar, Radar)	Time-of-flight for the return of emitted ultrasonic sound waves; Limits of specular reflection for non-smooth surfaces
	Infrared (IR)	Use reflective optosensor for infrared light waves; Modulated IR to reduce interference
	Camera	Binocular disparity or visual perspective
	Laser	Time-of-flight for the return of emitted laser light; No specular reflection issue
	Hall effect	Ferromagnetic materials
Contact (Tactile)	Bump switch	Binary on/off contact
	Analogical touch sensors	Spring coupled with a shaft; Soft conductive material that change its resistance according to compression
	Skin	Sensors distributed over body
Position and Localization	GPS	Global Positioning System Accuracy from 1.5m (GPS) to 2cm (DGPS);
	SLAM (optical, sonar, vision)	Simultaneous Localization And Mapping; Use of light, sound or vision sensors
Force and torque	Shaft encoder	For number of rotations of the motor's shaft; Use break-beam optosensor Speedometer for speed of rotation; Odometer for number of rotations
	Quadratic shaft encoder	For the direction of rotation of the motor shaft
	Potentiometer	For motor's shaft position; In servo motors, to detect shaft position
Inclination and acceleration	Gyroscope	For inclination and acceleration
	Accelerometer	For acceleration

*Passive and Active Sensors

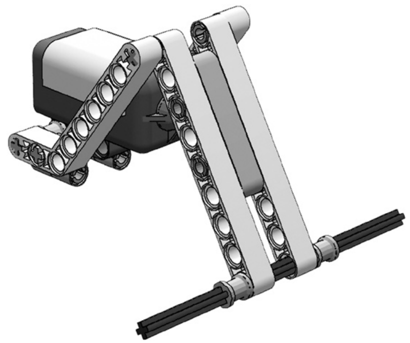
- Passive sensor: Signal detector
  - Switches, Resistive light, Cameras
- Active sensors: Emitter produces signal and Detector perceives it
  - Reflectance and Break beam sensors
  - Ultrasound (sonar) and laser sensors

*Basic Robot Sensors: Switches

- Switches
  - Sensing of an open vs. closed electronic circuit
- Functions
  - Contact sensor
  - Limit sensors
  - Shaft encoder



- Bump switch (contact switch)
  - Body (parts) contact
  - Wiskers and antennas



*Basic Robot Sensors: Light

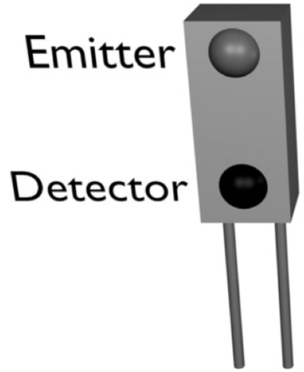
- Photocell
  - Low resistance in the circuit with light (dark sensor)
  - Also for ultraviolet and infra red light
  - Uses: (i) light intensity, (ii) differential intensity between photocells, (iii) break continuity (break beam)
  - Braitenberg vehicle’s light sensor
- Polaraised light
  - Polarising filter in front of the light source for a specific “characteristic plane” (direction)
  - Sensitive to polarized light only for particular direction
  - Combination of polarized filters

*Basic Robot Sensors: Light

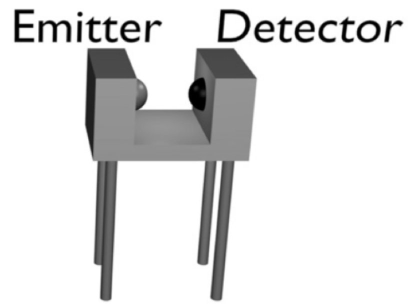
Reflective optosensors

- Active light sensors
  - Emitter with Light-Emitting Diode (LED)
  - Detector with photodiode/phototransistor
- Types
  - **Reflectance sensors**: Emitter and detector side by side, separated by barrier
  - **Break beam sensors**: Face one another
- Other light sensors
  - Reflectance Sensors, Infra-red sensors

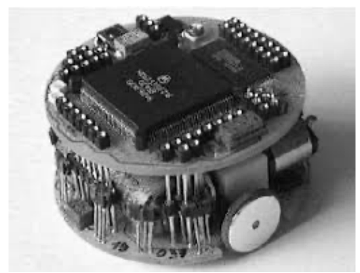
Reflective Optosensor



Break beam Optosensor



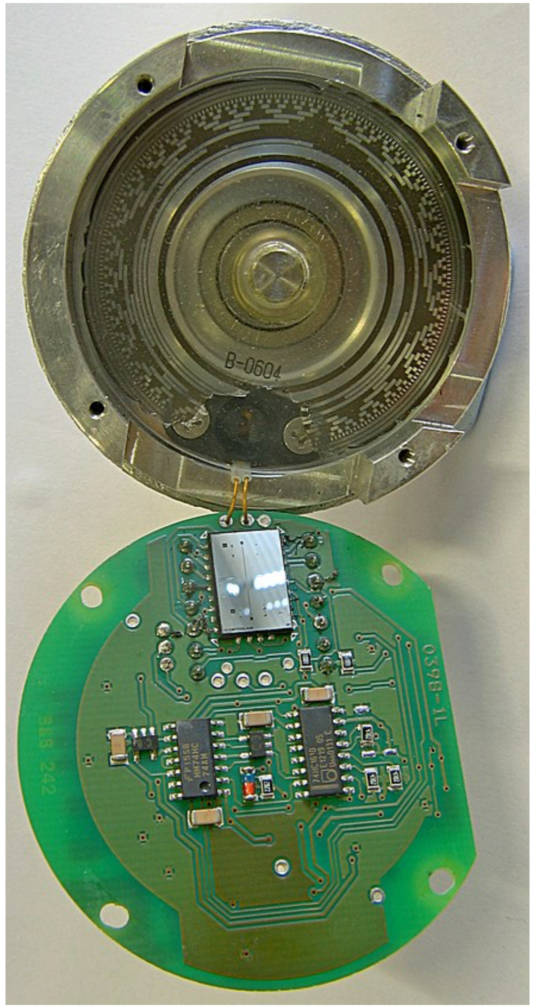
Infrared sensors



*Basic Sensors: Shaft Encoders

Measure angular rotation of a shaft or axle

- Break-beam or reflectance mechanisms
- For position and/or velocity information
  - Odometer for the number of rotations
  - Speedometer for wheel shaft speed (velocity)
- Quadrature shaft encoding
  - Measures direction of rotation (with 2 break beam sensors)
  - Used in ball-and-socket joints
  - Used in **Cartesian robots** for precision tasks (arm moves back and forth, along axis/gear)

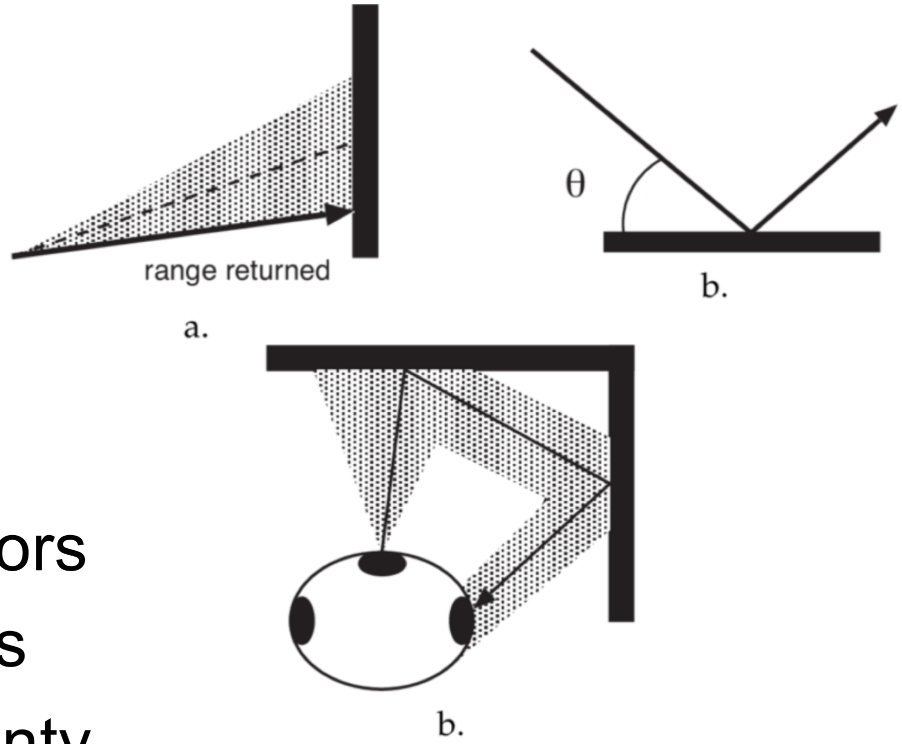


Complex Robot Sensors: Sonars

- Sonar: **SO**und **NA**vigation and **R**anging
  - Ultrasonar sound frequencies
- Used for **echolocation**
  - To find own position using echo
  - Time-of-flight principle
  - Cheap, small transducer: **Polaroid Ultrasound Sensor**
  - Multiple sensor units for increased coverage/accuracy
  - Typically 30^o cone

Complex Robot Sensors: Sonars

- Very popular, affordable, but…

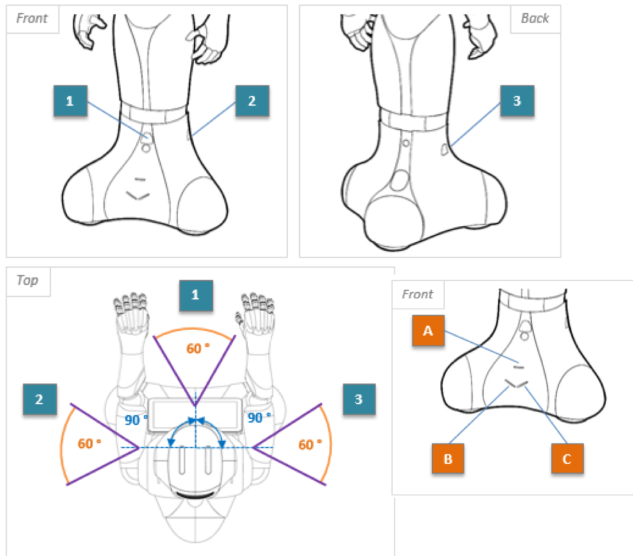


Issues

- Specular reflection
  - Use phased arrays of sensors
  - Use history of past readings
  - Active sonar when uncertainty
- Foreshortening: Different reflections from 30^o cone
- Cross-talk: Signals from different sonars

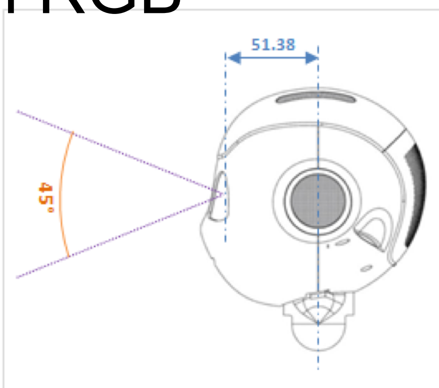
Complex Robot Sensors: Laser/LIDAR

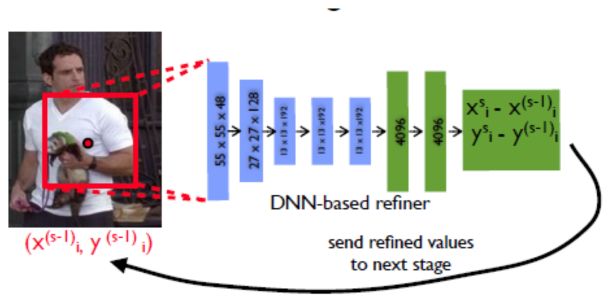
- Laser range sensors: LIDAR
  LIght **D**etection and **R**anging
  - (aka Laser radar, Ladar).
  - For indoor navigation and mapping
  - Emits highly amplified and coherent radiation at target frequency(ies)
  - Planar 2D horizontal
  - Time-of-flight principle (fast!)
  - Phase-shift measurements (for short-range distances)



Complex Robot Sensors: Vision

- 2D cameras
- 3D RGB-D cameras
  - A revolution in robotics
  - IR light striping system (random dots) + RGB camera
  - Low cost Microsoft Kinect / ASUS Xtion
  - Range 1.2m to 3.5m (Kinect)
  - now LeapMotion (manipulation)
  - Now DeepPose from RGB





Summary

- Actuators and Effectors
  - Active vs Passive effectors
  - DOF Degrees of Freedom (human and robot arms)
  - Embodied intelligence / Morphological computation
- Sensors
  - Sensor uncertainty, active vision
  - Sonar, LIDAR, Cameras
- **Reading**
  - Cangelosi & Schlesinger, Chapter 2 (see Blackboard)
  - (Optional) Matarić (2007). The Robotics Primer. MIT Press. (Chapters 4, 8, 9)