Sensors & Actuators in Robotics

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- Introduction to Robotics, Sensors & Actuators
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- Sensors in Robotics
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Robotics

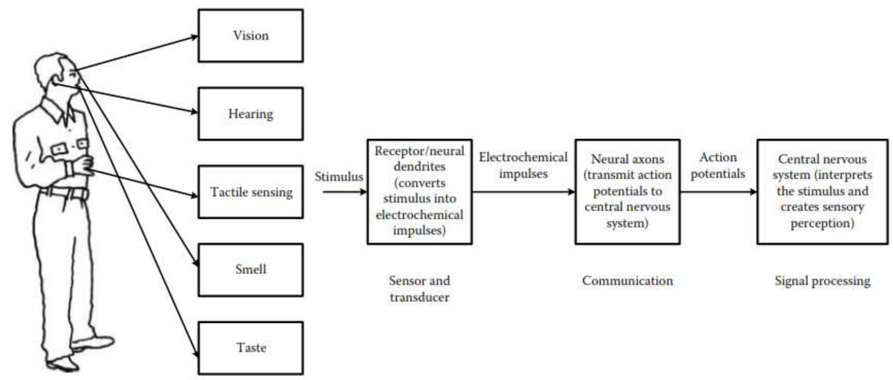
- The branch of technology that deals with the design, construction, operation, and application of robots.
- Robotics is a multi-disciplinary field. Best robotics researchers and engineers will touch upon all disciplines:
- **Mechanical Engineering** – concerned primarily with manipulator/mobile robot design, kinematics, dynamics, compliance and actuation.
- **Electrical Engineering** – concerned primarily with robot actuation, electronic interfacing to computers and sensors, and control algorithms.
- **Computer Science** – concerned primarily with robot programming, planning, and intelligent behavior.

Robot

- Defined by Robotics Industry Association (RIA) as
  - A **re-programmable, multifunctional manipulator** designed to move material, parts, tools or specialized devices through variable programmed motion for a variety of tasks.
- possess certain anthropomorphic characteristics
  - mechanical arm
  - sensors to respond to input
  - Intelligence to make decisions

Biological Sensing & Engineering Sensing Analogy

- A stimulus (e.g., light for vision, sound waves for hearing) is received at the receptor where the dendrites of the neurons convert the energy of the stimulus into electromechanical impulses in the dendrites of the neurons.



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- The axons of the neurons then conduct the corresponding action potentials into the central nervous system (CNS) of the brain.
- These potentials are then interpreted by the brain to create the corresponding sensory perception.
- An engineering sensory process, such as that used in a robot, basically uses similar processes.

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Sensors & Actuators

- **Sensor is a device used for the conversion of physical events or characteristics into the electrical signals**.
- This is a hardware device that takes the input from environment and gives to the system by converting it.
- For example, a thermometer takes the temperature as physical characteristic and then converts it into electrical signals for the system.
- **Actuator is a device that converts the electrical signals into the physical events or characteristics**. It takes the input from the system and gives output to the environment. For example, motors and heaters are some of the commonly used actuators.

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Actuators

- Actuators are required to move joints, provide power and do work.
- Serial robot actuators must be of low weight
  - Actuators of distal links need to be moved by actuators near the base.
- Parallel robots – Often actuators are at the base.
- Actuators drive a joint through a *transmission device*

Three commonly used types of actuators:

- Hydraulic
- Pneumatic
- Electric motors

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HYDRAULIC ACTUATORS FOR ROBOTS

- Early industrial robots were driven by hydraulic actuators.
- Pump supplies high-pressure fluid (typically oil) to a linear cylinders, rotary vane actuator or a hydraulic motor at the joint
- Large force capabilities.
- Large power-weight ratio – The pump, electric motor driving the pump,
- Control is by means of on/off solenoid valves or servo-valves controlled electronically.
- The entire system consisting of Electric motor, pump, accumulator, cylinders etc. is bulky and often expensive –
- Limited to 'big' robots.

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PNEUMATIC ACTUATORS FOR ROBOTS

- Working fluid is air.
- Air is supplied from a compressor to cylinders and flow of air is controlled by solenoid or servo controlled valves.
- Less force and power capabilities.
- Less expensive than hydraulic drives.
- Chosen where electric drives are discouraged or for safety or environmental reasons such as in pharmaceutical and food packaging industries.
- Closed-loop servo-controlled manipulators have been developed for many applications.

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ELECTRIC ACTUATORS FOR ROBOTS

- Electric or electromagnetic actuators are widely used in robots.
- Readily available in wide variety of shape, sizes, power and torque range.
- Very easily mounted and/or connected with transmission elements such as gears, belts and timing chains.
- Amenable to modern day digital control.

Main types of electric actuators:

- Stepper motors
- Permanent magnet DC servo-motor
- Brushless motors

ACTUATORS

Drive principle	Scope	Benefits	Disadvantages
Pneumatic	Passive Elements, Auxiliary devices	• Cheap • Low weight	• Compressibility of the air
Hydraulics	Manipulators with very high load capacity and very large working space	• High Dynamics • High-power • Weight ratio	• Necessary Directions: Pump, hoses, Servo Valves "Dirty" Maintenance Low efficiency Warming
Electric	Standard for Industrial robot	• High Dynamics • Very generally favorable opportunity • High performance Relationship • High Speed Ratio	• Necessary gear transmission • Warming

STEPPER MOTORS

- Stepper motors are of permanent magnet, hybrid or variable reluctance type.
- Actuated by a sequence of pulses — For a single pulse, rotor rotates by a known step such that poles on stator and rotor are aligned.
- Typical step size is 1.*8◦ or 0.9◦.*
- Speed and direction can be controlled by frequency of pulses.
- Can be used in open-loop as *cumulative error and* maximum error is one step.
- Micro-stepping possible with closed-loop feedback control.
- Used in ‘small’ robots with small payload and “low” speeds.

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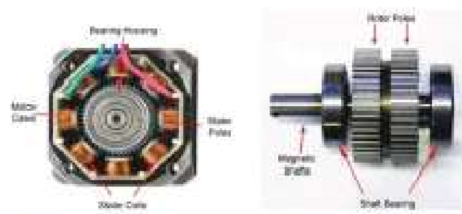
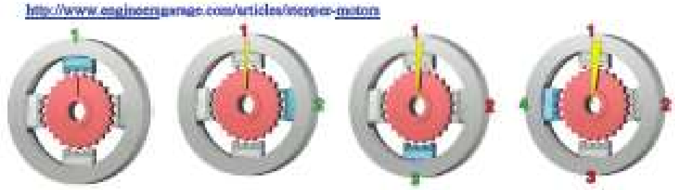
STEPPER MOTORS



Parts of a Stepper Motor

http://www.engineersgarage.com/articles/stepper-motors



http://www.societyofrobots.com/member_tutorials/node/28

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DC/AC SERVO-MOTORS

- Rotor is a permanent magnet and stator is a coil.
- Permanent magnets with rare earth materials (Samarium-Cobalt, Neodymium) can provide large magnetic fields and hence high torques.
- Commutation done using brushes or in brushless motor using Hall-effect sensors and electronics.
- Widely available in large range of shape, sizes, power and torque range and low cost.
- Easy to control with optical encoder/tacho-generators mounted in-line with rotor.
- Brushless AC and DC servo-motors have low friction, low maintenance, low cost and are robust.

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DC/AC SERVO-MOTORS

http://www.brushlessdcmotorparts.info

http://www.rc-book.com/wiki /brushless-electric-motor

Small RC Servo motors http://www.drivecontrol-details.info /rc-servo-motor.html

Slotted-brushless DC Servo motors http://www.motioncontroltips.com/

Direct drive motor, Applimotion, Inc http://news.thomasnet.com/ company_detail.html?cid=20082162

Brushless Hub motor for E-bike http://visforvoltage.org/ system-voltage/49-60-volts

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TRANSMISSIONS USED IN ROBOTS

- Purpose of transmission is to transfer power from source to load.
- The purpose of a transmission is *also to transfer power at* appropriate speed.
- Typical rated speed of a DC motor is between 1800 & 3600 rpm.
- 3000 rpm = 60 rps ≈ *360 radians/sec.*
- For a (typical) 1 m link → *Tip speed is 36 m/sec —*
- Greater than speed of sound
- Need for large reduction in speed.

- Transmissions can (if needed) also convert rotary to linear motion and vice-versa.
- Transmissions also transfer motion to different joints and to different directions.

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TRANSMISSIONS USED IN ROBOTS

- Transmissions in robots are decided based on motion, load and power requirements, and by the placement of actuator relative to the joint.
- Transmissions for robots must be

  (a)stiff,

  (b) low weight,

  (c) backlash free, and

  (d) efficient.
- Direct drives with motor directly connected to joint. It has advantages of low friction and low backlash but are expensive.

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Typical transmissions

- Gear boxes of various kinds – Spur, worm and worm wheel, planetary etc..
- Belts and chain drives.
- Harmonic drive for large reduction.
- Ball screws and rack-pinion drives – To transform rotary to linear motions.
- Kinematic linkages – 4-bar linkage

Typical transmissions

Parts of a harmonic drive
http://www.harmonicdrive.net/reference/applicationnotes/principles.php
See also http://en.wikipedia.org/wiki/Harmonic_drive for animation

RV series gear reduction mechanism
http://precision.nabtesco.com/en/

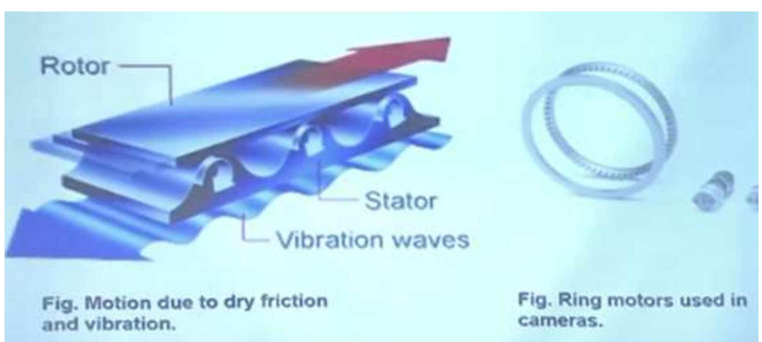
A ball screw
http://www.thk.com/in/products/class/ballscrew/

A four-bar mechanism to move gripper jaws
http://www.cs.cmu.edu/~amampell/pastProjects.html

Advanced Actuators

- Small, Low Power Consumption, Micro motion
- Ultrasonic Motors: Micro Robots, Cameras, Micro motion devices
- Artificial Muscles: Prosthetic, Bio-applications
- Molecular Motors: bio applications

Ultrasonic Motors



Smart Actuators

- Piezo electric materials- Large forces, small strains and fast response time
- Ionomeric Polymer Metal Composite (IPMC)- Small forces, large strains, slower response time

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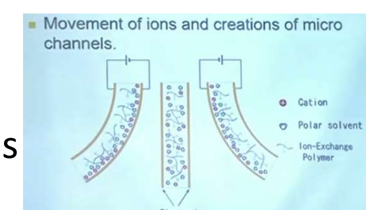
Electro Active Polymers

- Ionomeric Polymer Metal Composite (IPMC)- a polymer coated with a metal electrode
- Material- Nafion 117
- Electrode-Platinum, Gold
- Electroplating by Electrolysis



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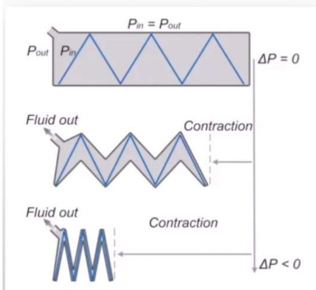
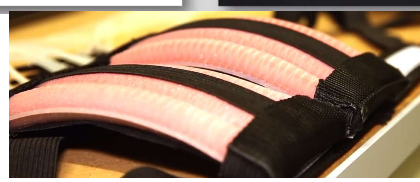
Artificial Muscles





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Air Muscle

- **Air Muscle is an extraordinary actuator that is small, light, simple and 'friendly'. It is soft, has no stiction, is easily controllable and exceptionally powerful.**
- The Air Muscle consists of a rubber tube covered in tough plastic netting which shortens in length like a human muscle when inflated with compressed air at low pressure.
- Air Muscle has a power-to-weight ratio as high as 400:1, vastly outperforming both pneumatic cylinders and DC motors that can attain a ratio of only about 16:1.
- Air Muscles are normally operated using compressed air in the 0-70psi (0-5 bar) range.

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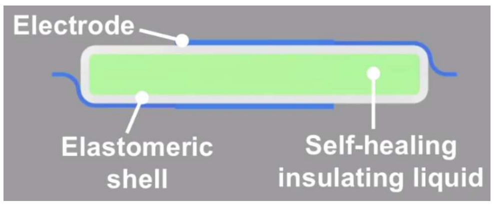
Advantages of Air Muscle

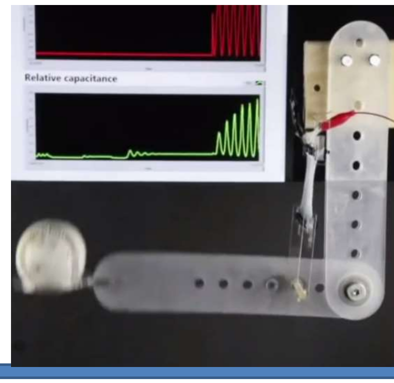
- **Lightweight** - Air Muscles weigh as little as 10 grammes - particularly useful for weight-critical applications.
- **Lower Cost** - Air Muscles are cheaper to buy and install than other actuators and pneumatic cylinders.
- **Smooth -** Air Muscles have no 'stiction' and have an immediate response. This results in smooth and natural movement.
- **Flexible** - Air Muscles can be operated when twisted axially, bent round a corner, and need no precise aligning.
- **Powerful** - Air Muscles produce an incredible force especially when fully stretched.
- **Damped** - Air Muscles are self-dampening when contracting (speed of motion tends to zero), and their flexible material makes them inherently cushioned when extending.
- **Compliant** - Being a soft actuator, Air Muscles systems are inherently compliant.

Thumbnails	Diameter	Length (Fully Stretched)	Weight (approx.)	Pull (3.5 bar)	Maximum Pull
	6 mm	150 mm (Stretched)	10 g	3 Kg	7 Kg
	20 mm	210 mm (Stretched)	40 g	12 Kg	20 Kg
	30 mm	290 mm (Stretched)	80 g	35 Kg	70 kg

HASEL Actuators

- HASEL (hydraulically amplified self-healing electrostatic)





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Sensors in Robotics

- A robot without sensors is like a human being without eyes, ears, sense of touch, etc.
- Sensor-less robots require costly/time consuming programming.
- Can perform only in “playback” mode.
- No change in their environment, tooling and work piece can be accounted for.

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Sensors in Robotics

- Sensors constitute the perceptual system of a robot designed:
  - ✓ To make inferences about the physical environment,
  - ✓ To navigate and localise itself,
  - ✓ To respond more “flexibly” to the events occurring in its environment, and
  - ✓ To enable learning, thereby endowing robots with “intelligence”.
- Sensors allow less accurate modeling and control.
- Sensors enable robots to perform complex and increased variety of tasks reliably thereby reducing cost.

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Sensor

- Sensor is a device to make a measurement of a physical variable of interest and convert it into electrical signal.
- Broad classification of sensors in robots
  - ➢ Internal state sensors.
  - ➢ External state sensors.

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Desirable features of Sensor

- High accuracy.
- High precision.
- Linear response.
- Large operating range.
- Low response time.
- Easy to calibrate.
- Reliable and rugged.
- Low cost
- Ease of operation

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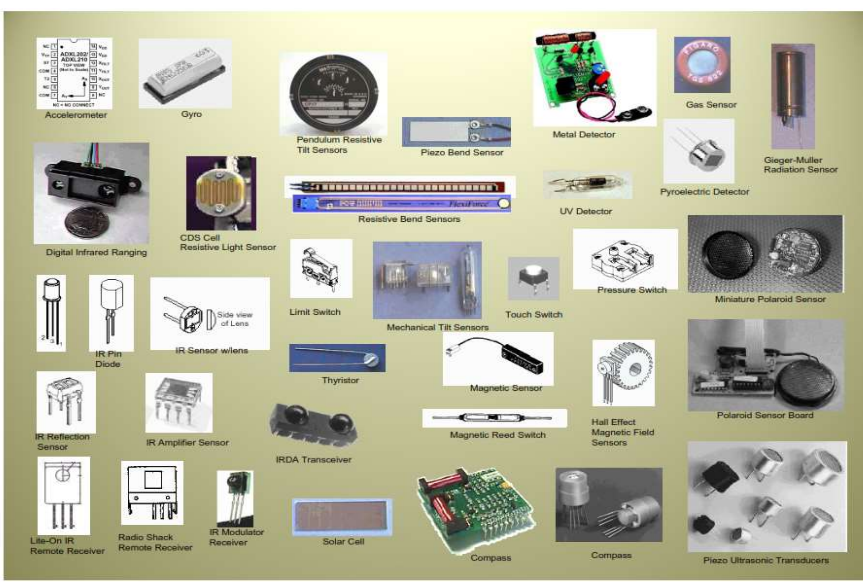
Various sensors



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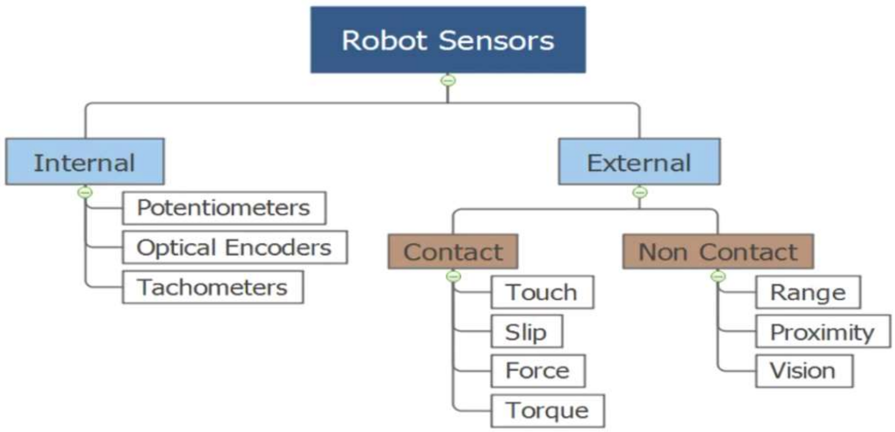
Robot Sensors Classification



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INTERNAL SENSORS IN ROBOTS

- **Internal sensors measure variables** for control
  - ✓ Joint position.
  - ✓ Joint velocity.
  - ✓ Joint torque/force.

- **Joint position sensors (angular or linear)**
  - ✓ Incremental & absolute encoders — Optical, magnetic or capacitive.
  - ✓ Potentiometers.
  - ✓ Linear analog resistive or digital encoders.

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INTERNAL SENSORS IN ROBOTS

- **Joint velocity sensors**
- ✓ DC tacho-generator & resolvers
- ✓ Optical encoders.

- **Force/torque sensors.**
- ✓ At joint actuators for control.
- ✓ At wrist to measure components of force/moment being applied on environment.
- ✓ At end-effector to measure applied force on gripped object.

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EXTERNAL SENSORS IN ROBOTS

- Detection of environment variables for robot guidance, object identification and material handling.
- Two main types –
- ❑ Contacting and
- ❑ Non-contacting sensors.

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Contacting sensors

Contacting sensors respond to a physical contact

- Touch: switches, Photo-diode/LED combination.
- Slip
- Tactile: resistive/capacitive arrays.

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Non-contacting sensors

Non-contacting sensors detect variations in optical, acoustic or electromagnetic radiations or change in position/orientation.

- **Proximity:** Inductive, Capacitive, Optical and Ultrasonic
- **Range:** Capacitive and Magnetic, Camera, Sonar, Laser range finder, Structured light.
- **Colour sensors**.
- **Speed/Motion:** Doppler radar/sound, Camera, Accelerometer, Gyroscope.
- **Identification:** Camera, RFID, Laser ranging, Ultrasound.
- **Localisation**: Compass, Odometer, GPS.

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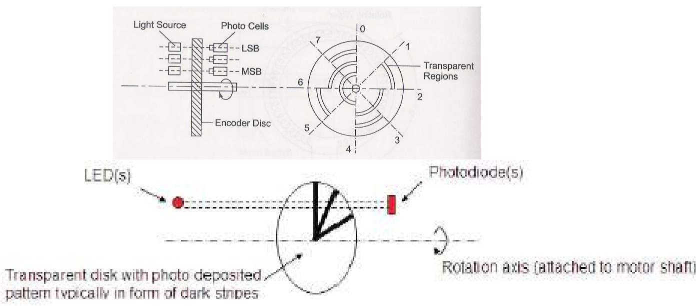
COMMON SENSORS USED IN ROBOTS

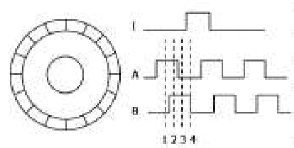
Sensors	Functions
Touch	Sensing an object's presence or absence
Force	Measuring force along a single axis
Vision	Detecting edges, holes and corners
Proximity	Non-contact detection of an object
Physical orientation	Co-ordinates of objects in space
Heat	Wavelength of infrared (IR) or ultra violet (UV) rays, temperature, magnitude and direction
Chemicals	Presence, identity and concentration of chemicals or reactants
Light	Presence, colour and intensity of light
Sound	Presence, frequency and intensity of sound

OPTICAL ENCODER

- One of the most important and widely used internal sensor.
- Consists of an etched encoding disk with photo-diodes and LEDS.
- Disk made from Glass, for high-resolution applications (11 to 16 bits).
- Plastic (Mylar) or metal, for applications requiring more rugged construction (resolution of 8 to 10 bits).
- As disk rotates, light is alternately allowed to reach photo-diode, resulting in digital output similar to a square wave.

OPTICAL ENCODER





State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

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OPTICAL ENCODER

- Typically 3 signals available – Channel A, B and I; A and B are phase shifted by 90 degrees and I is called as the *index* pulse obtained every full rotation of disk.
- Signals read by a microprocessor/counter.
- Output of counter includes rotation and direction.
- Output can be absolute or relative joint rotation.
- Can be used for estimating velocity.

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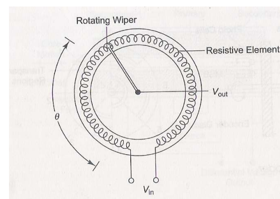
SENSORS FOR JOINT ROTATION

❑ **Potentiometers**

- Voltage ∝ resistance and resistance ∝ rotation at joint
- Not very accurate but very inexpensive.
- More suitable for slow rotations.
- Adds to joint friction.



SENSORS FOR JOINT ROTATION

❑ **Resolvers**

- Rotary electrical transformer to measure joint rotation
- Analog output, need ADC for digital control.
- Electromagnetic device — Stator + Rotor (connected to motor shaft).
- Voltage (at stator) ∝ sin(θ), θ = rotor angle.

SENSORS FOR JOINT ROTATION

❑ **Tachometers**

- Measures joint velocity
- Similar to resolver.
- Voltage (at stator) $\propto \theta'$, θ' = angular velocity of the rotor.
- Analog output → *ADC required for digital control.*

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FORCE/TORQUE SENSOR

- Employed for force/torque sensing – Can be achieved by *joint and wrist sensing.*

Force/Torque joint sensors

- Direct sensing of force/torque in a compliant shaft attached to motor by means of strain gages.
- A model of the motor and the shaft required.
- Introduced compliance at joint not desirable – System dynamics altered
- For DC motor – Joint torque $\propto$ armature current.
- Requires model of motor & accuracy not very good.

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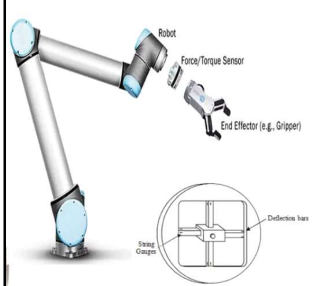
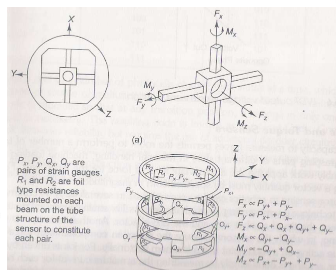
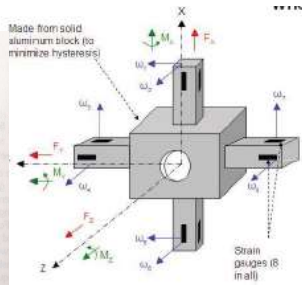
Force/Torque Wrist Sensors

- Mounted between end of robot arm and end-effector.
- Can measure all six components of force/torque using strain gages.
- Extensively used in *force control.*







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Force/Torque Wrist sensors

- Performance specifications to ensure that the wrist motions generated by the force/torque sensors do not affect the position accuracy of the manipulator:
- High stiffness to ensure quick dampening of the disturbing forces which permits accurate readings during short time intervals.
- Compact design to ensure easy movement of the manipulator.
- Need to be placed close to end-effector/tool.
- Linear relation between applied force/torque and strain gauge readings.
- Made from single block of metal → *No hysteresis.*

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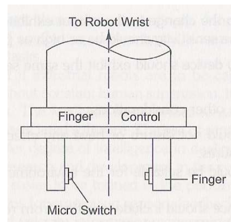
EXTERNAL SENSORS – TOUCH

- Allows a robot or manipulator to interact with its environment – to "touch and feel", "see" and "locate".
- Two classes of external sensors –
  - Contact
  - non-contact



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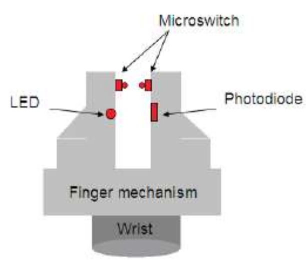
EXTERNAL SENSORS – TOUCH

- Simple – LED-Photo-diode pair used to detect
- presence/absence of object to be grasped
- Micro-switch to detect touch.



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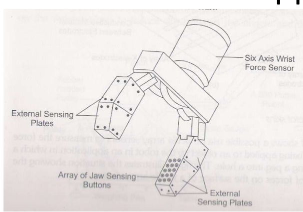
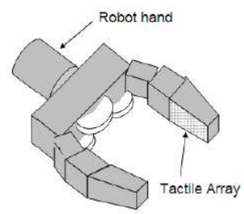
TACTILE ARRAY SENSOR

- “Skin” like membrane to “feel” the shape of the grasped object
- Also used to measure force/torque required to grasp object
- Change in resistance/capacitance due to local deformation from applied force





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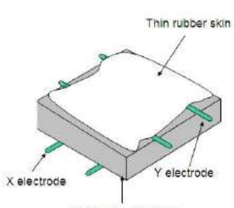
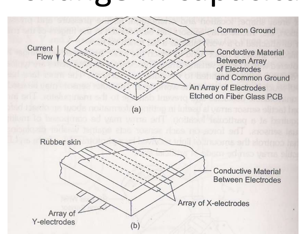
TACTILE ARRAY SENSOR

- Send current in one set, measure current in other set
- Magnitude of current ∝ change in resistance due to deformation
- Magnitude of current ∝ change in capacitance





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PROXIMITY

- Detect presence of an object near a robot or manipulator
- Works at very short ranges (<15-20 mm)
- Frequently used in stationary and mobile robots to avoid obstacles and for safety during operation
- Four main types of proximity sensors
  - ➢ Inductive proximity sensors
  - ➢ Capacitive proximity sensor
  - ➢ Ultrasonic proximity sensor
  - ➢ Optical proximity sensors

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ULTRASONIC PROXIMITY SENSORS

- Electro-acoustic transducer to send and receive high frequency sound waves.
- Emitted sonic waves are reflected by an object back to the transducer which switches to receiver mode.
- Same transducer is used for both receiving and emitting the signals – Fast damping of acoustic energy is essential to detect close proximity objects.
- Achieved by using acoustic absorbers and by decoupling the transducer from its housing.
- Typically of low resolution.

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ULTRASONIC PROXIMITY SENSORS

Important specifications –

- ➢ Maximum operating distance,
- ➢ Repeatability,
- ➢ Sonic cone angle,
- ➢ Impulse frequency,and
- ➢ Transmitter frequency.

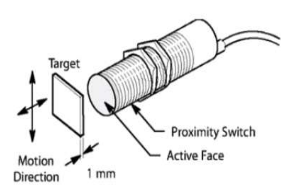
Some well-known applications –

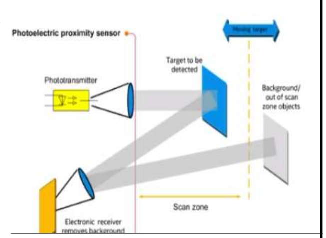
- ✓ Useful in difficult environments,
- ✓ Liquid level detection and
- ✓ Car parking sensors.

OPTICAL PROXIMITY SENSORS

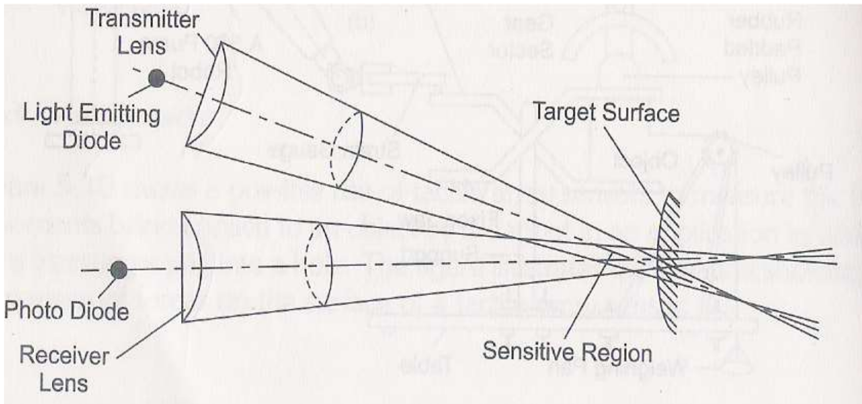
- Also known as light beam sensors – Solid state LED acting as a transmitter by generating a light beam.
- A solid-state photo-diode acts as a receiver.
- Field of operation of the sensor – Long pencil like volume, formed due to intersection of cones of light from source and detector.
- Any reflective surface that intersects the volume gets illuminated by the source and is seen by the receiver.
- Generally a binary signal is generated when the received light intensity exceeds a threshold value.
- Applications: 1) Fluid level control, 2) Breakage and jam

detection, 3) Stack height control, box counting etc.



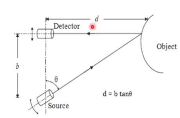


OPTICAL PROXIMITY SENSORS



RANGE SENSORS

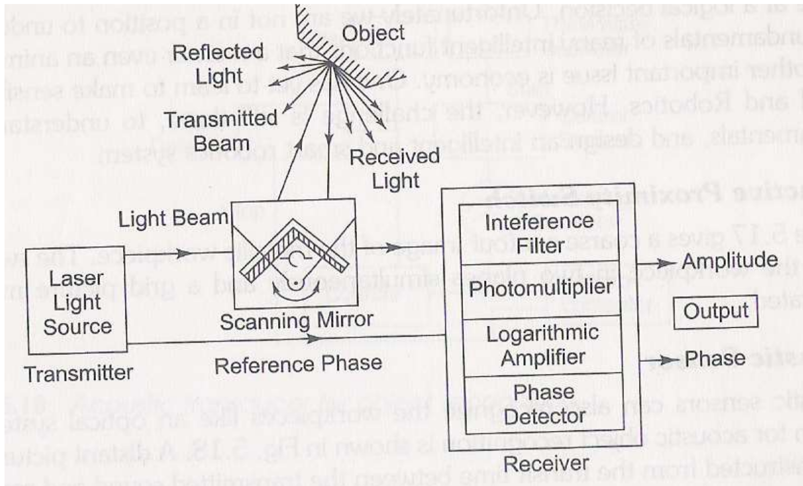
- Measure distance of objects at larger distances.
- Uses electromagnetic or electrostatic or acoustic radiation –Looks for changes in the field or return signal.
- Highly reliable with long functional life and no mechanical parts.



Four main kinds of range sensing techniques in robots
- Triangulation.
- Structured lighting approach.
- Time of flight range finders.
- Vision

Applications: 1) Navigation in mobile robots, 2) Obstacle avoidance, 3) Locating parts, etc.

Range Sensor



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Vision Sensors

- **Vision sensors** use images captured by a camera to determine presence, orientation, and accuracy of parts.
- These **sensors** differ from image inspection "systems" in that the camera, light, and controller are contained in a single unit, which makes the unit's construction and operation simple

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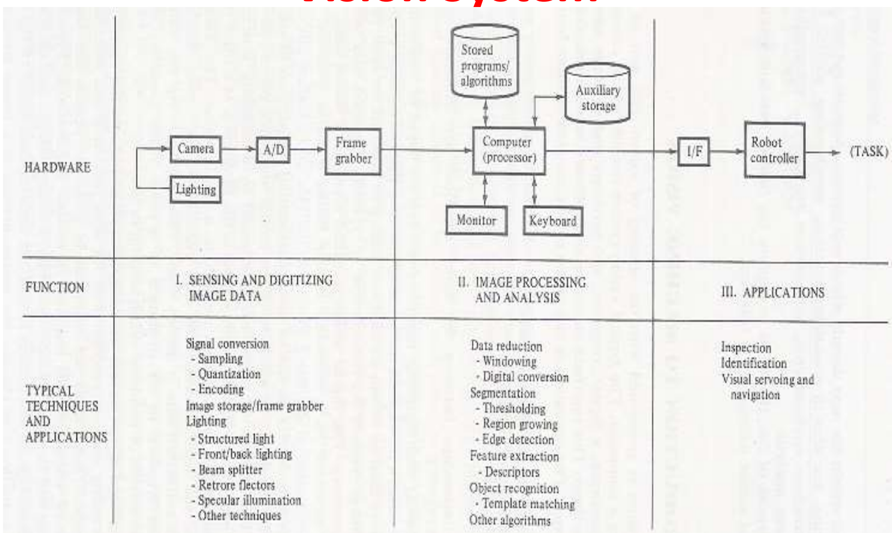
Vision System



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LiDAR Sensors

- **LiDAR** stands for **Light Detection And Ranging**.
- **LiDAR sensor** can use infrared and ultraviolet light to map out the environment around it.
- It can get a sense of both the physical dimensions and motion (if any) of objects in its vicinity.

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Haptic sensors

- **Haptic sensors** recreate the sense of touch by creating a combination of force, vibration and motion sensations to the user.
- **Haptic** technologies are significantly growing and are used in everything from automobiles, to games console controllers and smartphones

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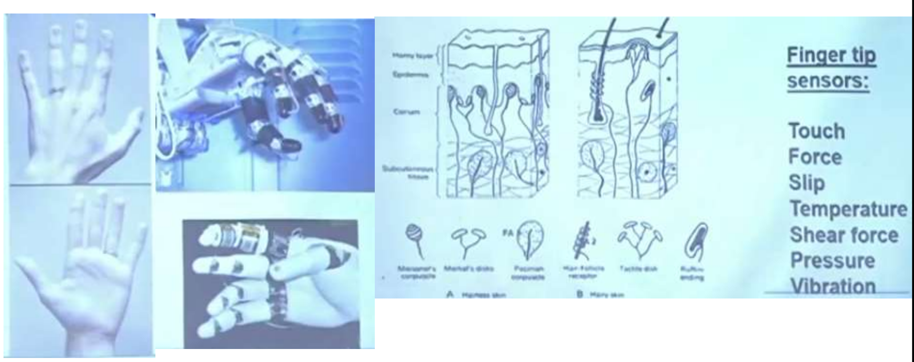
Haptic Sensors



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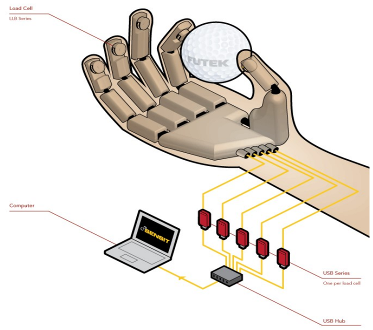
Haptic Sensors



https://metromatics.com.au/miniature-haptic-sensors-medical-applications/

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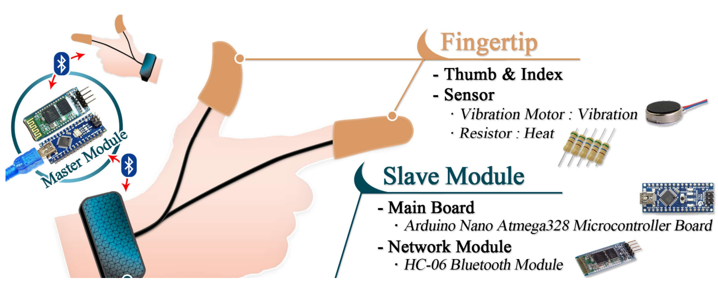
Immersive Virtual Reality



Mingyu Kim, Changyu Jeon and Jinmo Kim ,A Study on Immersion and Presence of a
Portable Hand Haptic System for Immersive Virtual Reality,
Sensors 2017, 17, 1141; doi:10.3390/s17051141

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Sensors used in AI

- Sensors used in AI robots are the same as, or are similar to, those used in other robots.
- Fully-functional human robots with AI algorithms require numerous sensors to simulate a variety of human and beyond-human capabilities.
- Sensors provide the ability to see, hear, touch and move like humans. These provide environmental feedback regarding surroundings and terrain.

Sensors used in AI

- Distance, object detection, vision and proximity sensors are required for self-driving vehicles. These include camera, IR, sonar, ultrasound, radar and lidar.
- A combination of various sensors allows an AI robot to determine size, identify an object and determine its distance.
- Radio-frequency identification (RFID) are wireless sensor devices that provide identification codes and other information.

Sensors used in AI

- Force sensors provide the ability to pick up objects.
- Torque sensors can measure and control rotational forces.
- Temperature sensors are used to determine temperature and avoid potentially-harmful heat sources from the surroundings.
- Microphones are acoustical sensors that help the robot receive voice commands and detect sound from the environment.
- Some AI algorithms can even allow the robot to interpret the emotions of the speaker.

Humanoid robots with AI

- Humanoid robots with AI algorithms can be useful for future distant space exploration missions.
- Atlas is a 183cm (6-feet) tall, bipedal humanoid robot, designed for a variety of search-and-rescue tasks for outdoor, rough terrains.
- It has an articulated sensor head that includes stereo cameras and a laser range finder.

Optoelectronic torque sensors

- These sensors are used for collaborative robot applications, ensuring safer and more effective human-machine-collaboration.
- These have less than one microvolt of noise even in low-torque range, can self-calibrate and measure to an accuracy of 0.01 per cent.
- A contactless measurement principle ensures that the sensors are insensitive to vibration and are wear resistant.

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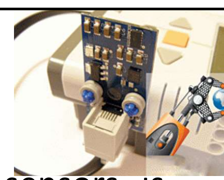
Inertial sensors



- Motion sensing using MEMS inertial sensors is applied to a wide range of consumer products including computers, cell phones, digital cameras, gaming and robotics.
- There are various types of inertial sensors depending on applications.
- LORD MicroStrain manufactures industrial-grade inertial sensors that provide a wide range of tri-axial inertial measurements, and computed attitude and navigation solutions.

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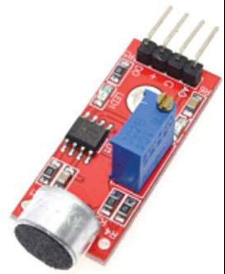
Sound sensors

- Sound sensors are used in robots to receive voice commands.
- High-sensitivity microphones or sound sensors are essential in voice assistants like Google Assistant, Alexa and Siri.



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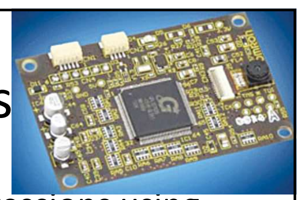
Emotion sensors



- Robots can react to human facial expressions using emotion sensors.
- B5T HVC face-detection sensor module from Omron Electronics is a fully-integrated human vision component (HVC) plug-in module that can identify faces with speed and accuracy.
- The module can evaluate the emotional mood based on one of the five programmed expressions.

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Leading Manufacturers of Sensors for Robotics

- Analog Devices
- Dexter Industries
- LORD Microstrain
- Murata
- Omron
- Pressure Profile Systems Inc
- Rockwell Automation
- Seeed Technology Co Ltd.
- Siemens
- Tamagawa Seiki

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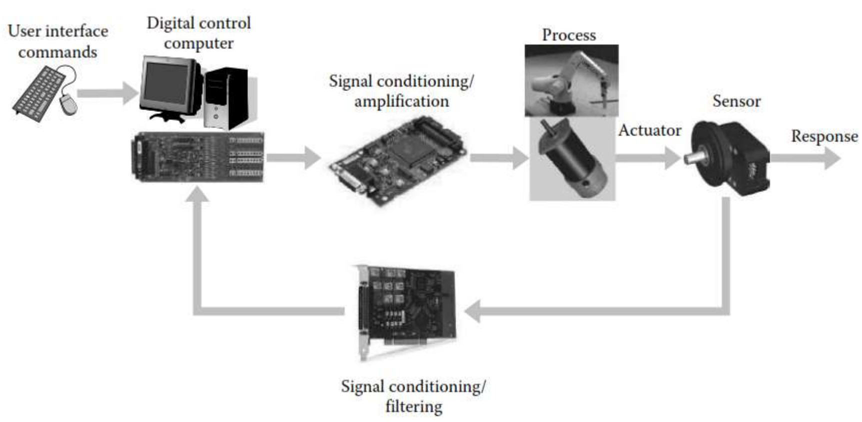
Sensors & Actuators in Feedback Control



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Innovative and advanced sensors

- Microminiature sensors (IC-based, with built-in signal processing).
- Intelligent sensors (built-in information preprocessing, reasoning, and inference making to provide high-level knowledge).
- Integrated (or, embedded) and distributed sensors. (These are integral with the components/agents of a multi-agent system, and communicate with each other. In distributed sensing, there can be significant geographic separation between sensor nodes.)
- Hierarchical sensory architectures (low level sensory information is preprocessed to meet higher level requirements) → compatible with hierarchical control; each control layer is serviced by a corresponding sensor layer.

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- Dr.Ashish Dutta, Sessions on Sensors and Actuators, IITK
- S.R.Deb, Industrial robotics, TMH
- https://metromatics.com.au/miniature-haptic-sensors-medical-applications/
- Mingyu Kim, Changyu Jeon and Jinmo Kim , A Study on Immersion and Presence of a Portable Hand Haptic System for Immersive Virtual Reality, Sensors 2017, 17, 1141

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