POLITECNICO DI MILANO

Robotics – Sensors & Actuators

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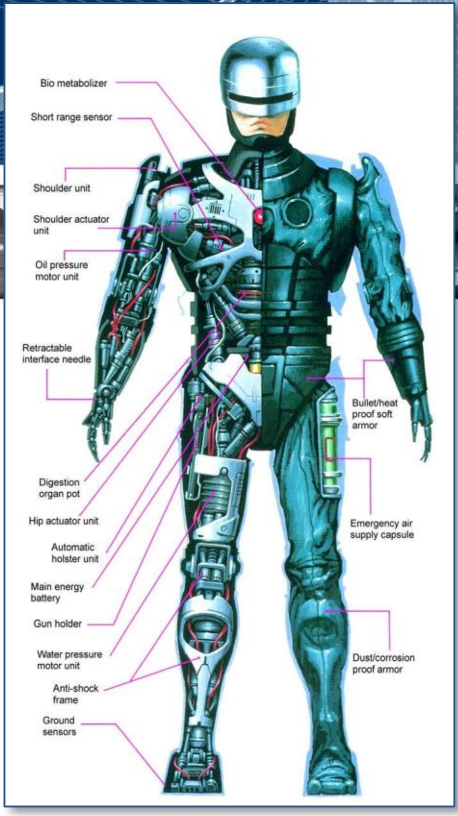


What does it make a mobile robot?

Sensors perceive:

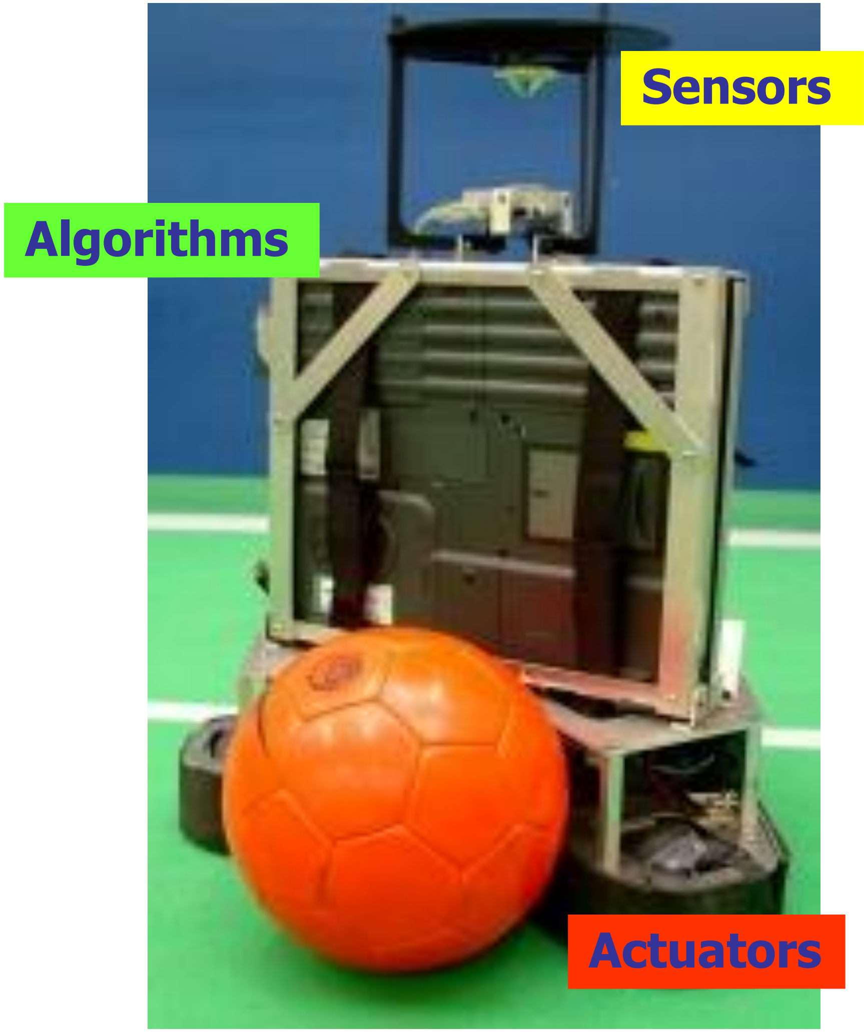
- Internal state of the robot (proprioceptive sensors)
- External state of the environment (exterocemptive sensors)

Effectors modify the environment state

- Match the robot task
- E.g. wheels, tracks, legs, grippers

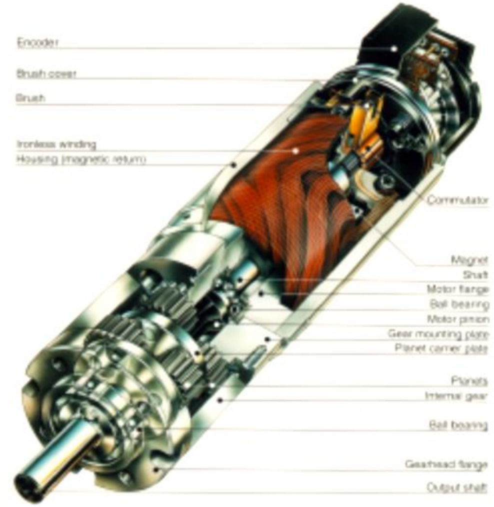
Actuators enable effectors to act

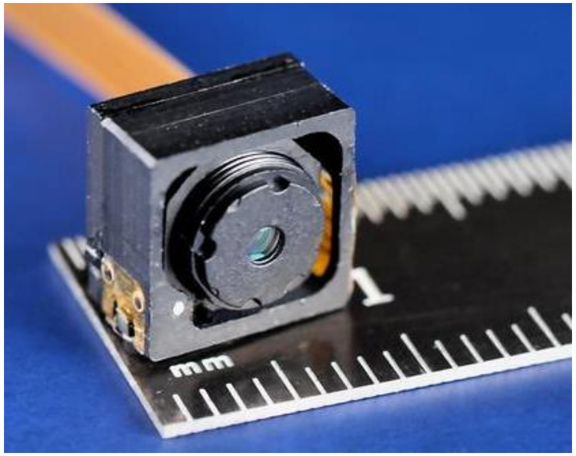
- E.g., passive actuation or motors of various types



Type of Actuators

- Electric motors
- Hydraulics
- Pneumatics
- Photo-reactive materials
- Chemically reactive materials
- Thermally reactive materials
- Piezoelectric materials

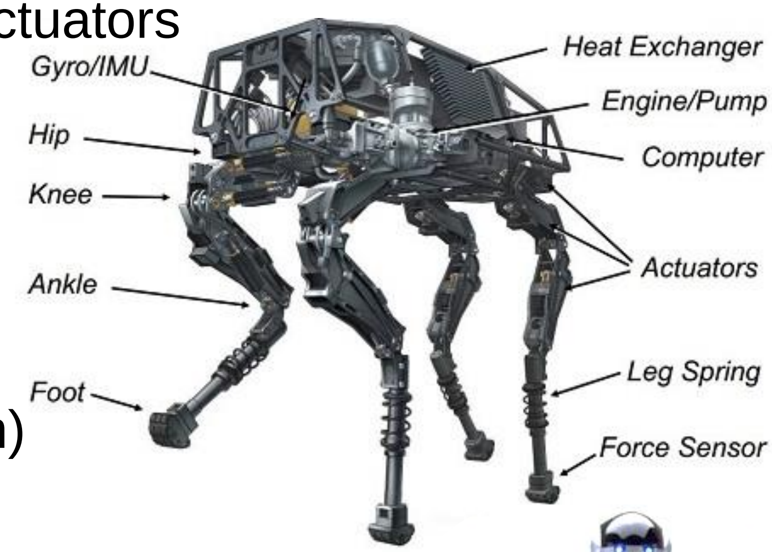




Most Popular Actuators

First robots used hydraulic and pneumatic actuators

- Hydraulic actuators are expensive, weighing, and hard to maintain (big robots)
- Pneumatic actuators are used for stop-to-stop applications such as pick-and-place (fast actuation)



Nowadays most common actuators are electrical motors

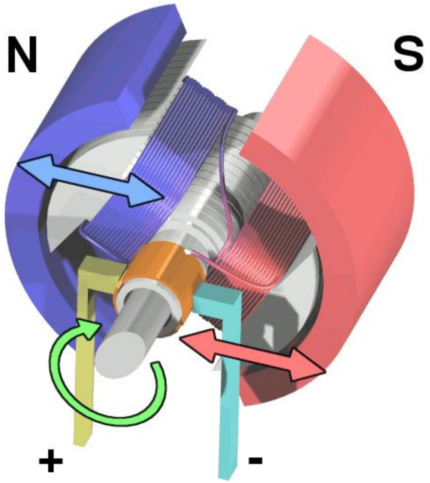
- Each joint has usually its own motor (and controller)
- High speed motors are reduced by (elastic) gearing
- They need internal sensors to be controlled
- Stepper motors do not need internal sensors, but when an error occurs their position is unknown

Direct Current (DC) motors

- Convert electrical energy into mechanical energy
- Small, cheap, reasonably efficient, easy to use

How do they work?

- Electrical current traverses loops of wires mounted on a rotating shaft
- Loops of wire generate a magnetic field which reacts against the magnetic fields of permanent magnets placed around
- These two magnetic fields push against one another and the armature turns



DC Motors


Nylon end cap
Axle
Steel can
Lead wires to battery
Dime
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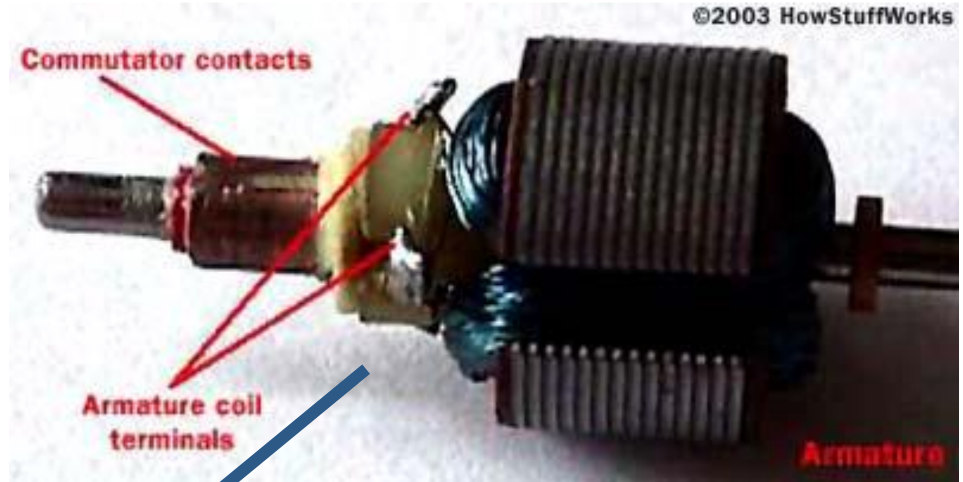
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Commutator contacts
Armature coil terminals
Armature


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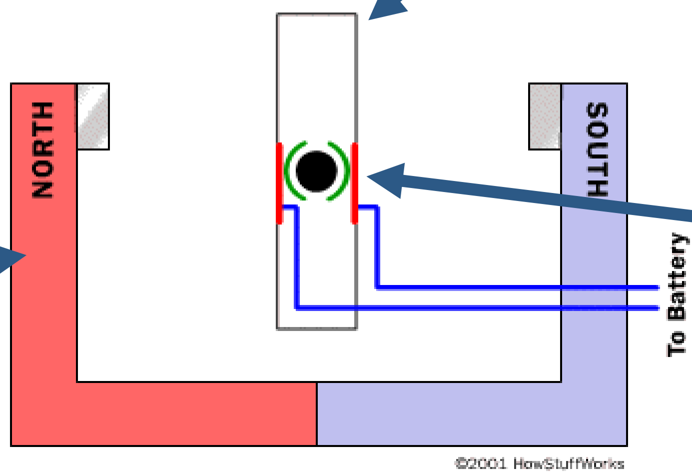
NORTH
SOUTH
To Battery
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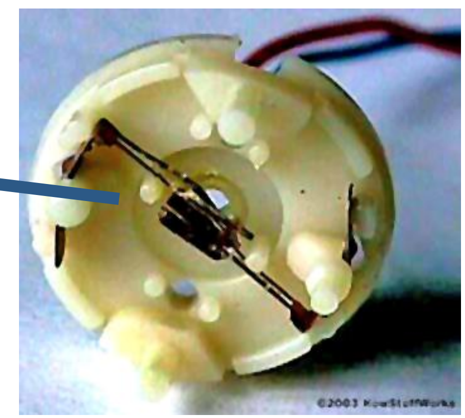
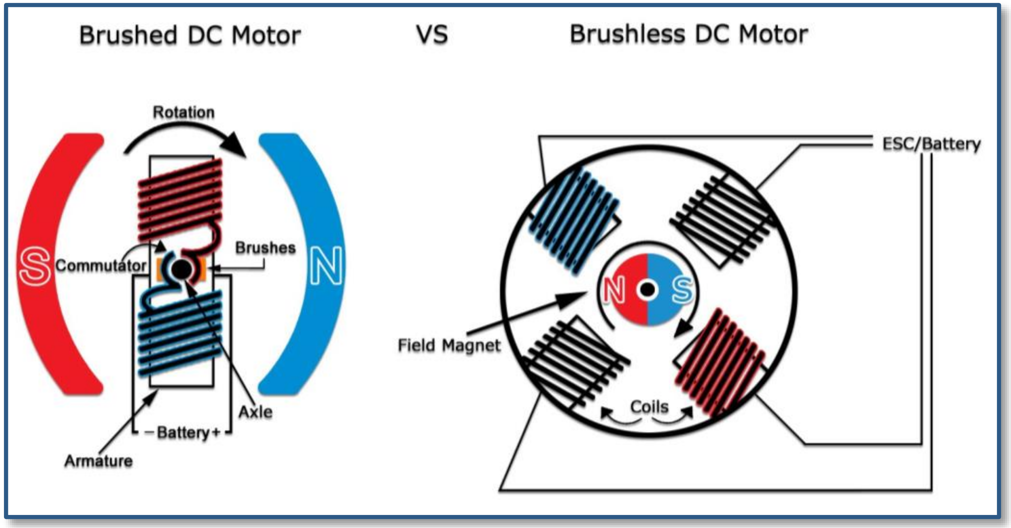


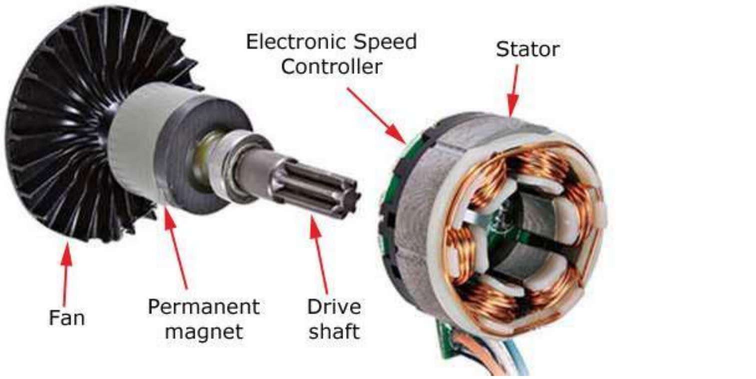
Brushes used to change magnetic polarity, they're cheap but ..

- Brushes eventually wear out
- Brushes make noise
- Limit the maximum speed
- Hard to cool
- Limit the number of poles



Brushless motors overcome these problems but they are more expensive

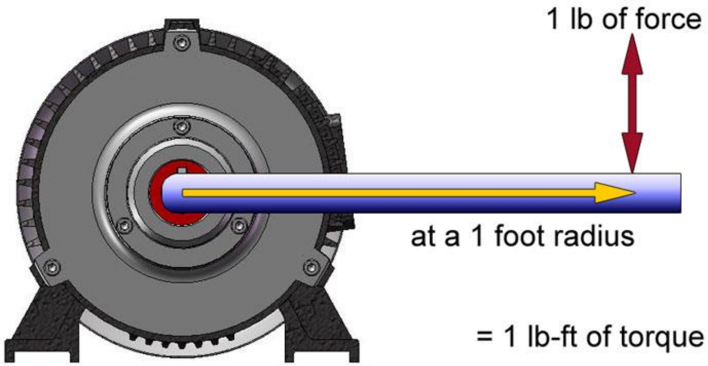
- Brushes are replaced by computer
- Permanent magnets on the rotor
- Electromagnets on the stator



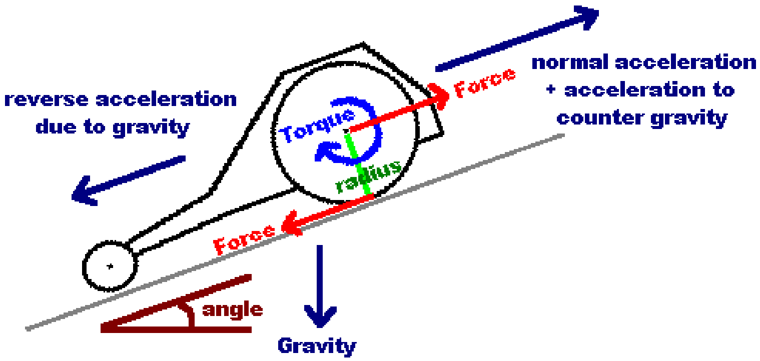
Torque in a DC motor

Torque: force that a motor can deliver at a certain distance from the shaft

- Strength of magnetic field generated is directly proportional to the amount of current flowing and thus the torque on motor's shaft



Stall torque: the amount of rotational force produced when the motor is stalled at its recommended operating voltage, drawing the maximal stall current at this voltage



Torque units: ounces*inches or N*m

- 9.8 N*m torque means motor can pull a weight of 1kg through a pulley 1m away from the shaft

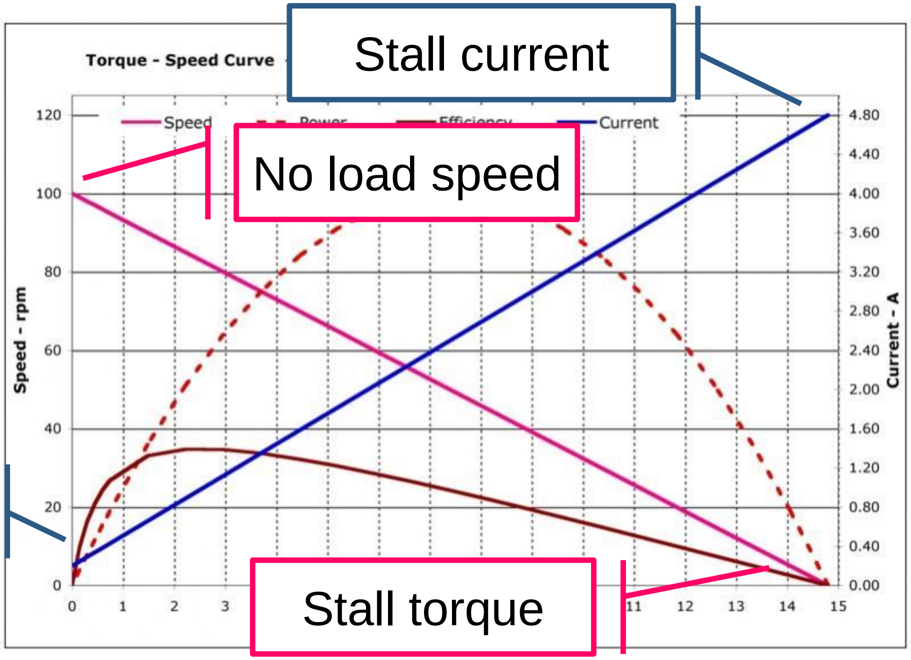
Power (P): product of the output shaft's rotational velocity and torque

With no load on the shaft then P=0

- Rotational velocity is maximum, but the torque is 0
- The motor is spinning freely

With motor stalled then P=0

- Producing its maximal torque
- Rotational velocity is zero



A motor produces the most power in the middle of its performance range

$$\tau_m = \tau_s\left(1 - \frac{\omega_m}{\omega_{max}}\right) \qquad \omega_m = \omega_{max}\left(1 - \frac{\tau_m}{\tau_s}\right)$$

Motor Efficiency

Motor efficiency is power out divided by power in $$\eta = \frac{P_{output}}{P_{input}}$$

Power out is mechanical energy

$$P_{output} = \tau \cdot \omega$$

Power in is electrical energy

$$P_{input} = V \cdot I$$

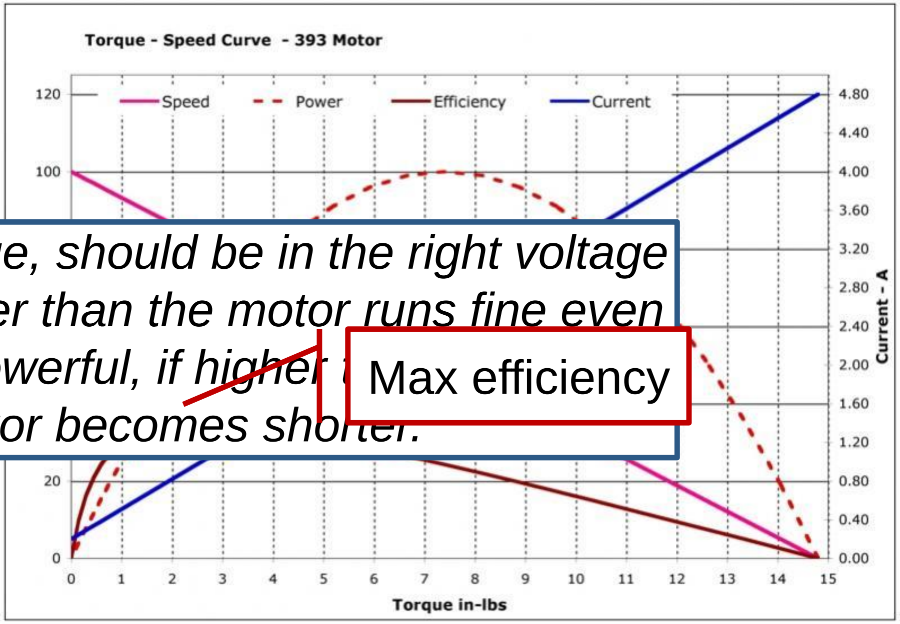
$$I = \frac{V_s - V_e}{R}$$

$$V_e = k_e \cdot \omega$$

Supplied voltage, should be in the right voltage range, if is lower than the motor runs fine even if it is less powerful, if higher the motor becomes shorter.

Back - EMF

Max efficiency



DC motors are not perfectly efficient

- Due to friction some energy is wasted as heat
- Industrial-grade motors (good quality): 90%
- Toy motors (cheap): 50%
- Micro-motors for miniature robots < 50%

How fast do motor turn?

Free spinning speeds (most motors)

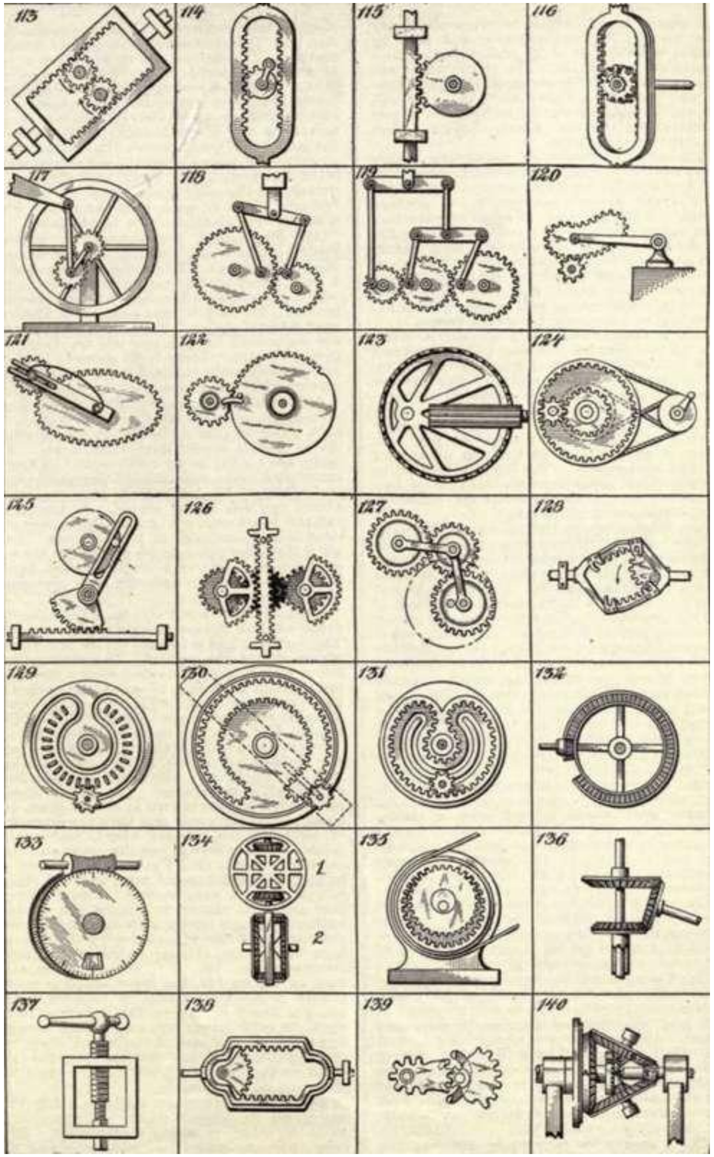
- 3000-9000 RPM (50-150 Hz)
- High speed, low torque to drive light things that rotate very fast

What about heavy robots or manipulators?

- More torque and less speed

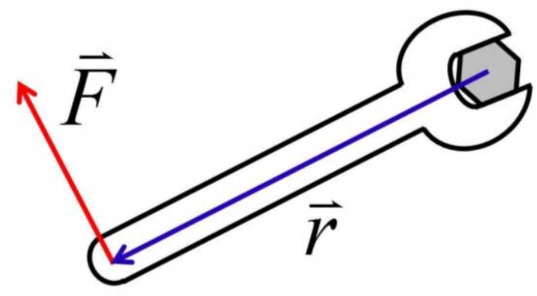
The solution is using gearing

- Trade-off high speed for torque
- They introduce friction
- They introduce dynamics (flexible)



Torque: *T = F x r*

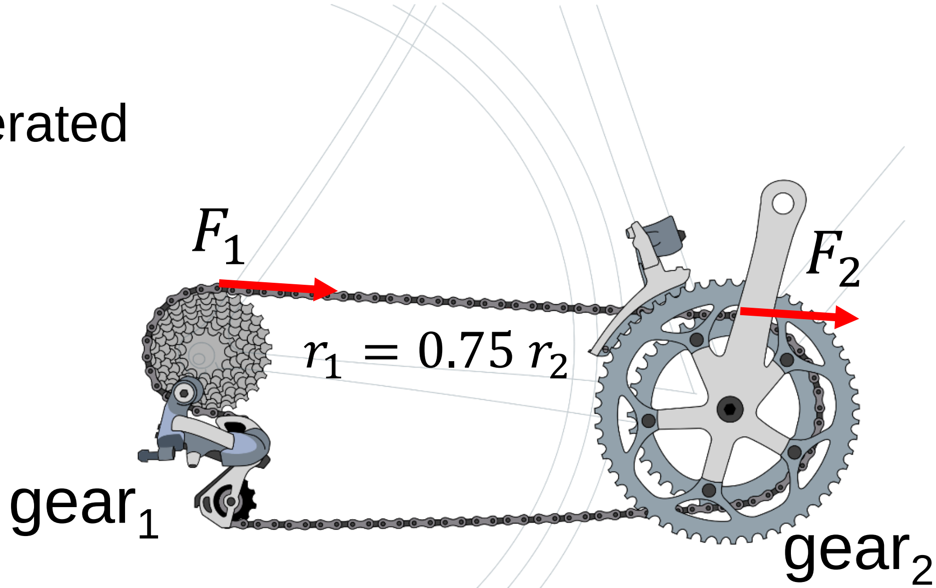
- Rotational force generated at the center of a gear is equal to the gear's radius times the force applied tangential at circumference



Meshing gears: by combining gears with different ratios we can control the amount of force and torque generated

Example: Bike chain force transfer

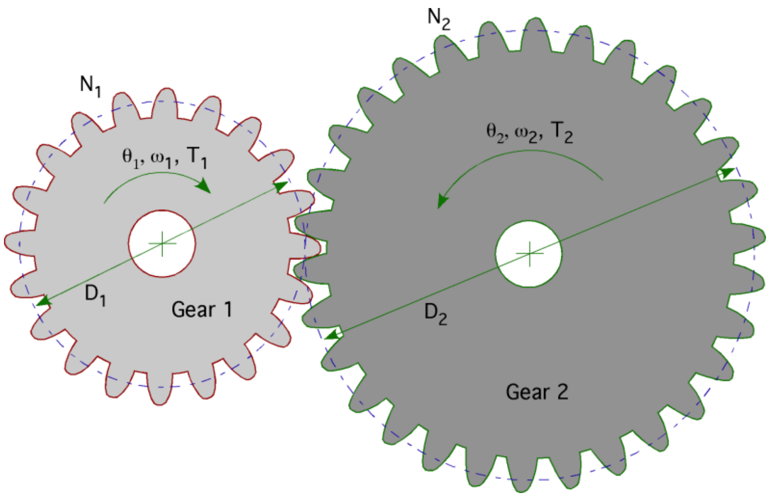
$$F_1 = F_2$$
$$T_1/r_1 = T_2/r_2$$
$$T_1/T_2 = r_1/r_2 = 0.75$$



Gearing Effect on Speed

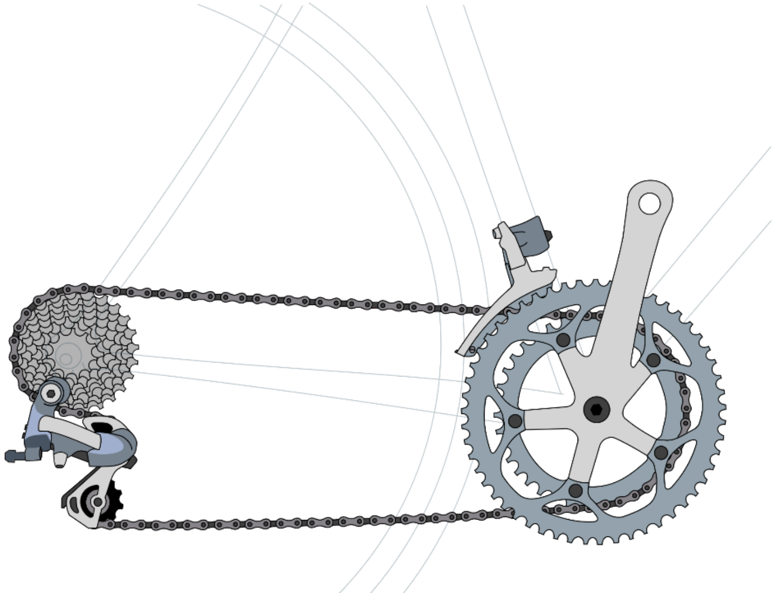
Combining gears has effect on speed too

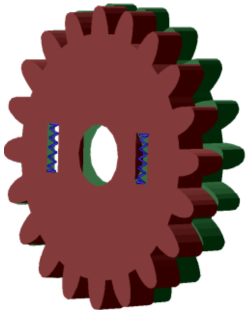
- A gear with a small radius runs faster to keep up with a larger gear
- Increasing gear radius reduces speed, while decreasing the gear radius increases the speed



Torque vs Speed tradeoff

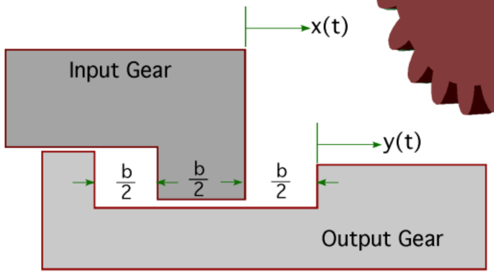
- When a small gear drives a large one, torque is increased and speed is decreased
- When a large gear drives a small one, torque is decreased and speed is increased





Backlash: the looseness between teeth needs to be reduced

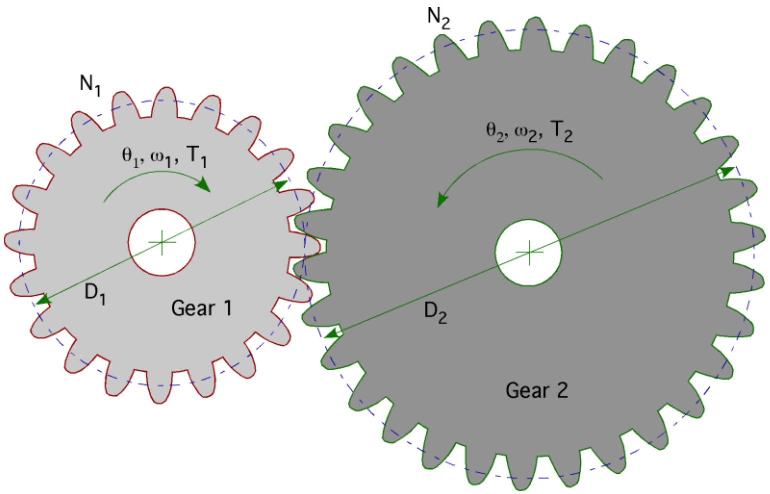
- Tight meshing between gears increases friction and coupling
- Usually proportionally sized gears are used, e.g, a 24-tooth gear must have a radius three times the size of an 8-tooth gear



Input Gear Tooth Shown Centered Between Two Output Gear Teeth

Example:

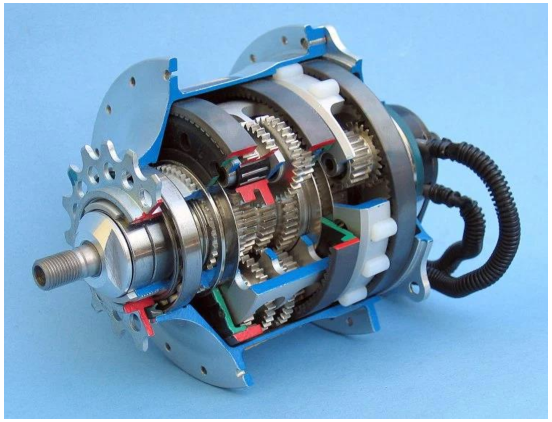
- Input (driving) gear: N_1= 8 teeth
- Output (driven) gear: N_2= 24 teeth
- Effect at the 24 teeth gear
  - N_1 / N_2 =1/3 reduction in speed
  - N_2 / N_1 = 3 times increase in torque



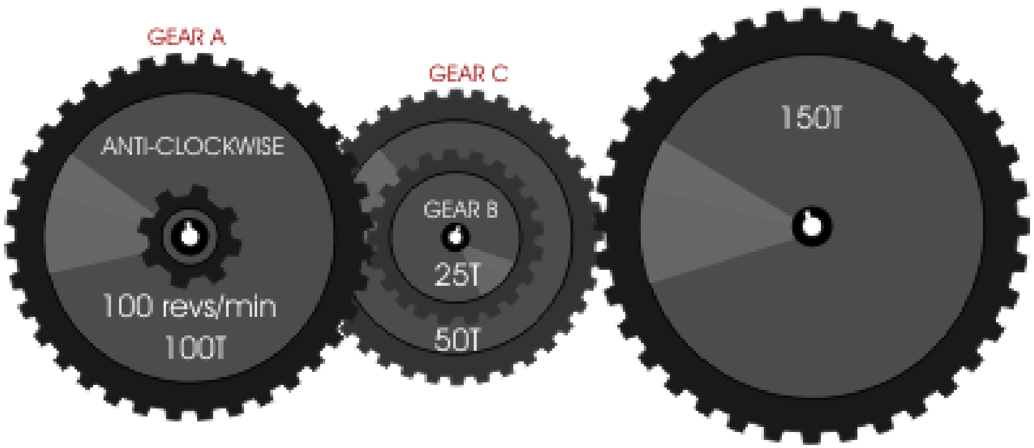
Gear Reduction in Series

Gear reductions can be put in series (“ganging”)

- Key to achieve useful power from DC motors
- The effect of each pair of reductions gets multiplied by the ganging
- By putting two 3:1 gear reductions in series a 9:1 gear reduction is created
- High speeds and low torques transformed ... powerful torques



“What is the final torque, speed, direction from A to D?”

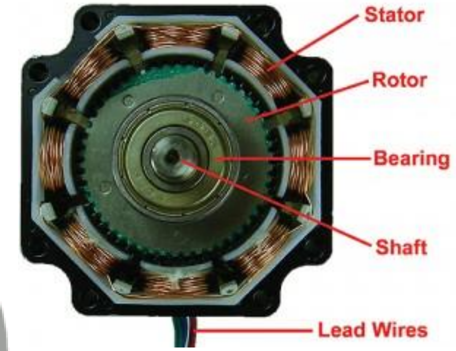


What kind of exercise about this ...

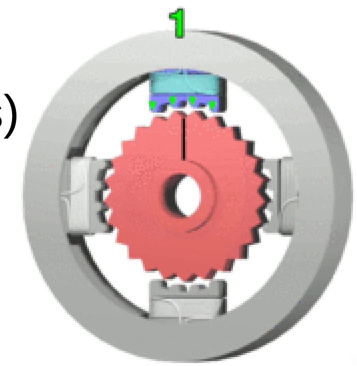
"Size motors, wheels, gears, and weight of RoboCom, so my son can speed up to 12Km/h on a 2% incline"

Stepper motors

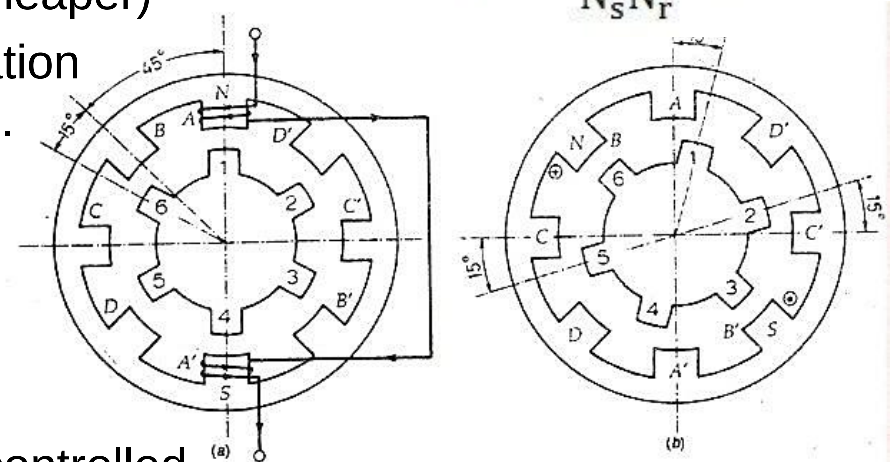
A *stepper motor* is a brushless, synchronous electric motor that converts digital pulses into mechanical shaft rotations.



- ✔ Rotation angle proportional to input pulse
- ✔ Full torque at standstill (energized windings)
- ✔ Precise positioning and repeatability
- ✔ Response to starting/stopping/reversing
- ✔ Very reliable (no contact brushes)
- ✔ Allow open-loop control (simpler and cheaper)
- ✔ Allow very low speed synchronous rotation with a load directly coupled to the shaft.
- ✔ Wide range of rotational speeds
- ✘ Require a dedicated control circuit
- ✘ Use more current than D.C. motors
- ✘ Torque reduces at higher speeds
- ✘ Resonances can occur if not properly controlled.
- ✘ Not easy to operate at extremely high speeds

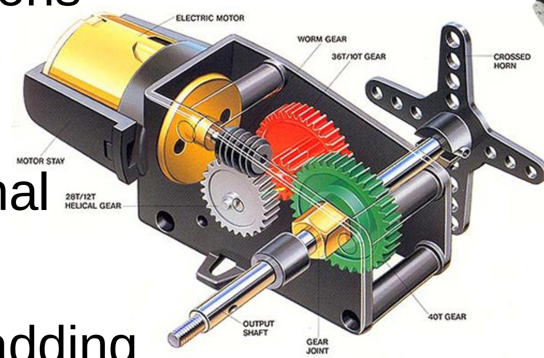


$$\alpha = \frac{N_s - N_r}{N_s N_r} \text{ x } 360°$$



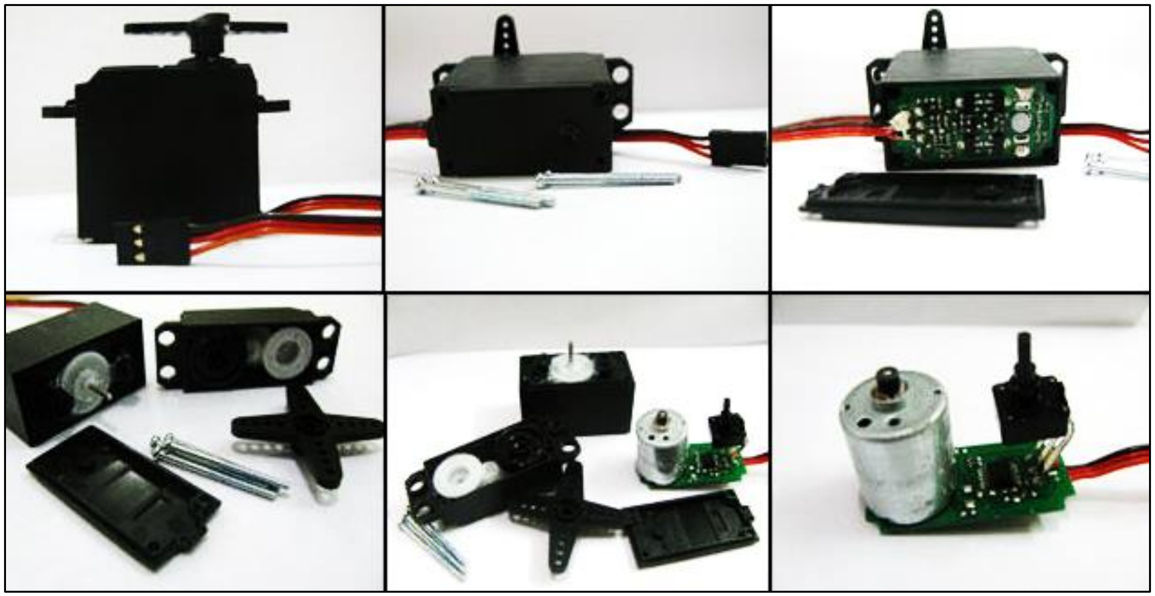
<u>"Servo"</u>: specialized motors that can move their shaft to a specific position

- Used in hobby radio control applications
- Measure their own position and compensate for external loads when corresponding to a control signal



Servo motors are built from DC motors by adding

- Gear reduction
- Position sensor
- Control electronics



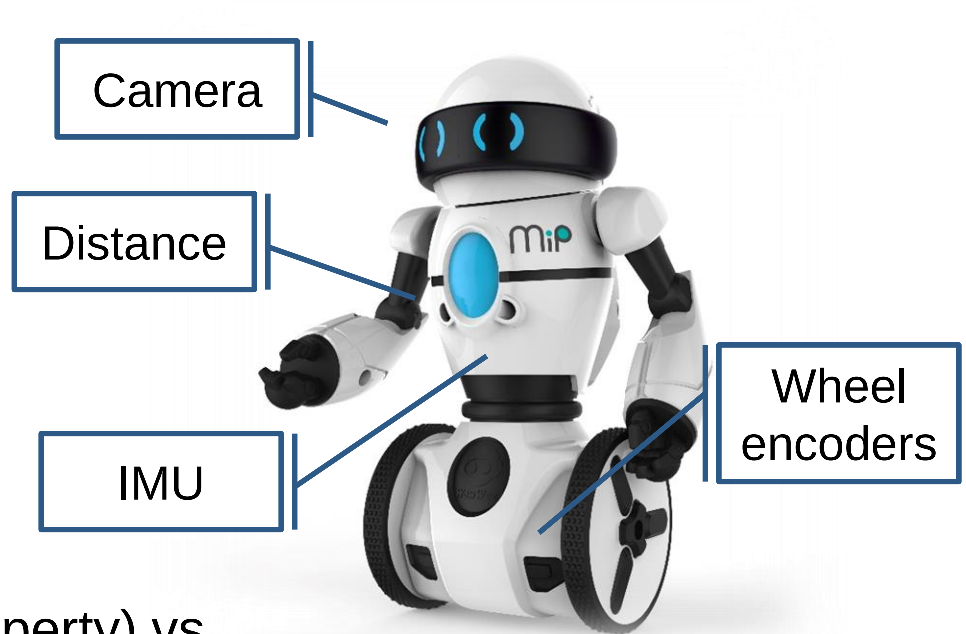
Shaft travel is restricted to 180 degrees but it is enough for most applications

Sensors

Sensors allow a robot to accomplish complex tasks autonomously

Two main categories

- Internal sensors (proprioceptive)
- External sensors (exteroceptive)



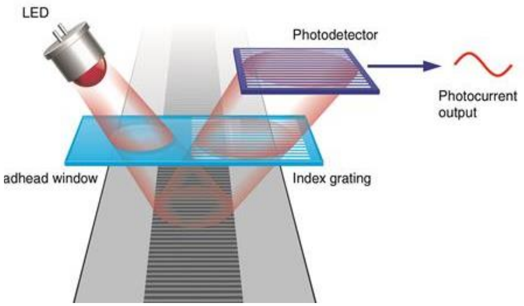
Other classification

- Passive (measure physical property) vs Active sensors (emitter + detector)

An encoder is a sensor for converting motor/joint rotary motion or position to a series of electronic pulses

Linear encoders

- Consist of a long linear read track, together with a compact read head



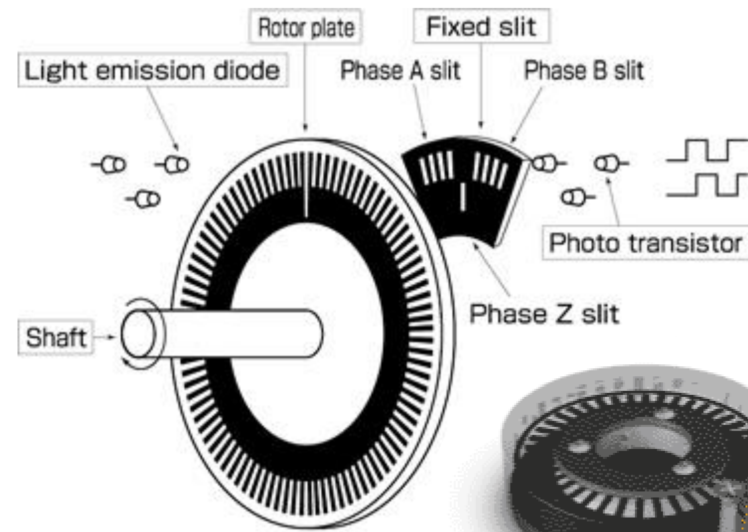
Rotary enoders

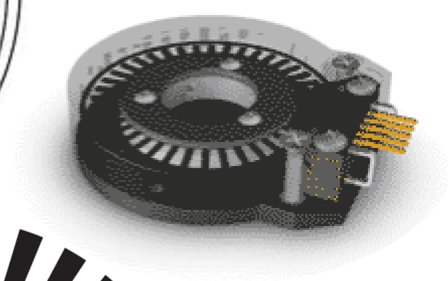
- Both for rotary and linear motion (in conjunction with some mechanism) convert rotary motion into electrical signals
- They can be incremental or absolute

Incremental rotary encoders

It is based on the photoelectric principle

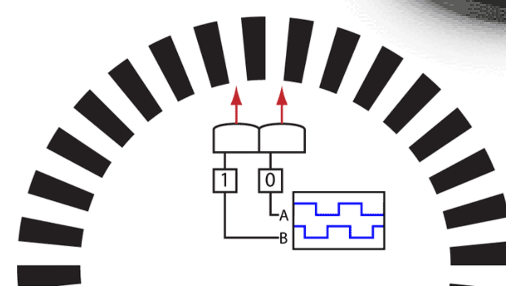
- It consists of a disk with two traces (or sensors) where transparent and opaque zones are alternated
- The presence of two traces allows to identify rotation direction and increases resolution (quadrature)

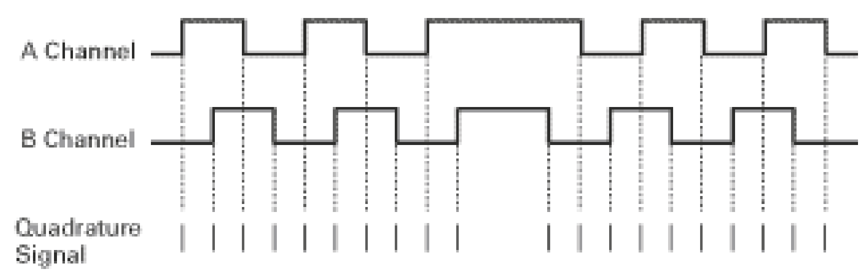




Quadrature technique

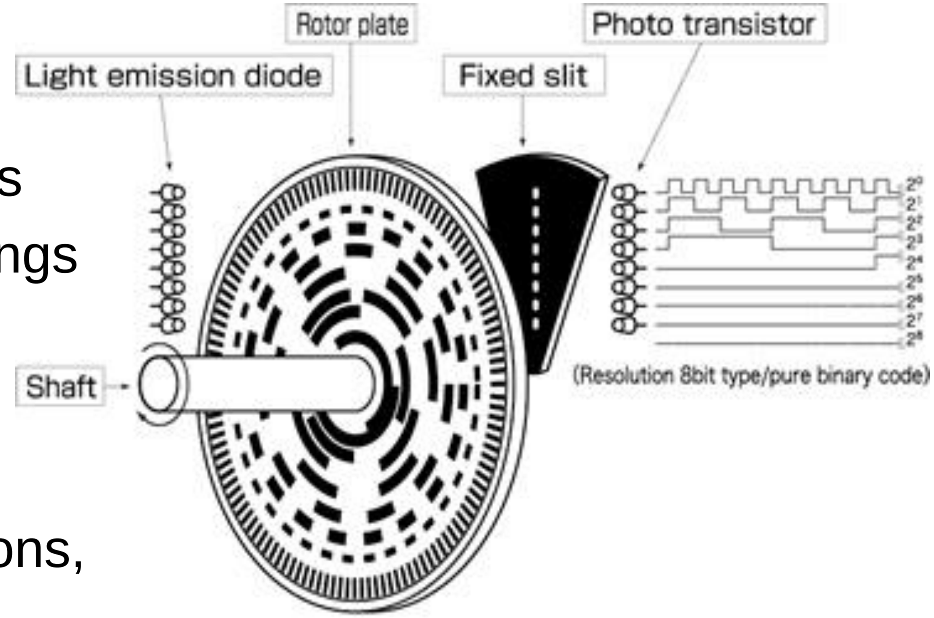
- The two signals are shifted by ¼ step
- N, is the number of steps, i.e., the number of light/dark zones, per turn
- Resolution is 360°/4N
- CCW: 1 1 is followed by 1 0
- CW: 1 1 is followed by 0 1

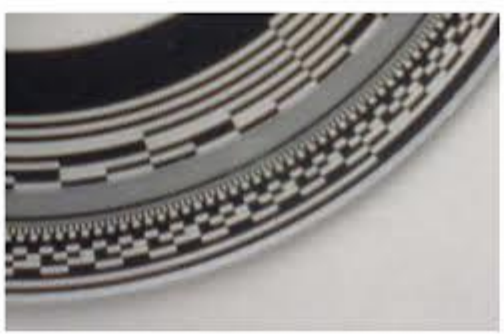


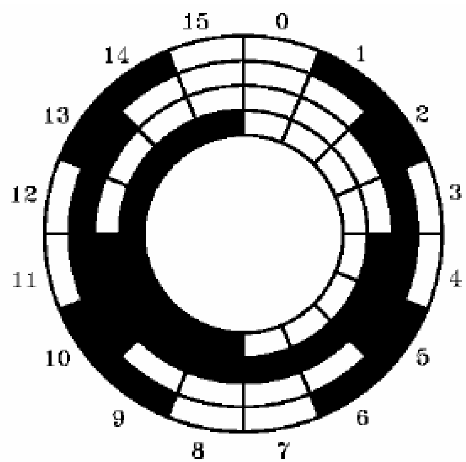


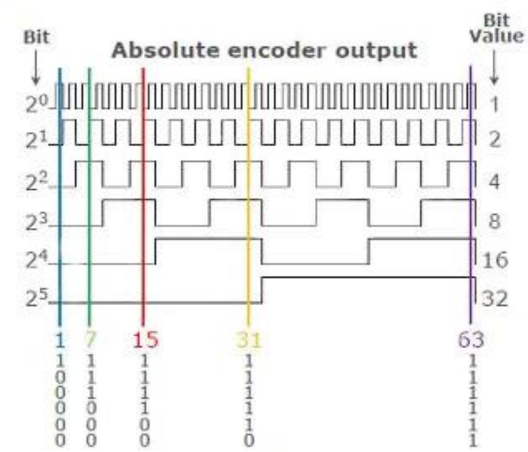
The disk econdes a position

- It has transparent and opaque areas placed on concentric rings
- For an N-bit word there are N rings
- Absolute resolution: $360°/2^N$
- In robotic applications at least 12 rings are used (360°/4096)
- Binary codes with single variations, i.e., Gray code, are used to avoid abiguities





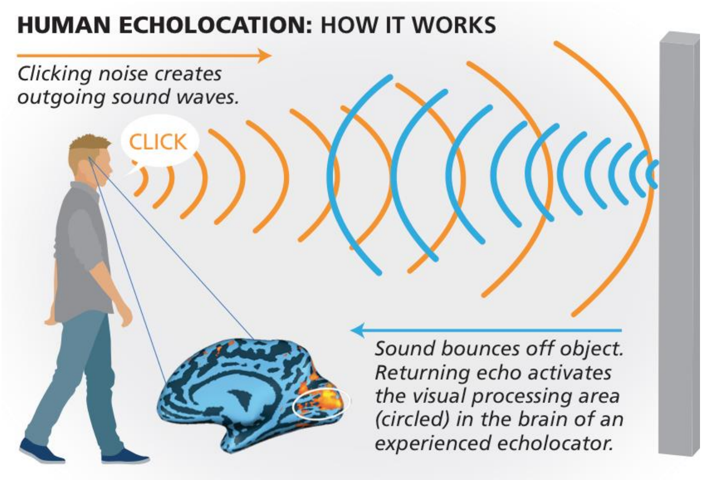




What is measured by sensors?

What is measured in not how it is measured, e.g., for distance

- Human beings use stereo-vision
- Other animals, e.g., bats, dolphins, and whales, use echolocation
- Some humans use echolocation too
- Useful for obstacle avoidance and for more complex activities



Sensors may be classified according to what they measure

- Distance
- Proximity
- Contact
- Force and torque
- Position

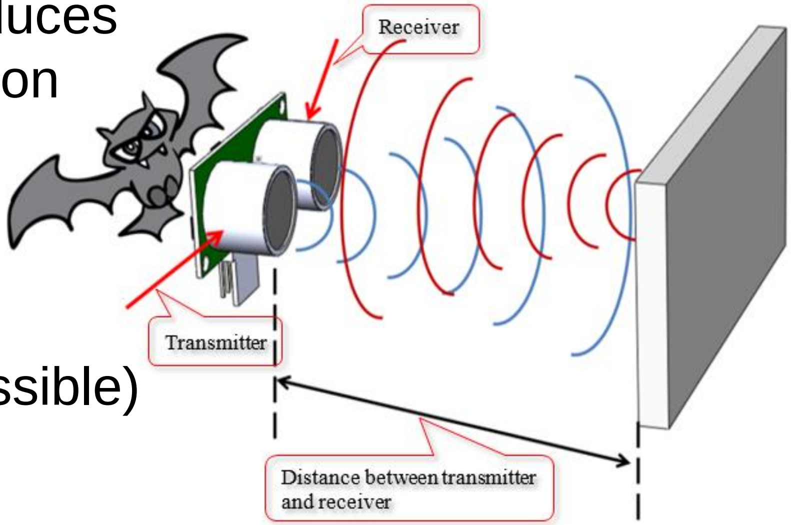
What about vision?

Formally it measures light ...

Distance perception: time-of-flight telemeter

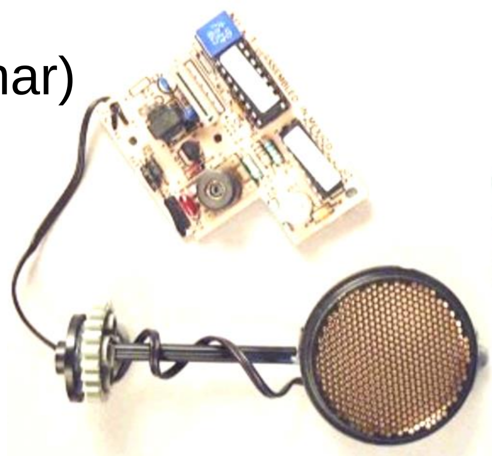
It measures the time between the emitter produces the signal and the detector receives its reflection

- Distance covered by the signal is *2d*
- Time of flight is $\Delta T = 2d/c$



Acoustic waves are used (although light is possible)

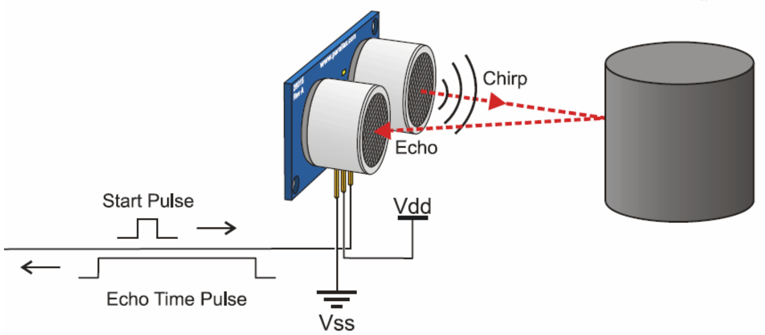
- Low speed: v=340 m/s
- Low directionality: 20 – 40°
- Polaroid ultrasonic sensors (sonar)
  - range 0.3 – 10m
  - accuracy 0.025m
  - cone opening 30°
  - frequency 50 KHz

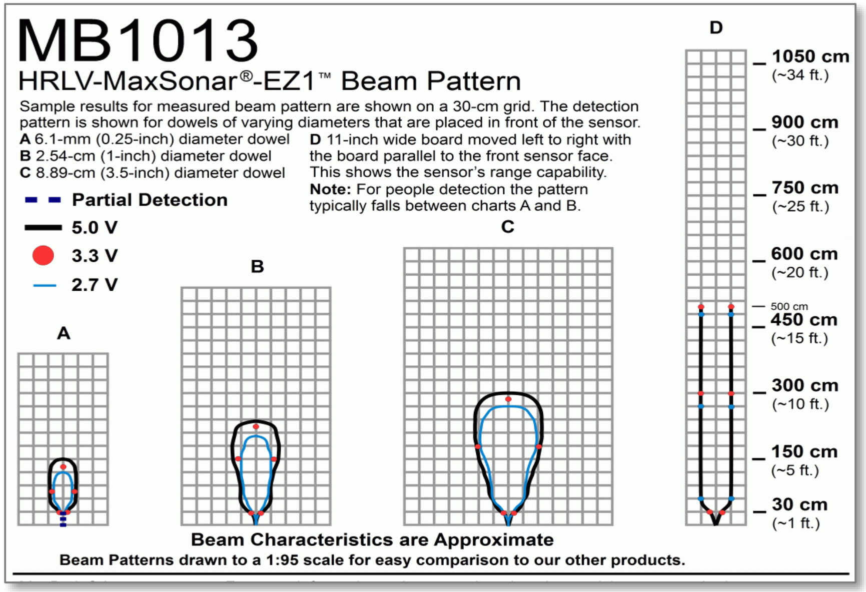


The signal is largely affected by noise with significant reflections …

Issues with sonars

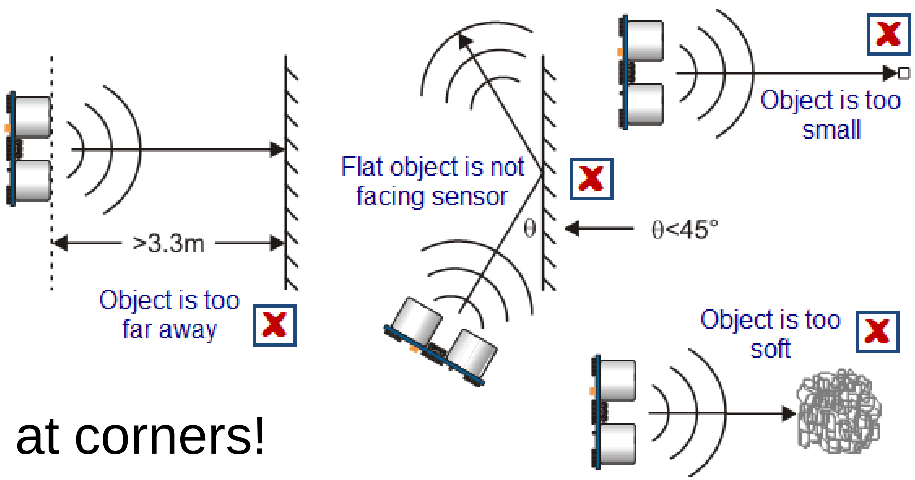
The range should be chosen according to the application





They do not work in all conditions

- Sampling frequency trade-off
- Reflections against walls
- Small objects
- Soft objects



Rooms may look larger than expected at corners!

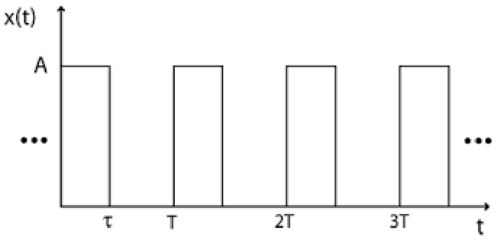
Reflective optosensors are active sensors (e.g., SHARP IR Sensors)

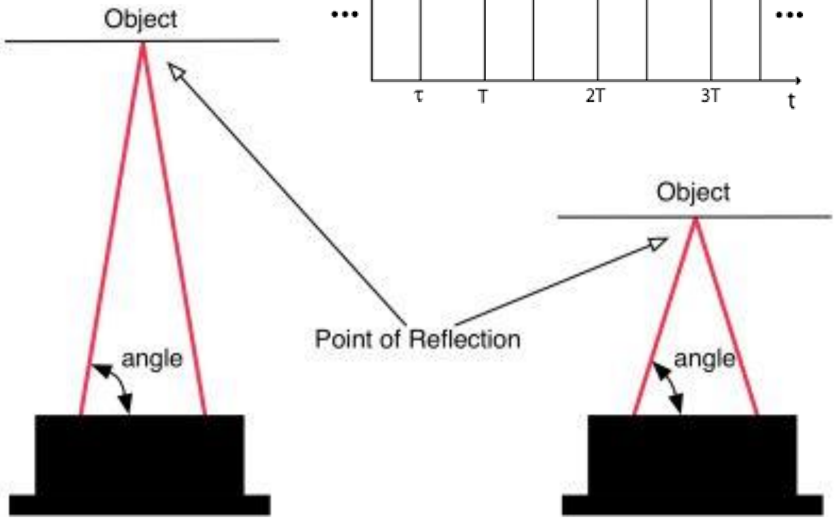
- Emitter: a source of light, e.g., LED (light emitter diode) or IR (infra red)
- Detector: a light detector, e.g., photodiode or phototransistor

It uses triangulation to compute distance

- The emitter casts a beam of light on the surface
- The detector measures the angle corresponding to the maximum intensity of returned light
- Being *s* the distance between the emitter and the detector, distance is computed as

$$d = \frac{s}{\tan \alpha_i}$$

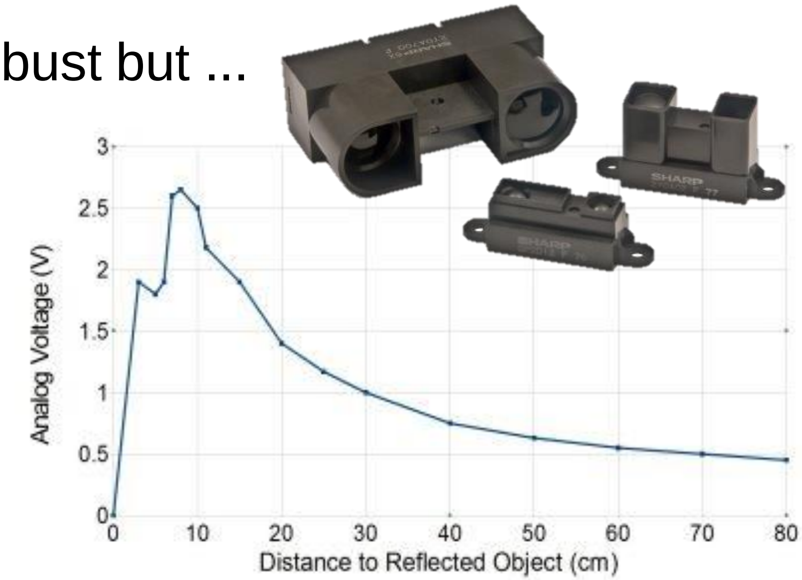


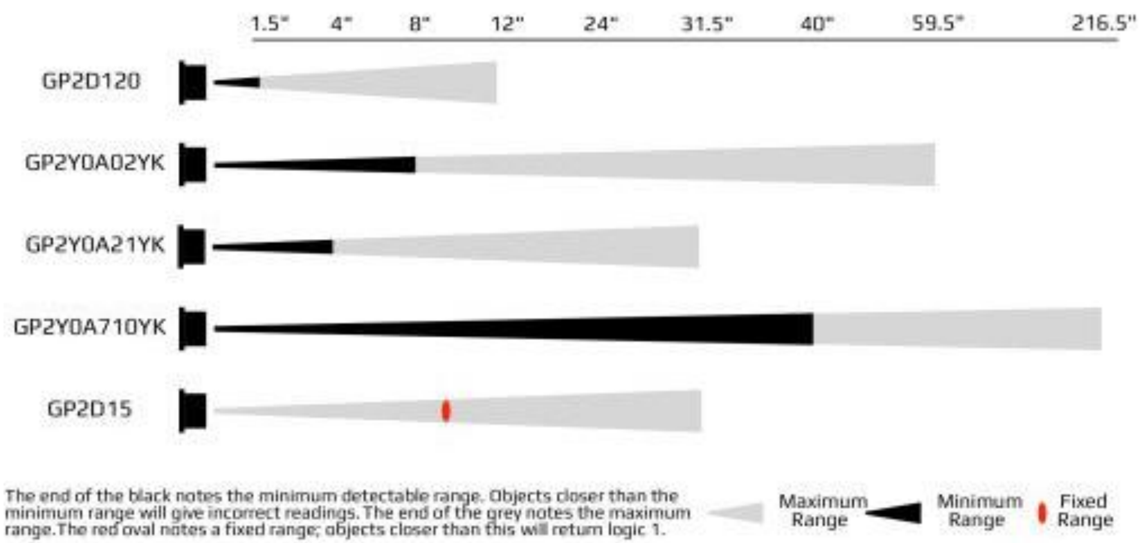


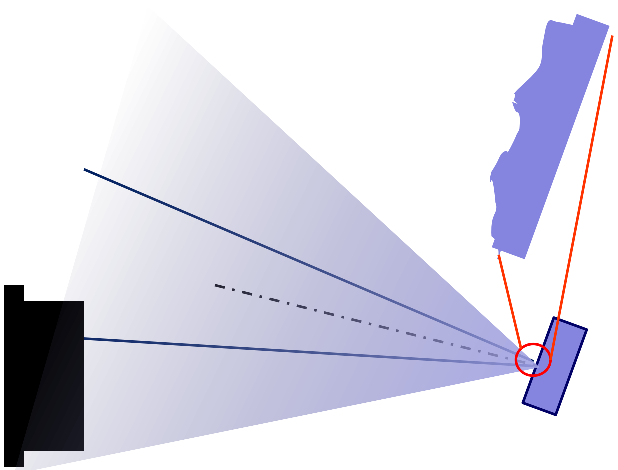
Issues with reflective optosensors

Infrared sensors are relatively cheap and robust but ...

- Have a non linear characteristics which need to be calibrated
- Have an ambiguity for short range (should be placed in the robot)
- Have fixed ranges / opening angles (requires proper selection)
- May suffer reflections ... sometimes





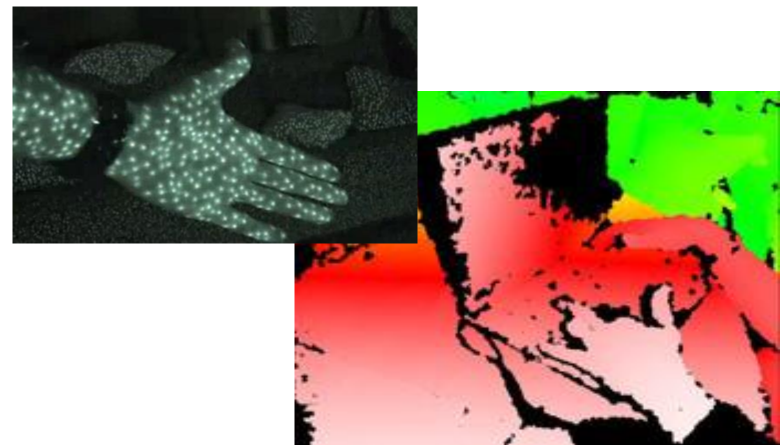


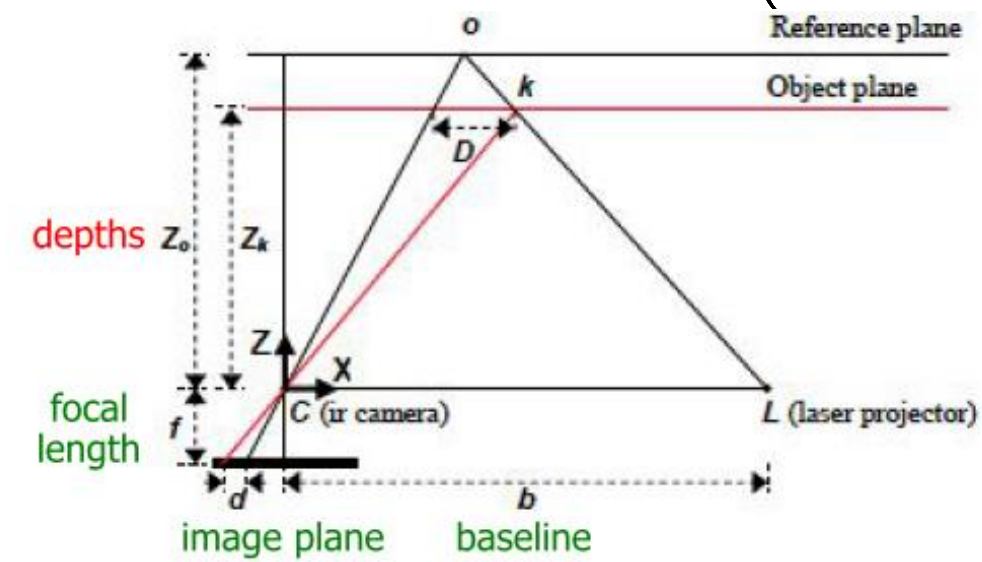
Distance Perception: Kinect

Kinect is a motion sensing input device built by Microsoft (Primesense) for Xbox 360

- 3D scanner
  - Infrared projector
  - Infrared camera (11-bit 640x480)
  - Range 1.2 – 3.5 m (up to 0.7-6 m)
  - Angular field of view: 57° h, 43° v
- 30Hz 8-bit RGB camera (640x480)

PrimeSense
Natural Interaction





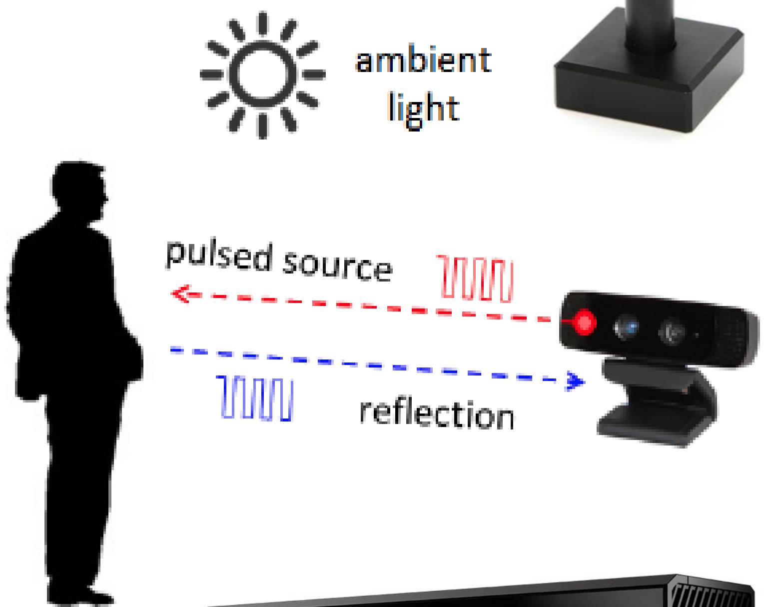
$$\frac{D}{b} = \frac{Z_0 - Z_k}{Z_0} \qquad \frac{d}{f} = \frac{D}{Z_k} \quad \Rightarrow \quad Z_k = \frac{Z_0}{1 + \frac{d}{fb} Z_0}$$

Distance perception: time-of-light camera

3D time-of-flight (TOF) cameras
- Illuminate the scene with a modulated light source and observe reflected light
- Phase shift between illumination and reflection is translated to distance

Some issues exist with these sensors
- Illumination is from a solid-state laser or a near-infrared (~850nm) LED
- An imaging sensor receives the light and converts the photonic energy to electrical current
- Distance information is embedded in the reflected component. Therefore, high ambient component reduces the signal to noise ratio (SNR).

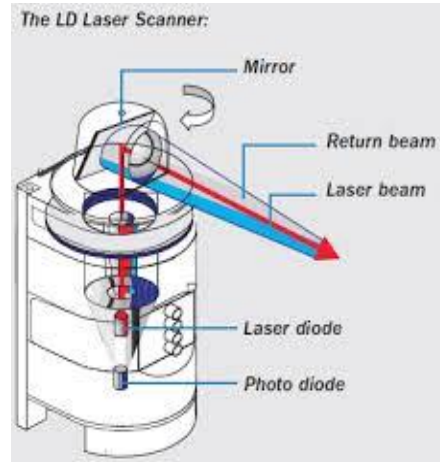




Distance perception: Laser Range Finder

Lasers are definitely more accurate sensors

- 180 ranges over 180°
  (up to 360 in some models)
- 1 to 64 planes scanned
- 10-75 scans/second
- <1cm range resolution
- Max range up to 50-80 m
- Problems only with mirrors, glass, and matte black.



< 1000 €

~ 6000 €

~ 40.000 €

> 80.000 €

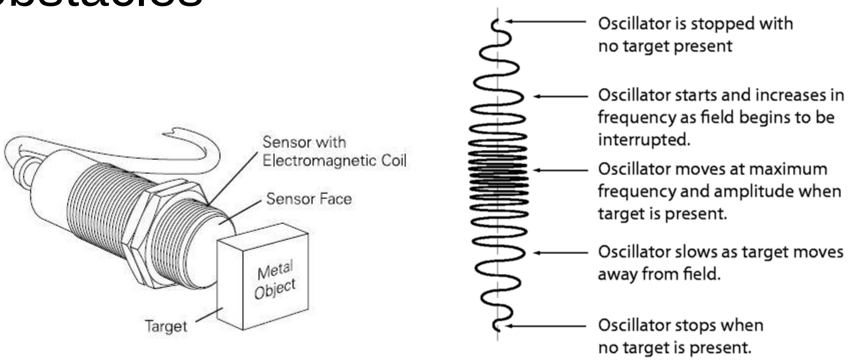
Matteo Matteucci – matteo.matteucci@polimi.it

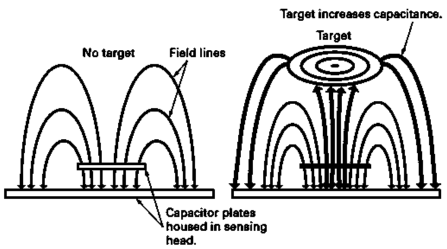
Measure the presence of objects within a specified distance range

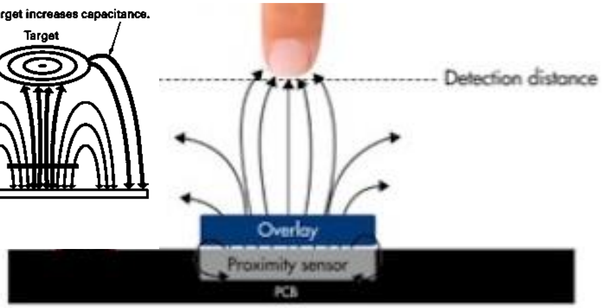
- Used to grasp objects and avoid obstacles

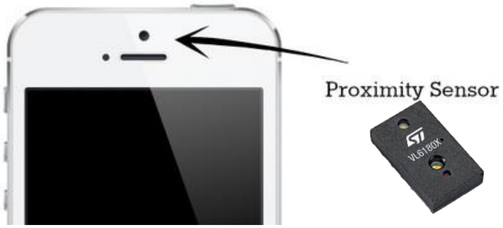
Several technologies:

- Ultrasonic (low cost)
- Inductive (ferromagnetic materials at distance <mm)
- Hall effect (ferromagnetic materials, small, robust, & cheap)
- Capacitive (any object, binary output, high accuracy when calibrated for a particular object)
- Optical (infrared light, binary output)





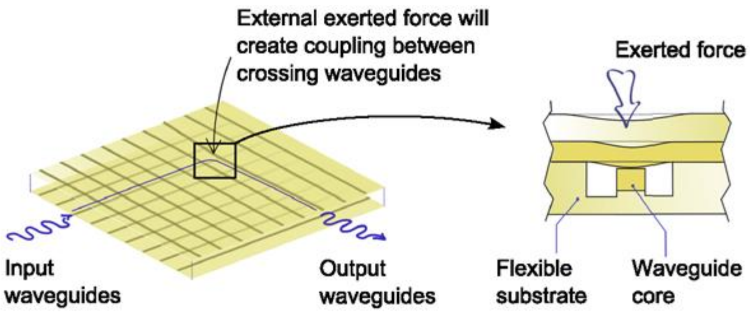


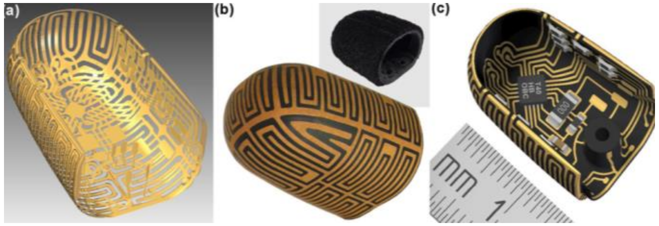


These sensors are used for manipulation purposes

Two main categories

- Binary
  - realized by switches
  - placed on the fingers of a manipulator
  - may be arranged in arrays (bumpers)
  - on the external side to avoid obstacles
- Analogical
  - soft devices that produce a signal proportional to the local force
  - a spring coupled with a shaft
  - soft conductive material that change its resistance with compression
  - measure also movements tangential to the sensor surface





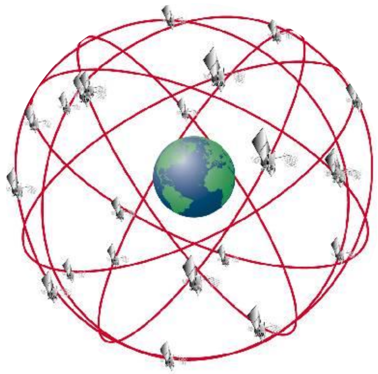
Position sensors (outdoor)

Position can be measure by a Global Navigation Satellite System

- Several constellations exist (GPS, GLONASS, Beidou, Galileo, …)

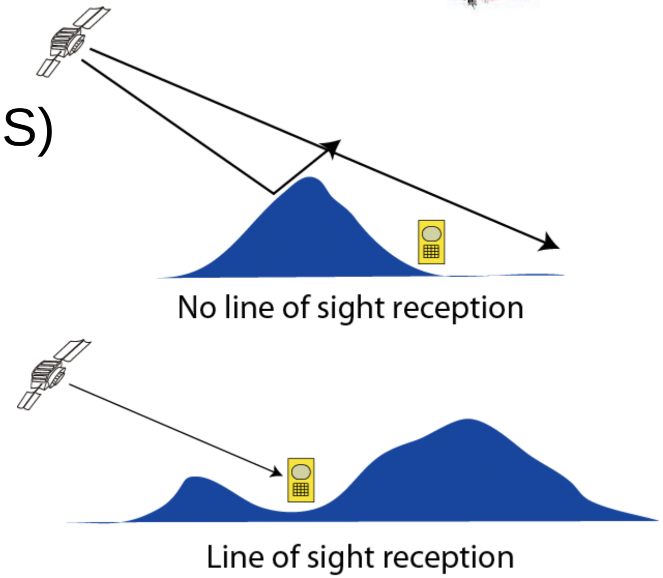
Global Positioning System (GPS)

- 24 satellites orbit the Earth twice a day
- They synchronously emit location and time
- GPS receiver compares the time a signal was transmitted with the time it was received.
- At least 4 sensors must be perceived
- Accuracy is about 2.5m@2Hz (20 cm DGPS)



Several issues

- May not be used indoor, underground, underwater, or in urban canyon
- Need line of sight reception
- Suffer multiple paths and reflections



Gyroscopes

- Angular velocities

Accelerometers

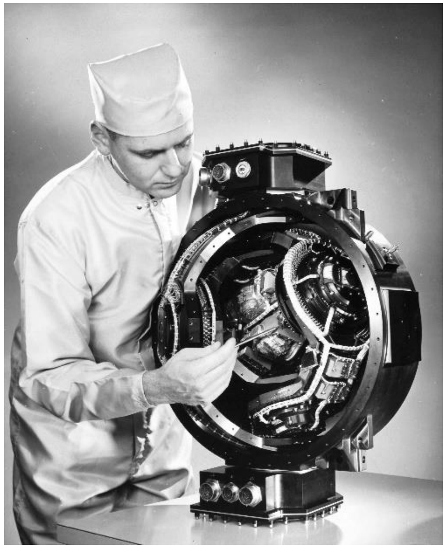
- Linear accelerations
- Gravitational vector

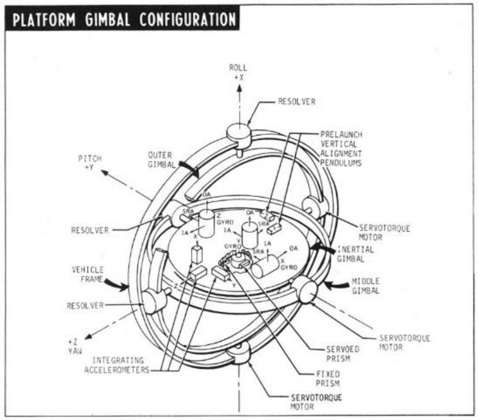
Magnetometers/compass

- Earth magnetic field vector

An Inertial Measurement Unit (IMU) fuses gyroscopes, accelerometers and magnetometers to provide full 6DoF pose estimate

ST-124 Inertial Guidance Platform used in the Saturn V, 1960s





Intertial measurements integration (e.g., to compute position) cumulate errors and drifts significantly over time, especially with cheap MEMS technology …

Sensor placement requires some skills ...

“Want to detect obstacles in a 150cm range in front of my differential drive soccer player … how many sensors and where should I place them?”