Sensors and Transducers

Textbook: W. Bolton, "Mechatronics --- Electronic control systems in mechanical and electrical engineering," 5th edition, Pearson Education Limited 2012, Chap 2

Ref. book: R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza, "Introduction to Autonomous Mobile Robots," 2nd edition, MIT Press, 2011, Chap 4

PowerPoint 中部分圖片擷取和修改自教科書和網路圖片

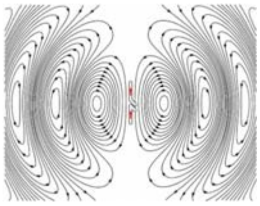
林沛群
國立台灣大學
機械工程學系

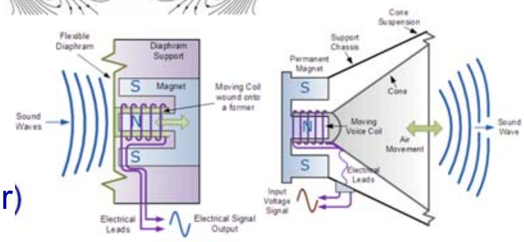
Definitions -1

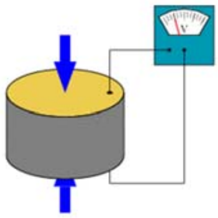
- Transducer
  - A transducer is a device that converts energy from one form to another
- Sensor
  - A sensor is a transducer that receives and responds to a signal or stimulus from a physical system
- Actuator
  - An actuator is a device (transducer) that is responsible for moving or controlling a mechanism or system

Definitions -2

- Bidirectional transducers
  - Bidirectional transducers convert physical phenomena to electrical signals and also convert electrical signals into physical phenomena
  - Examples
    - Antenna: electromagnetic waves ↔ electrical signals (a radio receiver vs. a radio transmitter)
    - Voice coils: sound waves ↔ electrical signals (a microphone vs. a loudspeaker)
    - Piezo transducer: force/displacement ↔ electrical signals





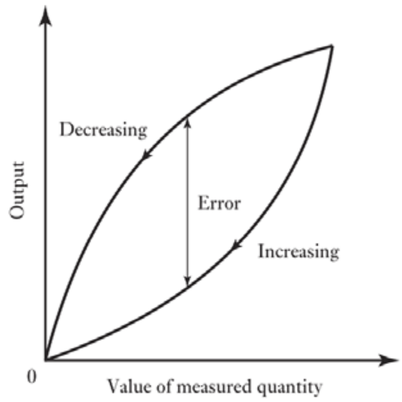


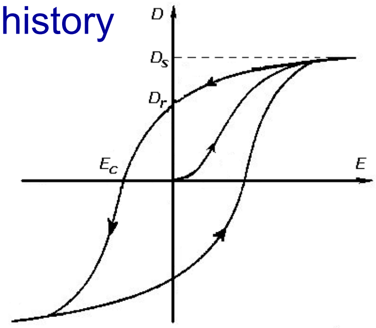
Performance Terminology -1

- Range and span
  - The limits between which the input can vary
  - Ex: LM35 temperature sensor, $\text{range}\ -55\ \text{to}\ 150\ ℃$
- Error
  - The difference between the result of the measurement and the true value
  - Ex: Sensor reading $24.6\ ℃$ and actual temp $25\ ℃$, $\text{error} = -0.4\ ℃$
- Accuracy
  - The extent to which the value indicated by a measurement system might be wrong
  - Ex: $\pm 0.5\ ℃$

Performance Terminology -2

- Sensitivity
  - The relationship indicating how much output there is per unit input
  - Ex: 10 mv/℃
- Hysteresis
  - The dependence of the state of a system on its history

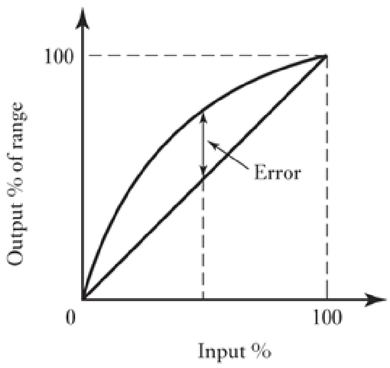




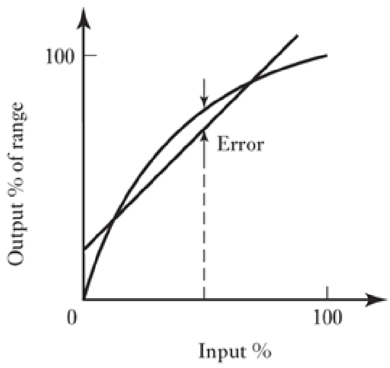
Electric displacement field D of a ferroelectric material as the electric field E is first decreased, then increased. The curves form a hysteresis loop.

Performance Terminology -3

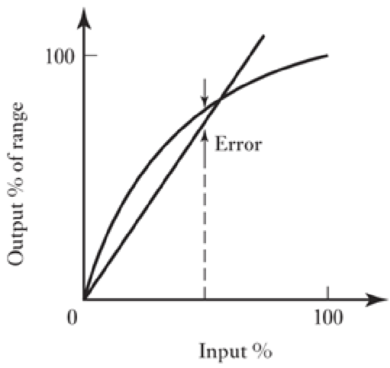
- Non-linearity error
  - Defined as the maximum difference from the linear approximation



End-range



Best-straight line



Best-straight line through zero input

  - Ex:±0.25 ℃

Performance Terminology -4

- Repeatability / reproducibility
  - The ability to give the same output for repeated applications of the same input value
  - $= \frac{max.-min.\,values\ given}{full\ range} \times 100\%$
- Stability
  - The ability to give the same output when used to measure a constant input over a period of time
  - Drift: Describing the change in output that occurs over time; expressed as a percentage of the full range output

Performance Terminology -5

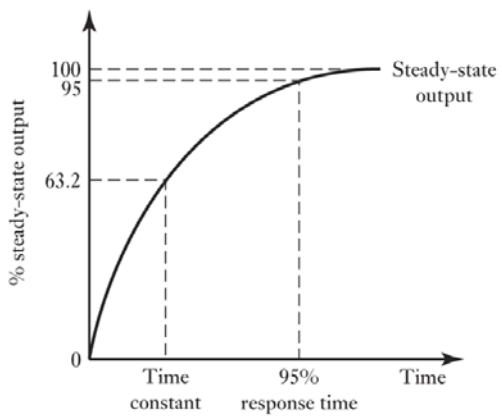
- Resolution
  - The smallest change in the input that will produce an observable change in the output
  - Digital sensors: Usually the A/D resolution, e.g. $\frac{5V}{2^8-1}$ (8 bit)
- Dynamic range
  - Ratio of the maximum input to the minimum measurable input value, usually in decibels (dB, “power”)
  - e.g. Power measurement from 1 Milliwatt to 20 Watt, $= 10\log\left(\frac{20}{0.001}\right) = 43\ dB$
  - e.g. Voltage measurement from 1 Millivolt to 20 Volt, $= 10\log\left(\frac{20}{0.001}\right)^2 = 20\log(\frac{20}{0.001}) = 86\ dB$

Performance Terminology -6

- Dead band
  - The range of input values for which there is no output
- Bandwidth
  - The speed with which a sensor can provide a stream of readings
- Output impedance
  - Ex: 0.1 Ω for 1 mA load
- Others
  - EX: supply voltage, current drain…

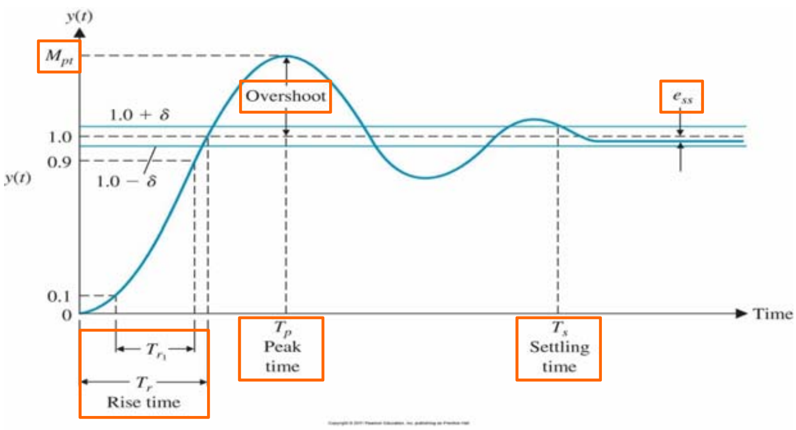
Static and Dynamic Characteristics -1

- Static characteristics
  - The values given when the steady-state conditions occur
- Dynamic characteristics
  - The behavior between the time that the input changes and the time that the value given by the transducer settles down to the steady-state value
  - Response time
    - To the step input
  - Time constant
    - $1 - \frac{1}{e} = 63.2$



Static and Dynamic Characteristics -2

- Rise time
  - The time taken for the output to rise from 10% to 90% of the steady-state value
- Settling time
  - The time taken for the output to settle within some percentage, e.g. 2% of the steady-state value



Classification -1

- Method 1
  - Proprioceptive sensors
    - Measuring values internally to the system

      Ex: Motor speed, wheel load, robot arm joint angle, battery voltage
  - Exteroceptive sensors
    - Acquiring information from the system's environment

      Ex: Distances measurement, light intensity, sound amplitude

Classification -2

- Method 2
  - Passive sensors
    - Measuring ambient environmental energy entering the sensor

      Ex: temperature probe, microphone, CCD, CMOS
  - Active sensors
    - Emitting energy into the environment, then measuring the environmental reaction
    - Often achieving superior performance because of more controlled interactions with the environment
    - May suffer from interference between the signals emitted by other sensors

Classification -3

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

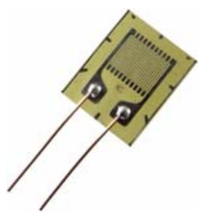
A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

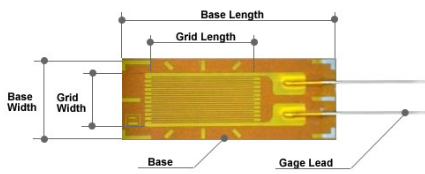
Classification -4

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

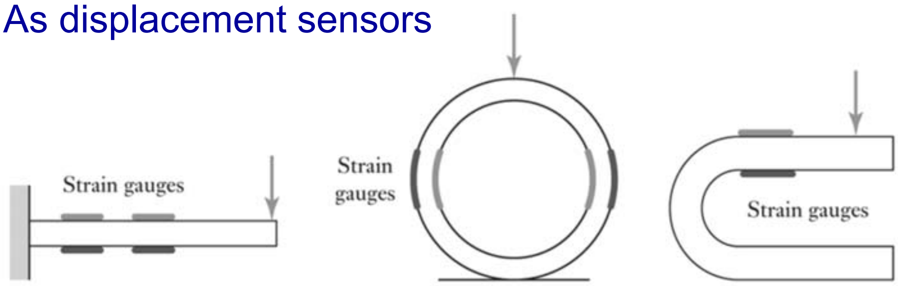
Elements -1

- Strain gauge
  - A device used to measure strain on an object
  - $\frac{\Delta R}{R} = G\varepsilon,\ G =$ gauge factor
  - $G = \sim 2, metal\ wire$; $G = \sim 100, semiconductor$



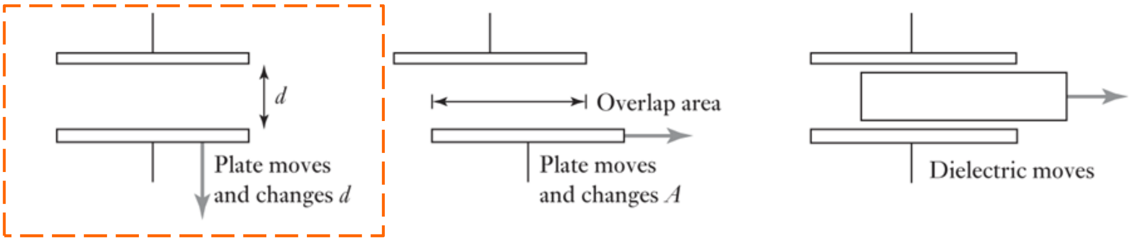


  - As displacement sensors



Elements -2

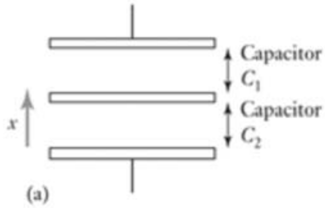
- Capacitive element
  - Capacitance: $C = \frac{\epsilon_r \epsilon_0 A}{d}$



$C - \Delta C = \frac{\epsilon_r \epsilon_0 A}{d+x}$ $\quad \frac{\Delta C}{C} = -\frac{d}{d+x} - 1 = -\frac{x/d}{1+x/d}$, nonlinear relation

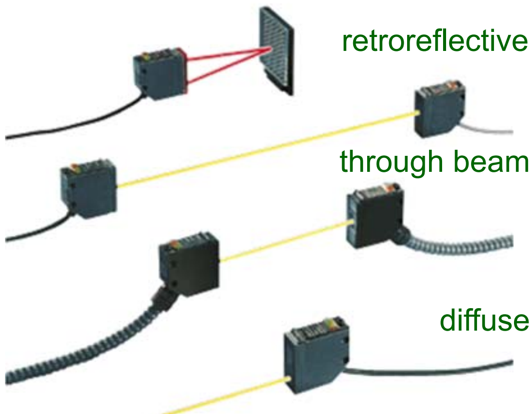
  - Push-pull displacement sensor: a few mm to hundreds of mm
    - Used in MEMS accelerometer (ex: ADXL50)

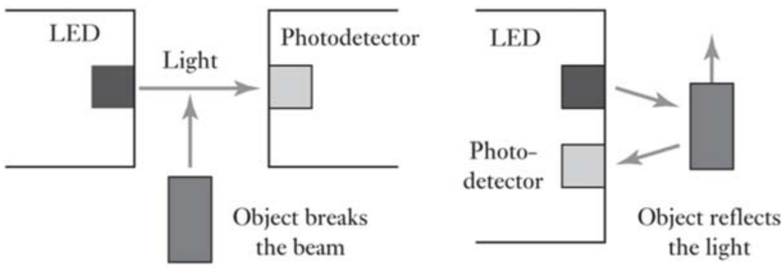
$$C_1 = \frac{\epsilon_r \epsilon_0 A}{d+x}, C_2 = \frac{\epsilon_r \epsilon_0 A}{d-x}$$



Elements -3

- Photoelectric sensors
  - An equipment used to discover the distance, absence, or presence of an object by using a light transmitter, often infrared, and a photoelectric receiver

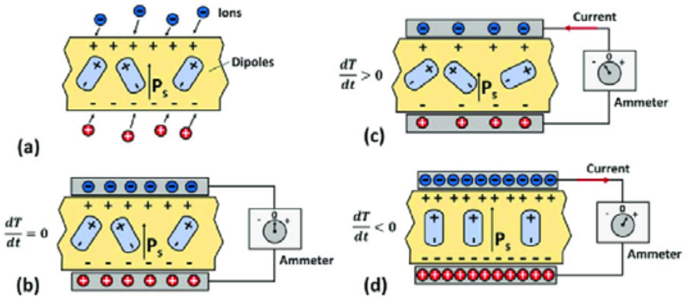




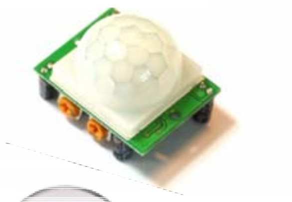
through beam retroreflective

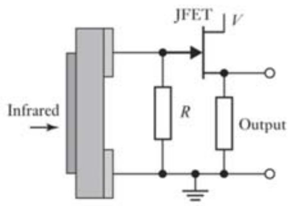
Elements -4

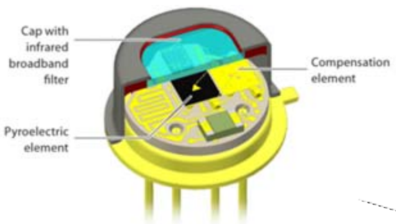
- Pyroelectric Material
  - Crystalline materials which generate charge in response to heat flow

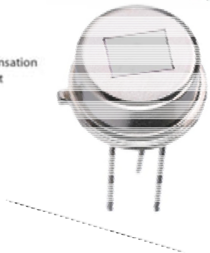


  - Pyroelectric sensor
    - Dual elements
    - Equivalent circuit
      - A moving human: $10^{-12}A$
      - $+ 50\ G\Omega$ resistor $\rightarrow 50mV$



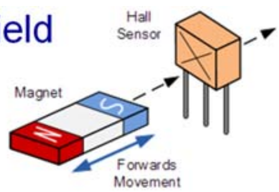




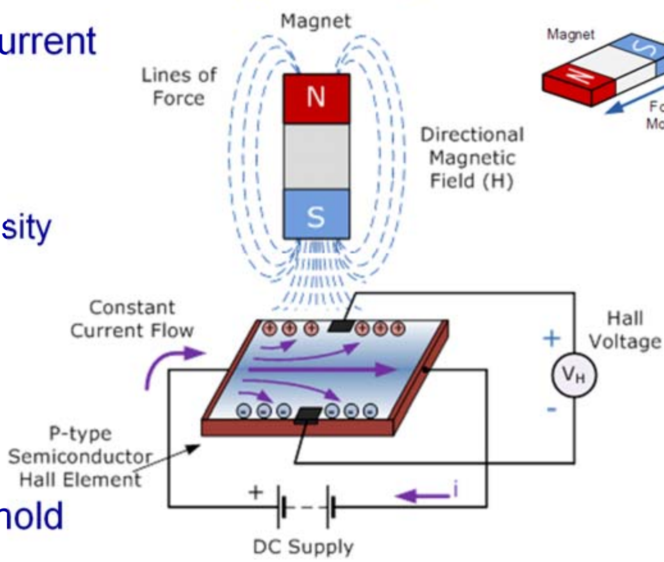


Elements -5

- Hall effect sensor
  - The Hall effect: the production of a voltage difference (the Hall voltage) across an electrical conductor, transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current

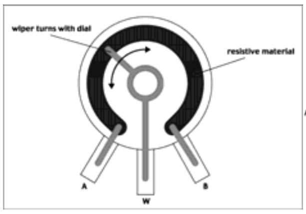


  - $V = K_H \frac{BI}{t}$
    - B: Magnetic flux density
    - I: current
    - t: plate thickness
    - K_H: Hall coefficient
  - Types: Linear & threshold

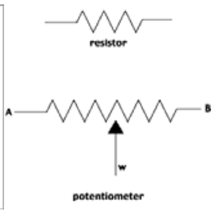


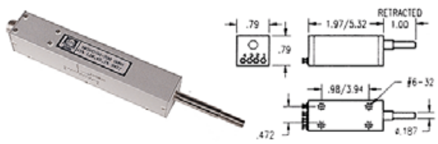
Body State: Position / Orientation -1

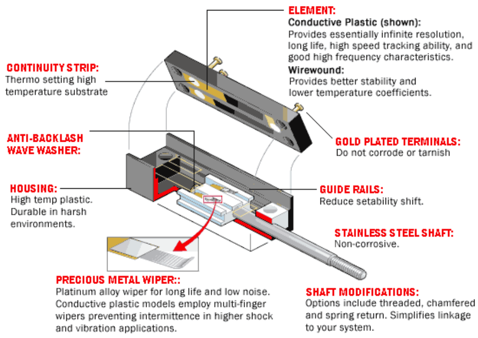
- Potentiometer
  - Consisting of a resistive element with a sliding contact which can be moved over the length of the element, measuring linear or angular displacement
  - Pro: The most straight forward form of displacement sensing
  - Con: Difficulties with resolution, linearity, and noise susceptibility



From www.markallen.com



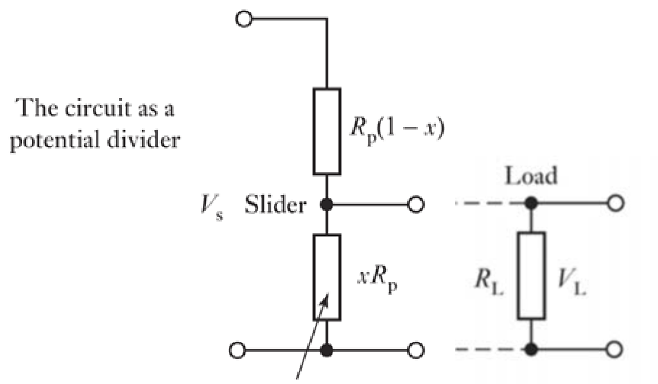




From ETI system

Body State: Position / Orientation -2

- The circuit to a load



Total resistance: $R_p(1-x)+R_L x R_p/(R_L+xR_p)$

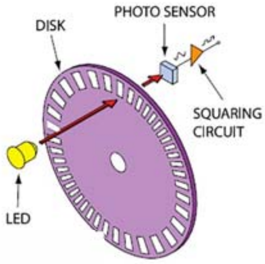
Voltage: $\frac{V_L}{V_S}=\frac{R_L x R_p/(R_L+xR_p)}{R_p(1-x)+R_L x R_p/(R_L+xR_p)}$

If the load is of infinite resistance, $R_L \to \infty$ ⇨ $V_L = xV_s$

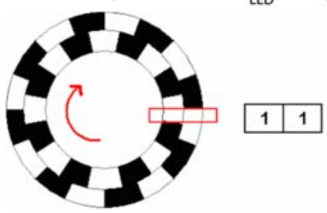
If the load is of finite resistance ⇨ $\text{error} = xV_s - V_L = V_s \frac{R_P}{R_S}(x^2 - x^3)$

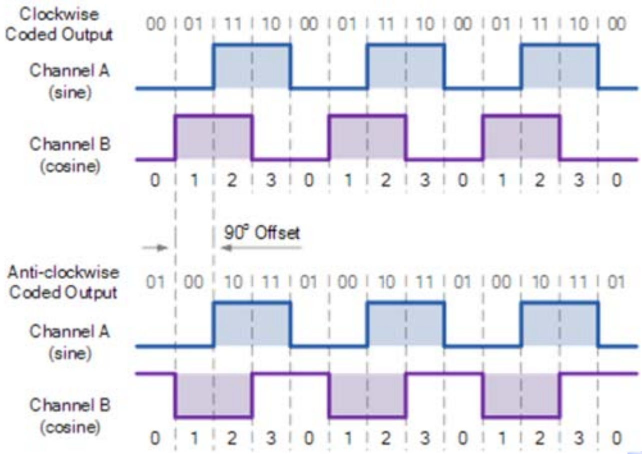
Body State: Displacement / Orientation -3

- Encoders
  - A device that provides a digital output as a result of a linear or angular displacement
  - Two categories
    - Incremental encoder (Typical resolutions: 2000 counts per revolution (CPR)



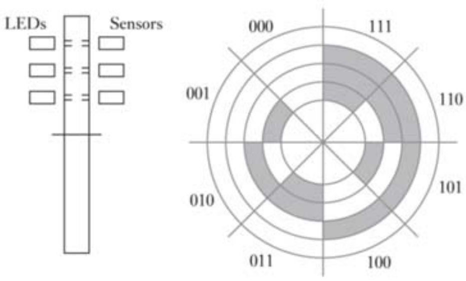
A&B phases





Body State: Position / Orientation -4

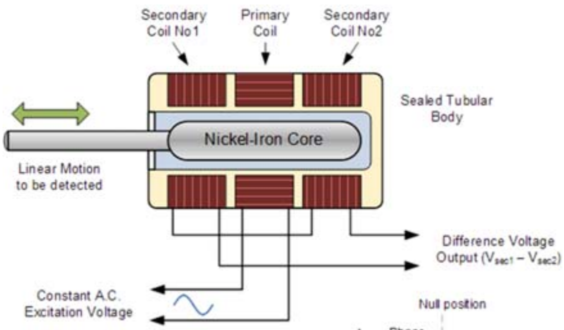
- Absolute encoder
  - Using Grey code, one "change" at a time

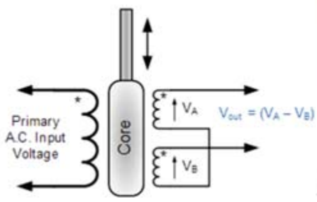


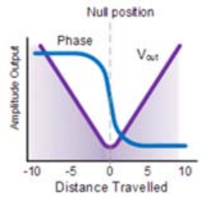
	Normal binary	Gray code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111

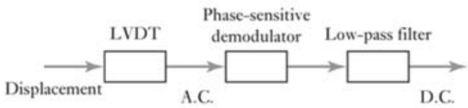
Body State: Position / Orientation -5

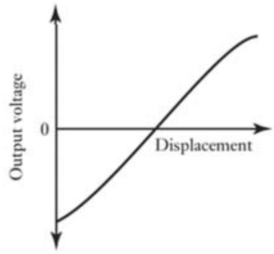
- Linear variable differential transformer (LVDT)
  - ± 2 to $\pm 400\ mm$
  - Non-linearity error $\pm 0.25\%$
  - Rotational counterpart: RVDT





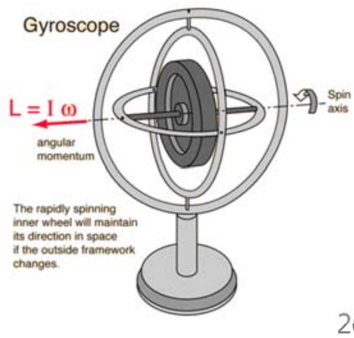






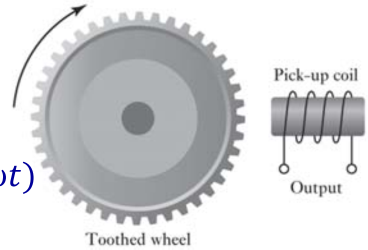
Body State: Position / Orientation -6

- Gyroscope
  - Measuring orientation
  - Mechanical gyroscope
    - Concept: A fast spinning rotor will resist any change to its angular momentum relative to inertial frame
    - Reactive torque t (tracking stability) is proportional to the spinning speed, the precession speed and the wheel's inertia



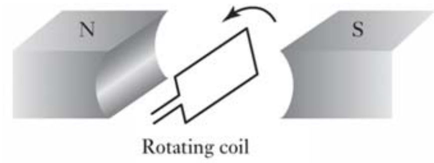
Body State: (Angular) Speed -1

- Tachometer
  - Type 1: Reluctance
    - $\Phi = \Phi_0 + \Phi_a \cos(n\omega t)$
    - $\text{e.m.f} = -N\frac{d\Phi}{dt} = N\Phi_a n\omega \sin(n\omega t) = \text{E}_{max}\sin(n\omega t)$
    - $\text{E}_{max} = N\Phi_a n\omega \propto \omega$



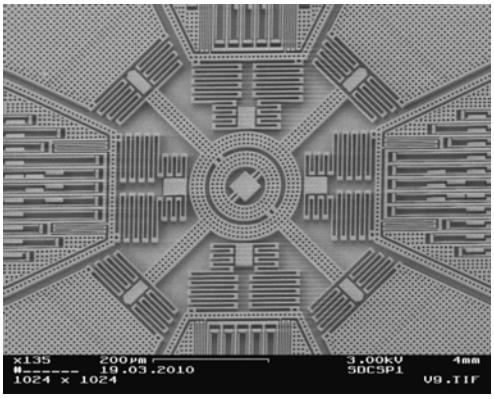
Ferromagnetic material

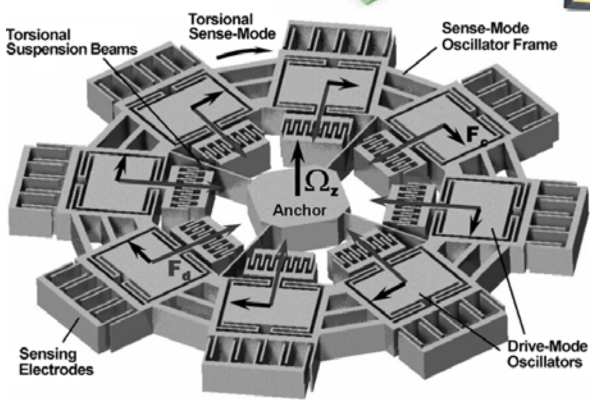
  - Type 2: Type 1 + pulse shaping signal conditioner $\propto$ pulse freq.
  - Type 3: A.C. generator type → $\propto$ e.m.f frequency



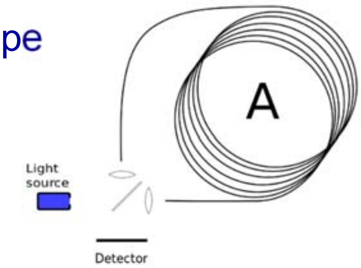
Body State: (Angular) Speed -2

- Rate gyro
  - Measuring angular velocity
  - MEMS – vibrating structure



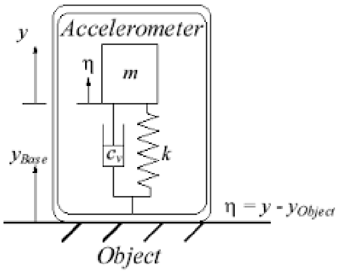


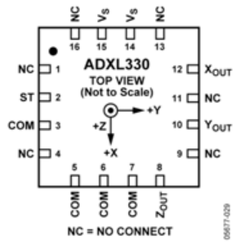
  - Fiber optic gyroscope
    - Sagnac effect:



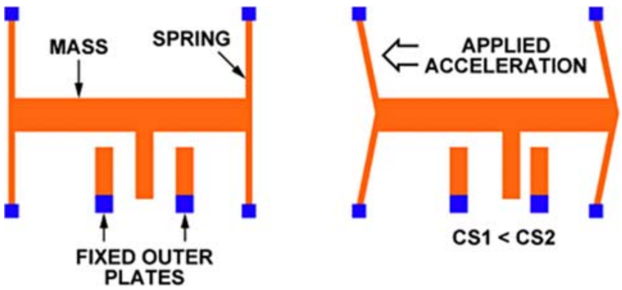
Body State: Acceleration

- Accelerometers
  - Measuring linear acceleration
  - Mechanical
    - $a = \frac{k(y - y_{object})}{m}$

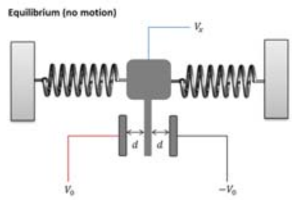




  - MEMS



Push-pull displacement measurement



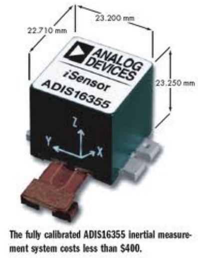
Absolute Heading

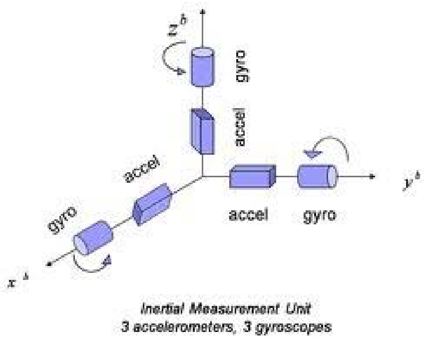
- Compass
  - Magnetic field on earth: absolute measure for orientation
  - Large variety of solutions to measure the earth magnetic field
    - Mechanical magnetic compass
  - Direct measure of the magnetic field
    - Hall-effect, magnetoresistive sensors

  - Major drawback
    - Weakness of the earth field
    - Easily disturbed by magnetic objects or other sources
    - Not feasible for indoor environments

Body State: Multi-function

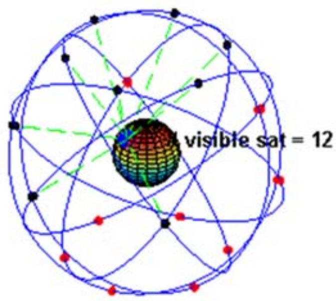
- Inertia measurement unit (IMU)
  - A tri-axis accelerometer
    - Linear acceleration
  - A tri-axis rate gyro
    - Angular velocity
- Combined with other sensors
  - A tri-axis magnetometer
  - Pressure sensor





Absolute Positioning

- Global Positioning System (GPS)
  - Developed for military use originally; now accessible for commercial applications
  - 33 satellites (including 2 spares) orbiting the earth every 12 hours at a height of 20.180 km
  - Location of any GPS receiver is determined through a time of flight measurement – need 4 satellites - allows to identify three values (x, y, z) for the position and the clock correction
- Other systems
  - Russia GLONASS
  - China 北斗衛星導航定位系統



Range Sensing -1

- Principle
  - Time of flight

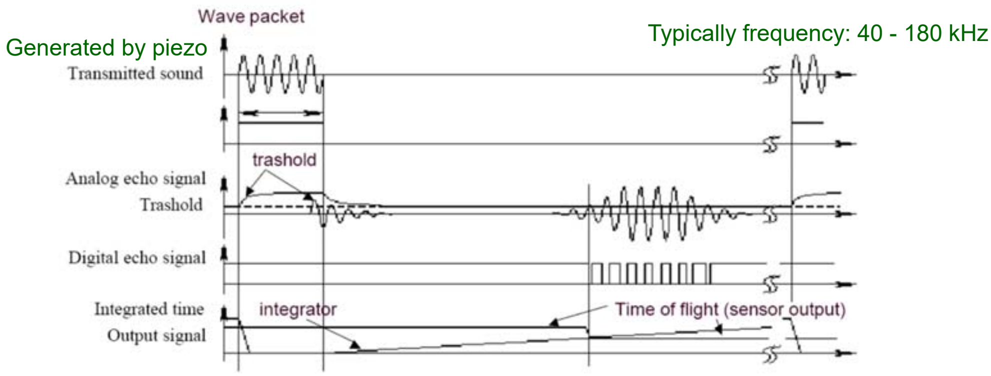
$$d = c \cdot t$$

Where
- d = *distance traveled (usually round-trip)*
- c = *speed of wave propagation*
- t = *time of flight.*

  - Ultrasonic sensor: sound waves, $0.3\ \mathrm{m/ms}$
    - $3\ m$ distance, $10\ ms$
  - Laser range sensor: electromagnetic waves, $0.3\ \mathrm{m/ns}$ (10^6 faster)
    - $3\ m$ distance, $10\ ns$

Range Sensing -2

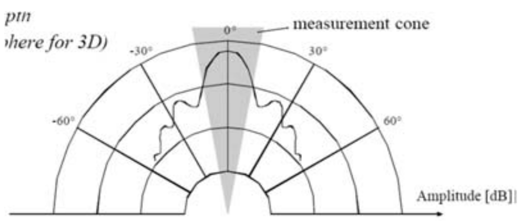
- Ultrasonic sensor
  - Transmit a packet of (ultrasonic) pressure waves
  - $d = \frac{c\,t}{2}$; d distance; c propagation speed of sound; t the time of flight
  - Signal transmitting & receiving

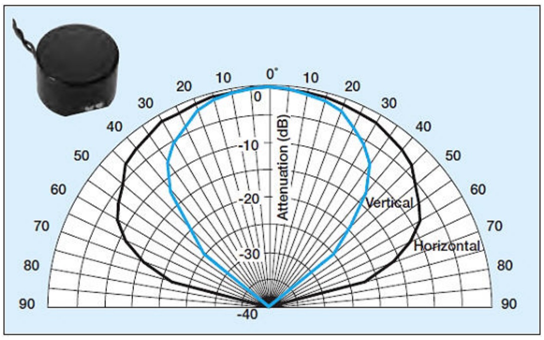


Signals of an ultrasonic sensor

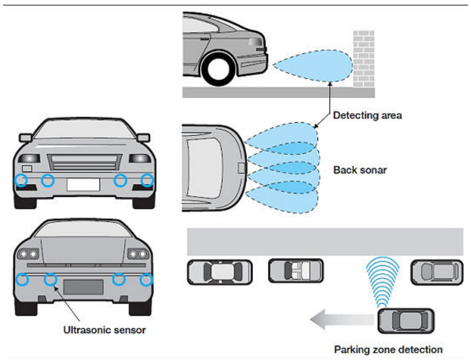
Range Sensing -3

- Measurement cone



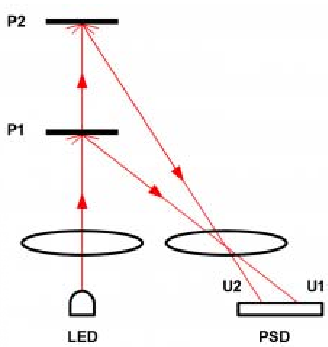


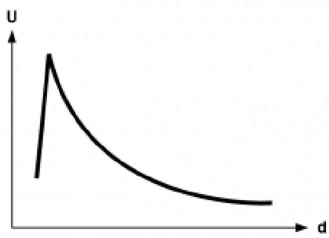
- Application: obstacle avoidance



Range Sensing -4

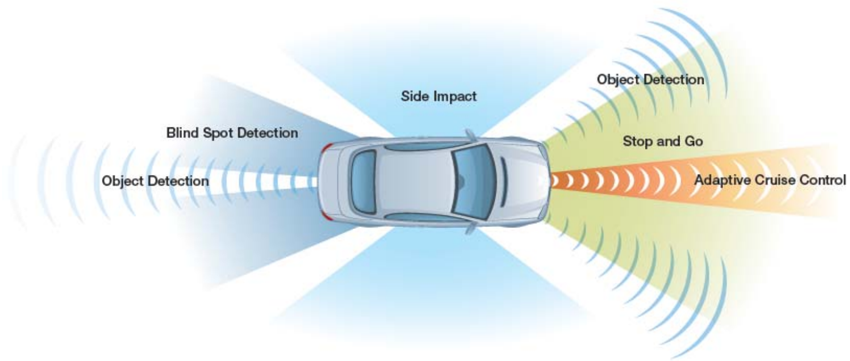
- Infrared distance sensor (IR)
  - IR LED & position-sensible photo detector (PSD)
  - Directional
  - Ex: Sharp GP2Y0A2YK





Range Sensing -5

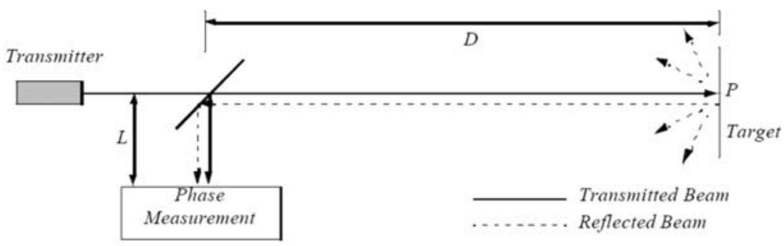
- Radio detection and ranging (RADAR)
  - Using radio waves to determine the range, altitude, direction, or speed of objects
  - More robust, not like LIDAR which is not functional in bad environment conditions such as rain, fog, etc.
  - Recent new application: Adaptive cruise control



24 GHz mediumrange radar

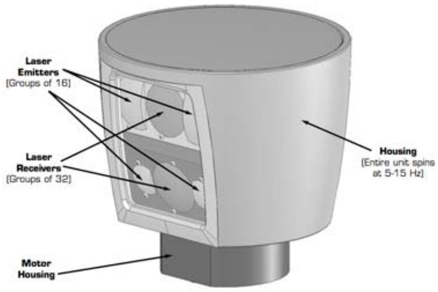
Range Sensing -6

- Laser range finder (LIDAR)
  - Using laser light to detect range
  - Light + RADAR
  - A mechanical mechanism with a mirror sweeps
  - Can NOT detect transparent materials

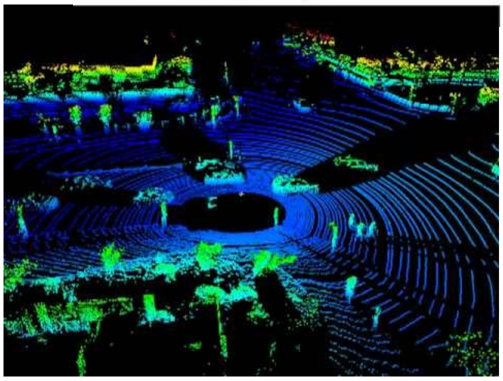


Range Sensing -7

- 3D laser range finder
  - 16-64 channels
  - 100-300 m range
  - 2-3 cm resolution

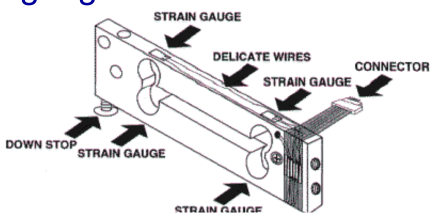


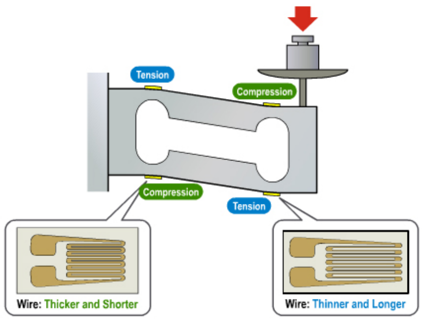
Velodyne HDL-64E



Force Sensing -1

- Load cell
  - Principle
    - External force yields deformation of internal mechanism
    - Local deformation is measured by the strain gauge
  - Assumptions
    - Local strain is proportional to the external force (depends on compliant mechanism design)
    - Local strain is proportional to output voltage of strain gauge (depends on strain gauge design)





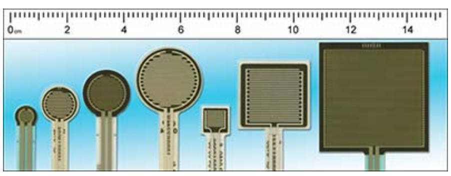
Force Sensing -2

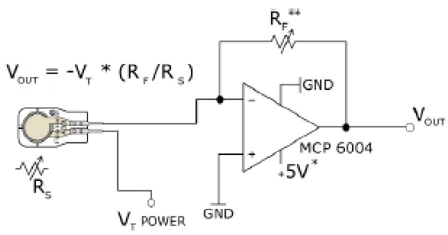
- Design issue
  - Mechanism stiffness vs. sensitivity
  - Hysteresis
  - Multi-channel decoupling
  - Signal conditioning – Wheatstone bridge

  - Gauge arrangements (each axis):
    - Economy choice – 1 strain gauge
    - Temperature compensation – 2 or 4 gauges
    - Maximum sensitivity – 4 gauge

Pressure Sensing

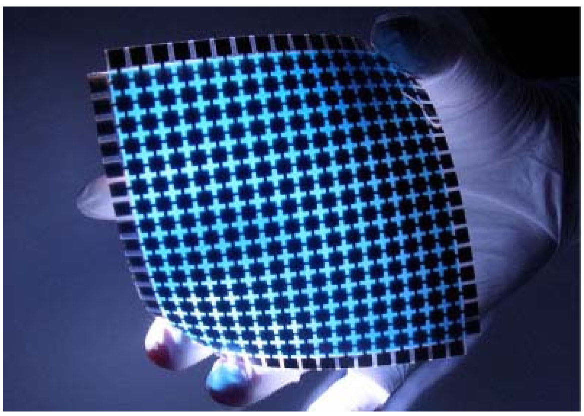
- Point sensing





- * Supply Voltages should be constant
- ** Reference Resistance R_F is 1kΩ to 100kΩ
- Sensor Resistance R_S at no load is >5MΩ
- Max recommended current is 2.5mA

- Array sensing



Vision-based Sensors

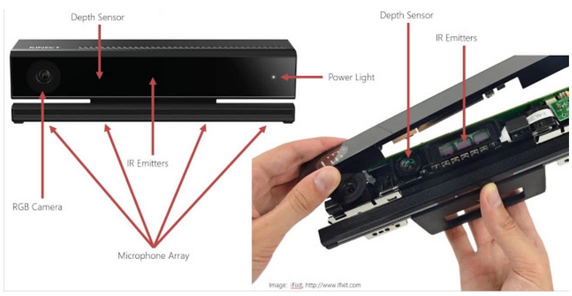
- Vision sensors: converting light into electrons
  - CCD (charge-coupled device)
  - CMOS (Complementary Metal Oxide Semiconductor)

Characteristic	CCD	CMOS
Signal from pixel	Electron packet	Voltage
Signal from chip	Analog Voltage	Bits (digital)
Readout noise	low	Lower at equivalent frame rate
Fill factor	High	Moderate or low
Photo-Response	Moderate to high	Moderate to high
Sensitivity	High	Higher
Dynamic Range	High	Moderate to high
Uniformity	High	Slightly Lower
Power consumption	Moderate to high	Low to moderate
Shuttering	Fast, efficient	Fast, efficient
Speed	Moderate to High	Higher
Windowing	Limited	Multiple
Anti-blooming	High to none	High, always
Image Artefact	Smearing, charge transfer inefficiency	FPN, Motion (ERS), PLS
Biasing and Clocking	Multiple, higher voltage	Single, low-voltage
System Complexity	High	Low
Sensor Complexity	Low	High
Relative R&D cost	Lower	Lower or Higher depending on series

RGBD Sensors -1

- Vision + Depth
  - Microsoft Kinect

Kinect 2.0



Features	Kinect v1	Kinect v2
Depth sensor type	Structured light	Time of Flight (ToF)
Red, Green & Blue (RGB) camera resolution	640 × 480, 30 fps	1920 × 1080, 30 fps
Infrared (IR) camera resolution	320 × 240, 30 fps	512 × 424, 30 fps
Field of view of RGB image	62° × 48.6°	84.1° × 53.8°
Field of view of depth image	57° × 43°	70° × 60°
Operative measuring range	0.8 m–4 m (Default); 0.4 m–3.5 m (Near)	0.5 m–4.5 m
Skeleton joints defined	20 joints	25 joints
Maximum skeletal tracking	2	6

RGBD Sensors -2

- Intel RealSense

TECH SPECS

D400	D410	D415	D420	D430
Depth Technology Passive IR Stereo	Depth Technology Active IR Stereo	Depth Technology Active IR Stereo	Depth Technology Passive IR Stereo	Depth Technology Active IR Stereo
Image Sensor Technology Rolling Shutter	Image Sensor Technology Rolling Shutter	Image Sensor Technology Rolling Shutter	Image Sensor Technology Global Shutter	Image Sensor Technology Global Shutter
Depth FOV (H × V for HD 16:9) 63.4° × 40.4°	Depth FOV (H × V for HD 16:9) 63.4° × 40.4°	Depth FOV (H × V for HD 16:9) 63.4° × 40.4°	Depth FOV (H × V for HD 16:9) 85.2° × 58°	Depth FOV (H × V for HD 16:9) 85.2° × 58°
RGB Frame Rate and Resolution —	RGB Frame Rate and Resolution —	RGB Frame Rate and Resolution 1920 × 1080 at 30 fps	RGB Frame Rate and Resolution —	RGB Frame Rate and Resolution —
Depth Resolution 1280 × 720	Depth Resolution 1280 × 720	Depth Resolution 1280 × 720	Depth Resolution 1280 × 720	Depth Resolution 1280 × 720
Depth Frame Rate Up to 90 fps	Depth Frame Rate Up to 90 fps	Depth Frame Rate Up to 90 fps	Depth Frame Rate Up to 90 fps	Depth Frame Rate Up to 90 fps

RGBD Sensors -3

- Asus Xtion Pro Live   Xtion 2

Asus Xtion Live Pro

~$150 USD
<2.5 W
0.8 m < x < 3.5 m
58° H; 45° V; 70° D
RGB, Depth and Microphone
VGA (640 × 480) 30 fps; QVGA (320 × 240) 60 fps
SXVGA (1280*1024)
Intel x86; AMD
Win 32/64 XP, Vista, 7; Linux Ubuntu 10.10: X86, 32/64 bit, Android
USB2.0
Open NI SDK bundled
C++/C# (Windows); C++ (Linux); Java
18 × 3.5 × 5 cm

* Horizontal, Vertical and Diagonal.

Sensor	Depth & RGB
Depth Image Size	640x480@30fps
Resolution	2592x1944@15fps (5MP) 1920x1080@30fps 1280x720@60fps
Field of View	Depth: 74° H, 52° V, 90° D RGB: 75.6° H, 60° V, 87.9° D (Horizontal, Vertical, Diagonal)
Distance of Use	0.8m-3.5m *Short range: Please refer to ASUS Xtion2 > Support> FAQ for setting
Power Consumption	Below 4.5W

A Famous Competition

- DARPA (Defense Advanced Research Projects Agency), Grand Challenge
  - 2004
    - 240km, all failed before 11.78km
  - 2005
    - 212km
    - 3 narrow tunnels
    - >100 sharp turns
    - Beer Bottle Pass

  A movie from YouTube
  A movie from YouTube

Stanley, the winner of the 2005

"sight"
- 5 laser rangefinders
- monocular video camera
- radar

"positioning"
- GPS
- wheel speed

"balance"
- 6DOF inertia measurement unit
- GPS compass

A Famous Competition

- DARPA, Urban Challenge
  - 2007
    - 96 km (60-mile) urban area course
    - Completed in less than 6 hours
    - Obeying all traffic regulations
    - Negotiating with other traffic and obstacles
    - Merging into traffic

  A movie from YouTube
  A movie from YouTube

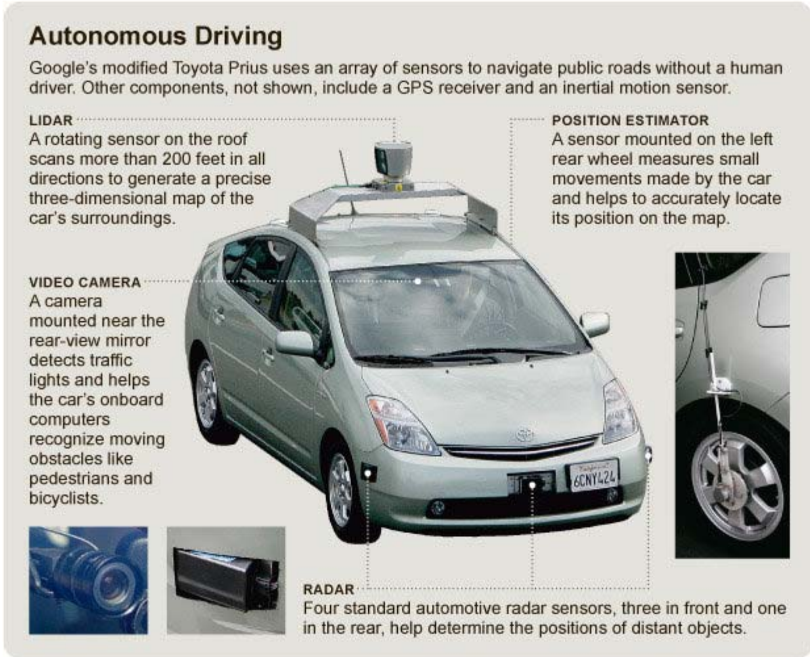
Boss, the winner of the 2007

"sight"
- 5 long-range Radar
- 4 long-range Lidar (->200m)
- 1 mid-range Lidar
- 8 short range Lidar

"pose estimation"
- GPS with dual anrenna
- 6DOF inertia measurement unit

Google Self-driving Car -1

- Starting from 2009
  - Lead by Sebastian Thrun

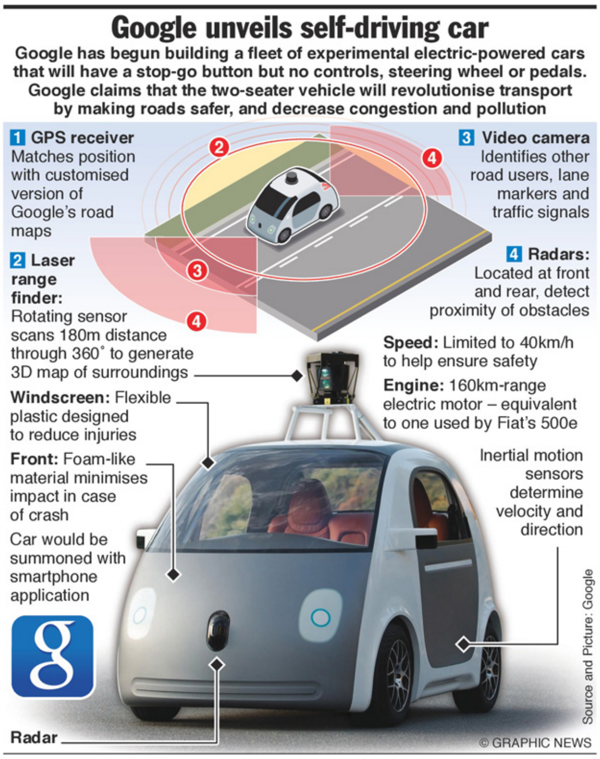


Source: Google THE NEW YORK TIMES; PHOTOGRAPHS BY RAMIN RAHIMIAN FOR THE NEW YORK TIMES

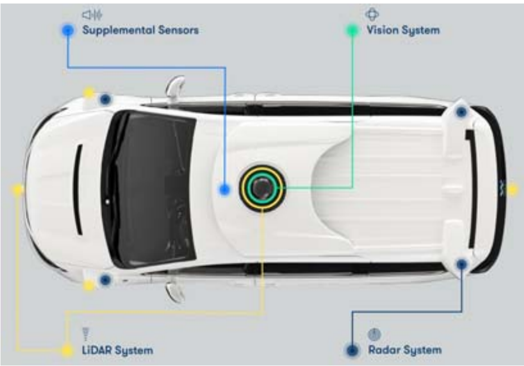
Google Self-driving Car -2

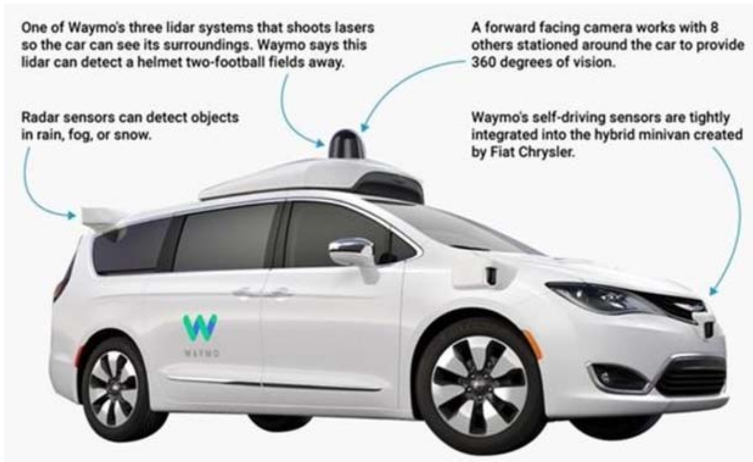
- Waymo, spin-off from Google in 2016

Source: Google Raoul Rañoa / @latimesgraphics



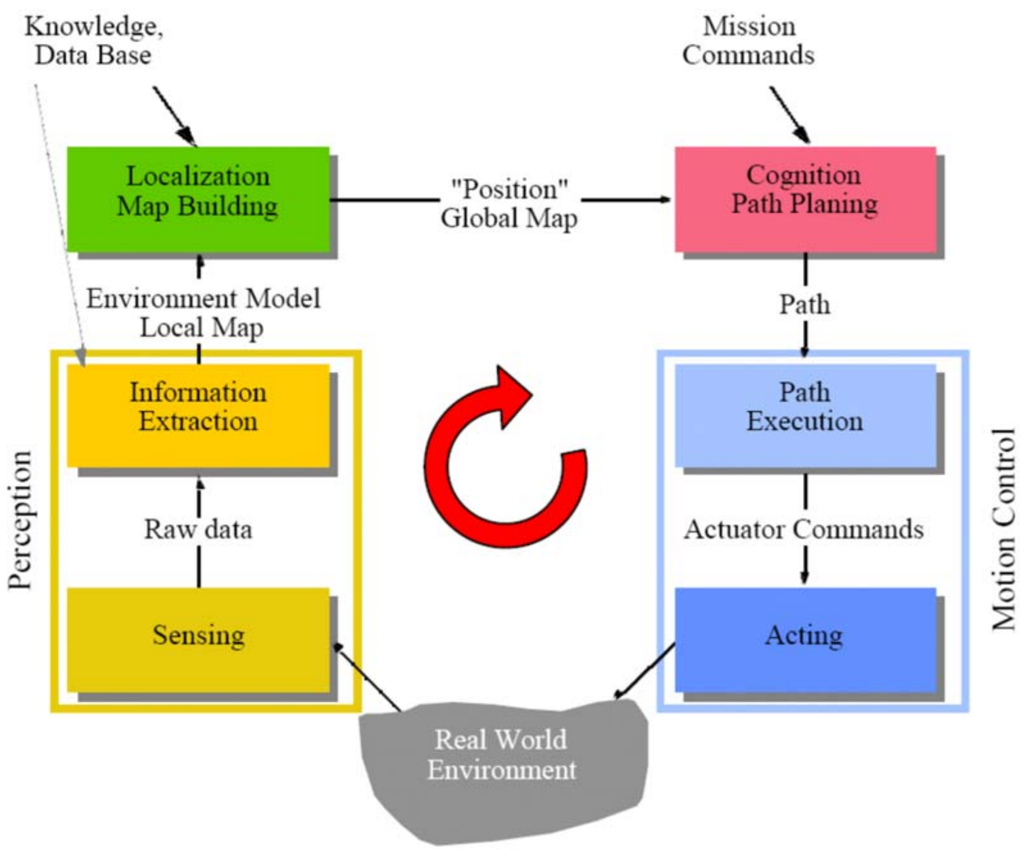
Google Self-driving Car -3



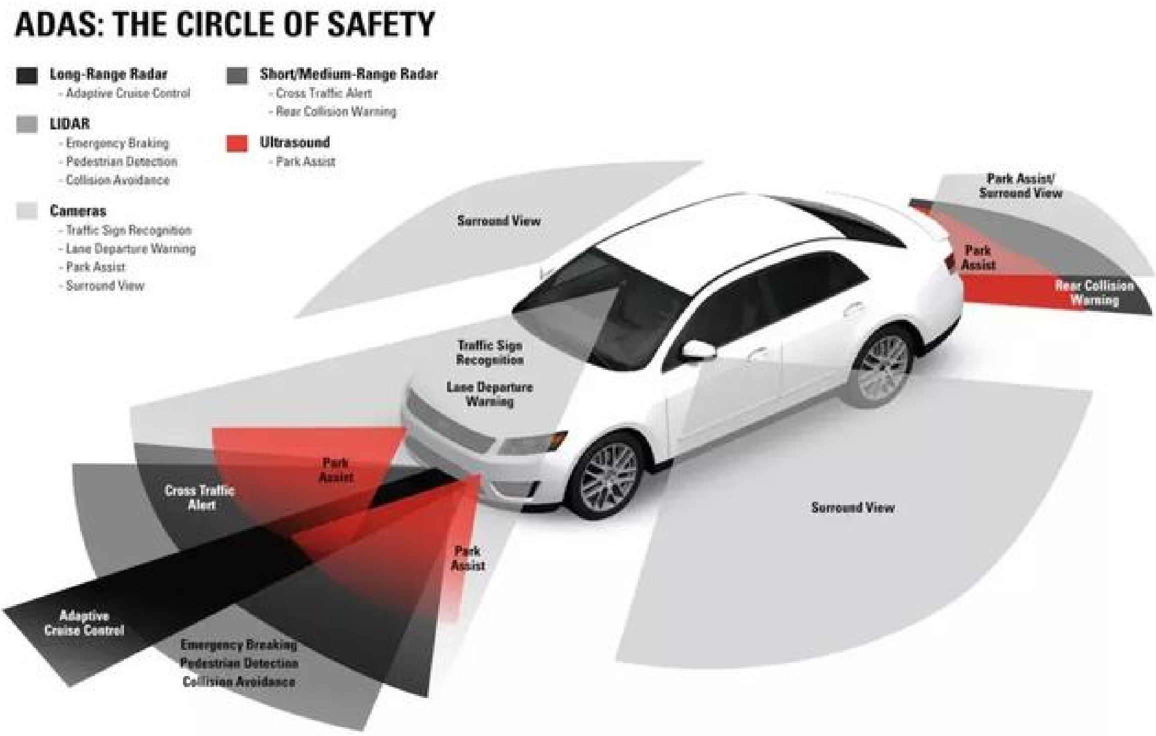


- 5th Generation Waymo Driver

General Control Scheme for Mobile Robot Systems



Advanced Driver Assistance Systems (ADAS)



End

- Questions?