Principles of Safe Autonomy: Robot Sensors and Applications

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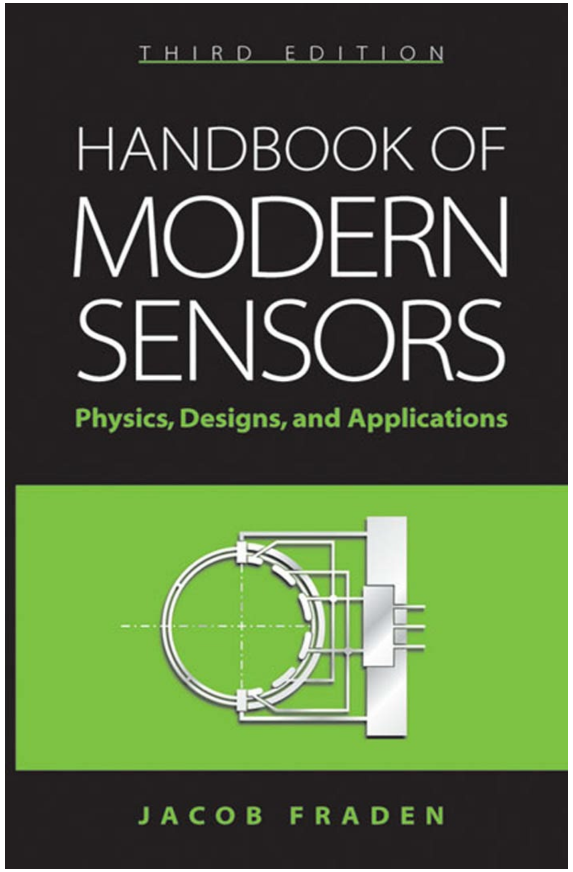
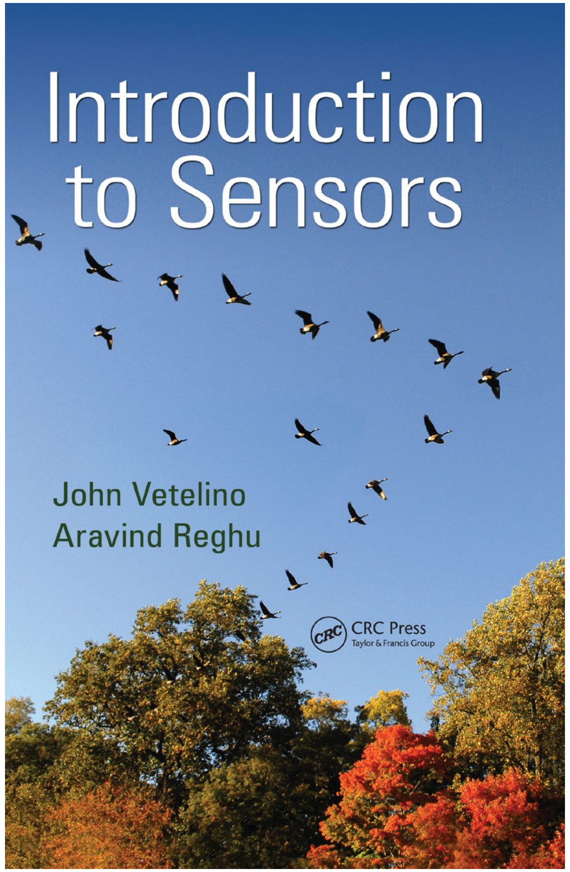
Outline

- Basics of Sensors
- Sensors in Robotics
- Robot Applications





Sensor

- Sensor?
  - Sensor is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor.

- Requirements for a good sensor
  - High sensitivity and selectivity, fast and predictable response, reversible behavior, high signal to noise ratio, compactness, low cost, immune to environment, easy calibration, stability, continuous operation without affecting original system

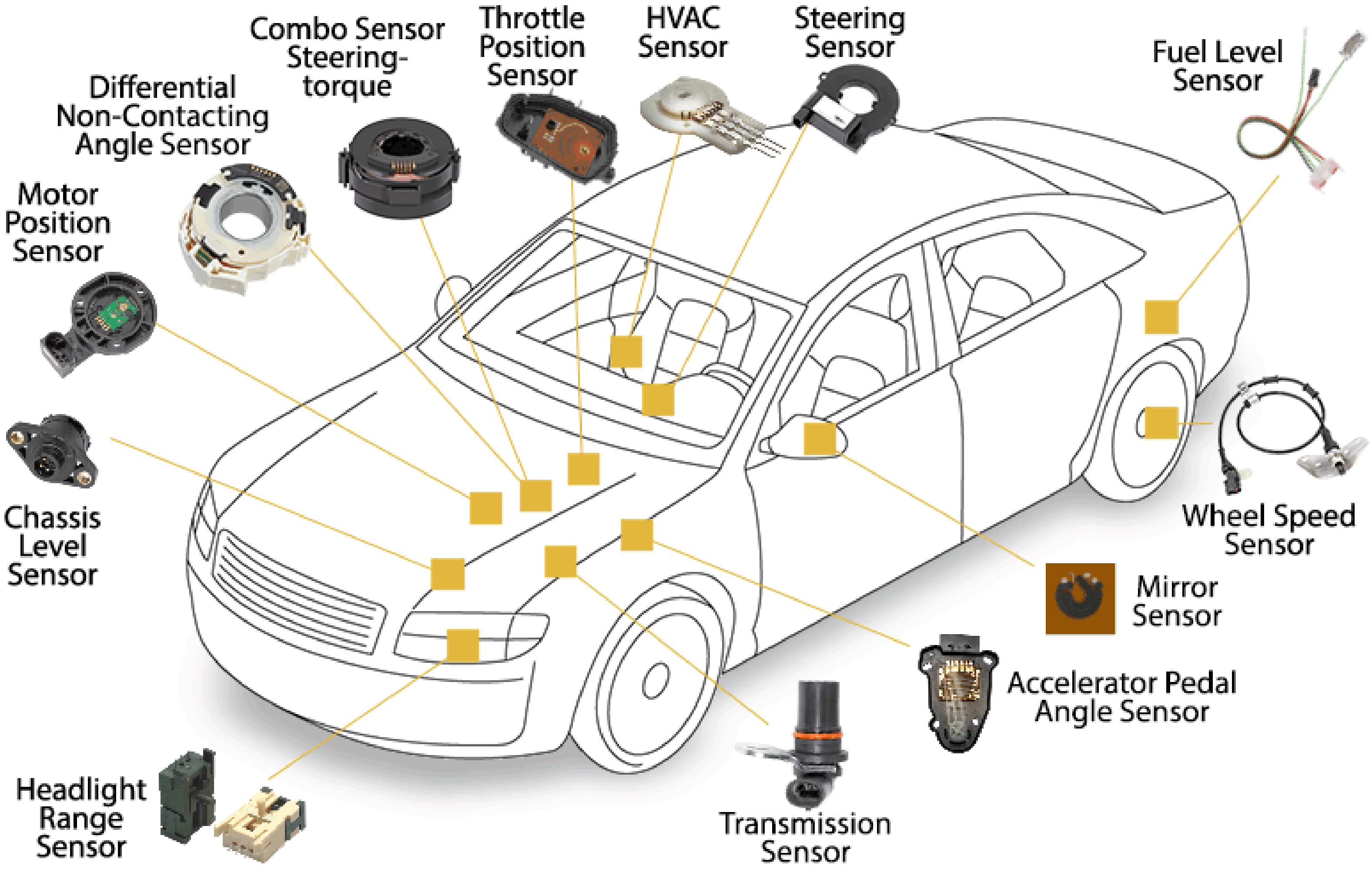
Various Sensors (1)

- Mechanical sensors
  - space- distance, angle, displacement, level, deformation,…
  - Time- Time, Lapse, Period,…
  - Movement- (Linear/Angular) Velocity/Acceleration, Vibration, Rotation, Flux,…
  - Force- Weight, Pressure, Torque,…
  - Others- Mass, Density, Viscosity, Elasticity, Hardness, Strength,…
- Electromagnetic
  - Electric- Voltage, current, power, charge, electric field, electric force,…
  - Magnetic- Magnetic field, Magnetic force, magnetic resistance, magnetic polarization,..
  - Electromagnetic wave – wavelength, frequency,…
  - Others- dielectric constant, resistivity, permittivity, permeability, polarizability

Various Sensors (2)

- Optical
  - Visible light- Intensity, Color, Polarization, Interference, Diffraction, Refraction, Reflection,…
  - Infrared/Utraviolet
  - Image
  - Other Flurescene
- Radiation
  - Charged particle
  - Electron
  - E-M wave radiation
- Acoustic
  - Acoustic wave
  - Ultrasonic wave
  - Voice/noise
- Thermal
  - Heat
  - Temperature
- Chemical
  - Gas
  - Ion
  - Component
  - Humidity
  - Particulate/smoke
- Biological
  - Biomolecules
  - Cells
  - Biofunction

Sensors in a car

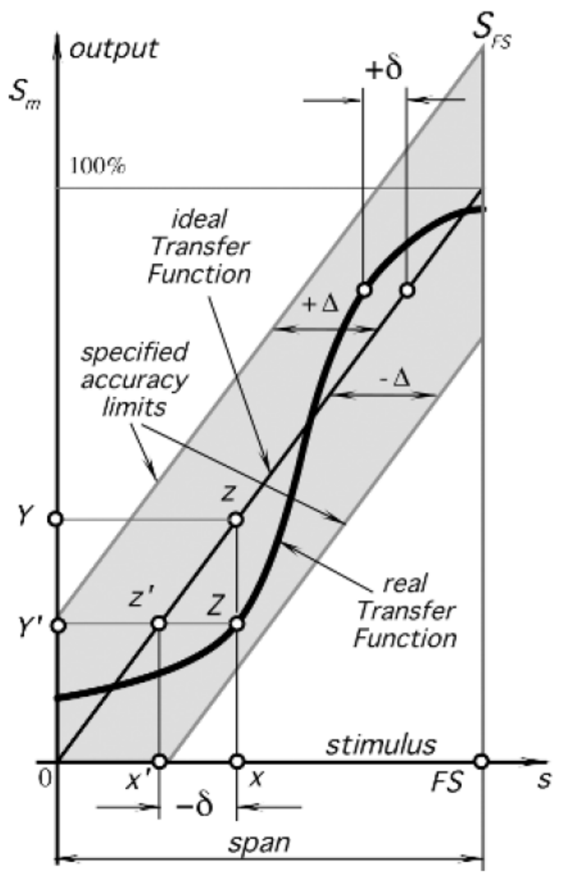


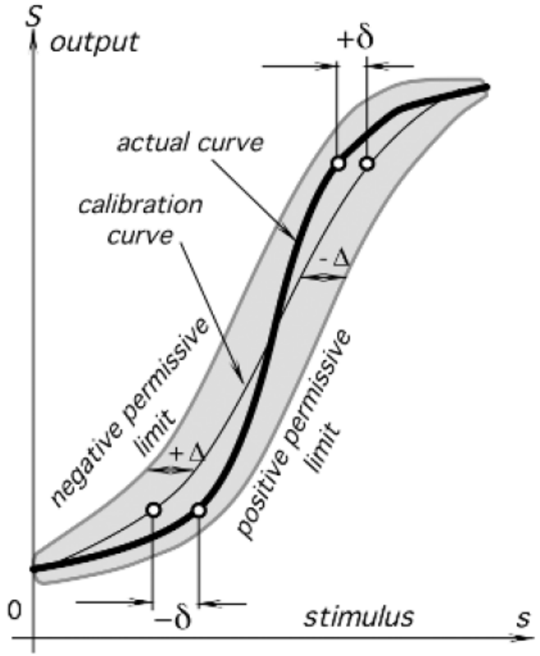
Physical Principles of Sensing

- Electric Charges, Fields, and Potentials
- Capacitance (Capacitor, Dielectric Constant)
- Magnetism (Faraday's Law)
- Induction
- Resistance
  - Specific Resistivity
  - Temperature Sensitivity
  - Strain Sensitivity
  - Moisture Sensitivity
- Piezoelectric Effect
- Pyroelectric Effect
- Hall Effect
- Seebeck and Peltier Effects
- SoundWaves
- Temperature and Thermal Properties of Materials
- Heat Transfer
- Light

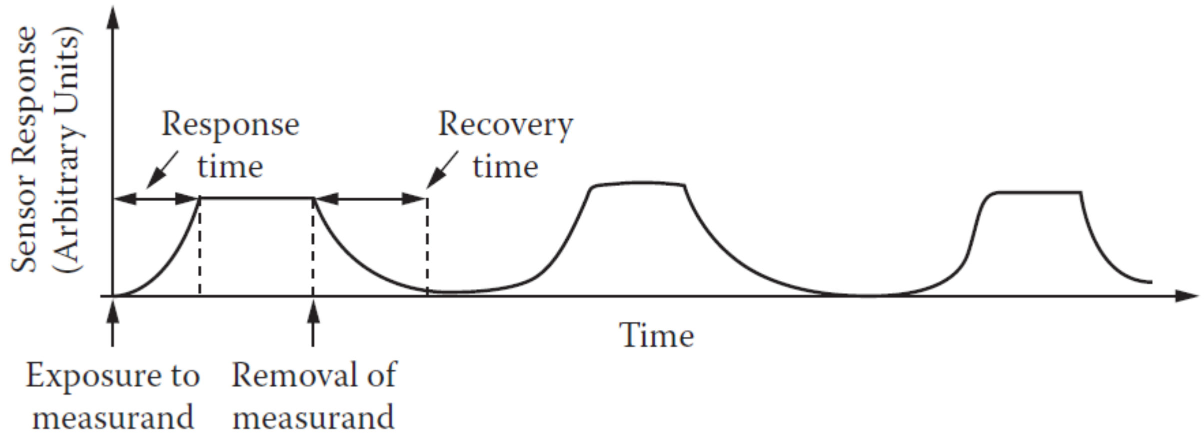
Sensor Characteristics

- Transfer Function
  - Relationship between physical input signal and electrical output signal
- Dynamic Range (Span or Full-Scale Input)
  - The range of input signals which may be converted to electric output signals by the sensor
- Sensitivity
  - Ratio between a change in output signal and a change in input signal
- Accuracy
  - Uncertainty is the largest expected error between actual and ideal output signals
  - A percentage of full scale or absolute term
- Resolution
  - Minimum detectable signal fluctuation



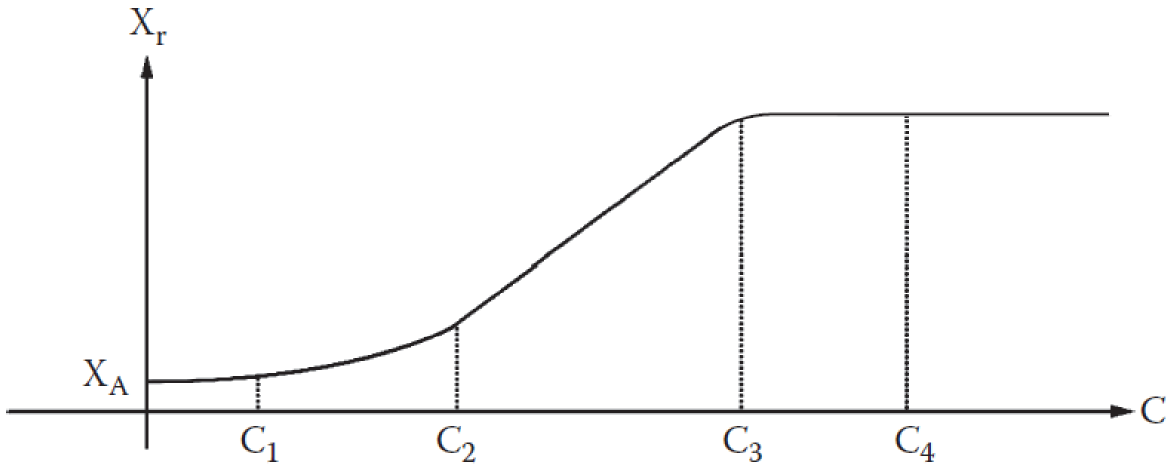


Response & Recovery time



- Response time: the time it takes the sensor to reach 90% of its steady-state value after the introduction of the measurand
- Recovery time: the time that it takes the sensor to be within 10% of the value it had before exposure to the measurand.
- Typically the response times are much shorter than the recovery times.
- Bandwidth: how sensors respond at different frequencies. Higher bandwidth sensors can measure higher frequency motion and vibration

Transfer Function



$0 \le C \le C_1$: below the sensor response threshold level

$C_1 \le C \le C_4$: complete sensor dynamic range

$C_2 \le C \le C_3$: ideal sensor dynamic range (linear region of X_r vs. C curve)

$C_1 \le C \le C_2$ and $C_3 \le C \le C_4$: nonlinear region of the sensor dynamic range

$C \ge C_4$: saturation region of sensor

Example

- Air pressure sensor

Features

- Proprietary Honeywell technology
- Protected by multiple global patents
- Industry-leading long-term stability: ±0.25 %FSS
- Total Error Band (TEB): ±1.5 %FSS
- Industry-leading accuracy: ±0.25 %FSS BFSL
- High burst pressures
- Industry-leading flexibility
- Wide pressure range: 60 mbar to 10 bar | 6 kPa to 1 MPa | 1 psi to 150 psi
- Meets IPC/JEDEC J-STD-020D.1 Moisture Sensitivity Level 1 requirements
- Optional internal diagnostic functions
- Energy efficient
- Output: ratiometric analog; I²C- or SPI-compatible 14-bit digital output (min. 12-bit sensor resolution)
- Small size: As small as 8 mm x 7 mm
- REACH and RoHS compliant
- Sleep mode option (see Technical Note)
- Temperature output option
- Liquid media option

DIP AN: Single axial barbed port

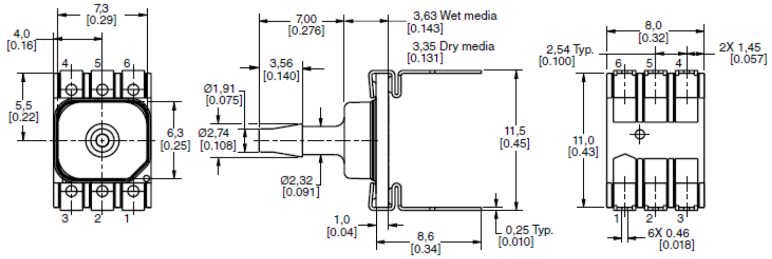


Table 1. Absolute Maximum Ratings[1]

Characteristic	Min.	Max.	Unit
Supply voltage (V_{supply})	-0.3	6.0	Vdc
Voltage on any pin	-0.3	V_{supply} + 0.3	V
Digital interface clock frequency: I²C SPI	 100 50	 400 800	kHz
ESD susceptibility (human body model)	2	–	kV
Storage temperature	-40 [-40]	85 [185]	°C [°F]
Soldering time and temperature: lead solder temperature (DIP) peak reflow temperature (Leadless SMT, SMT)	 4 s max. at 250 °C [482 °F] 15 s max. at 250 °C [482 °F]		

[1]Absolute maximum ratings are the extreme limits the device will withstand without damage.

Table 2. Environmental Specifications

Characteristic	Parameter
Humidity (Gases only; see "Options N and D" in Figure 2.)	0% to 95% RH, non-condensing
Vibration	15 g, 10 Hz to 2 kHz
Shock	100 g, 6 ms duration
Life[1]	1 million pressure cycles minimum
Solder reflow	J-STD-020-D.1 Moisture Sensitivity Level 1 (unlimited shelf life when stored at ≤30 °C/85 % RH)

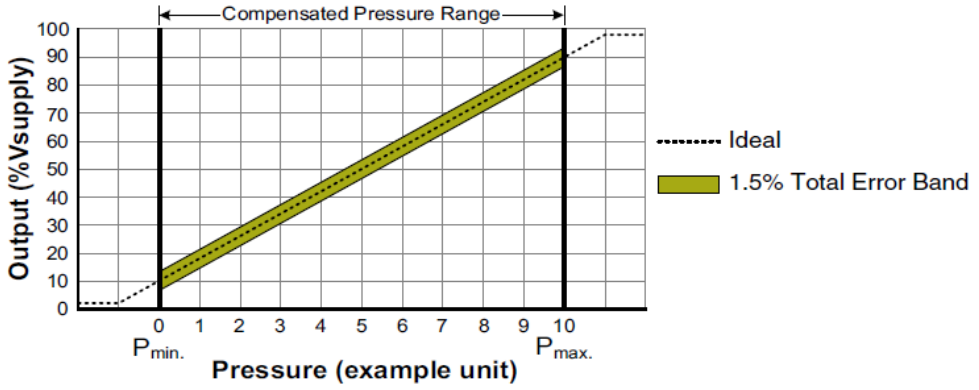
[1]Life may vary depending on specific application in which the sensor is used.

Table 5. Operating Specifications

Characteristic	Analog			Digital			Unit
	Min.	Typ.	Max.	Min.	Typ.	Max.	
Supply voltage (V_{supply}):[1, 2, 3]							
3.3 Vdc	3.0	3.3	3.6	3.0	3.3	3.6	Vdc
5.0 Vdc	4.75	5.0	5.25	4.75	5.0	5.25	
Supply current:							
3.3 Vdc	—	2.1	2.8	—	3.1	3.9	mA
5.0 Vdc	—	2.7	3.8	—	3.7	4.6	mA
sleep mode option	—	—	—	—	1	10	µA
Operating temperature range[4]	-40 [-40]	—	85 [185]	-40 [-40]	—	85 [185]	°C [°F]
Compensated temperature range[5]	0 [-32]	—	50 [122]	0 [-32]	—	50 [122]	°C [°F]
Temperature output option[6]	—	—	—	—	1.5	—	°C
Startup time (power up to data ready)	—	—	5	—	—	3	ms
Response time	—	1	—	—	0.46	—	ms
Clipping limit:							
upper	—	—	97.5	—	—	—	%Vsupply
lower	2.5	—	—	—	—	—	
SPI/I²C voltage level:							
low	—	—	—	—	—	20	%Vsupply
high	—	—	—	80	—	—	
Pull up on SDA/MISO, SCL/SCLK, SS	—	—	—	1	—	—	kOhm
Accuracy[7]	—	—	±0.25	—	—	±0.25	%FSS BFSL[8]
Output resolution	0.03	—	—	—	—	—	%FSS
	—	—	—	12	—	—	bits

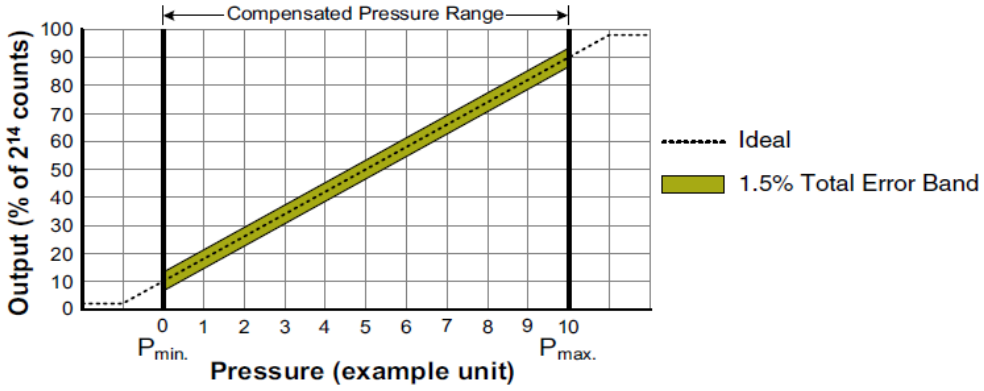
Figure 2. Transfer Function Limits[1]

Analog Versions



$$\text{Output (V)} = \frac{0.8 \times \text{Vsupply}}{P_{max.} - P_{min.}} \times (\text{Pressure}_{applied} - P_{min.}) + 0.10 \times \text{Vsupply}$$

Digital Versions



$$\text{Output (\% of } 2^{14} \text{ counts)} = \frac{80\%}{P_{max.} - P_{min.}} \times (\text{Pressure}_{applied} - P_{min.}) + 10\%$$

Sensors in Robotics

Sensors in Robots

- Internal Sensors
  - Getting data from the robot system itself
    - Position sensor, velocity sensor, acceleration sensors, Gyroscope, torque sensor, etc
- External Sensors
  - Getting data from the environment
    - Camera
    - Range sensors (IR sensor, laser range finder, ultrasonic sensor, etc)
    - Contact and proximity sensor (Photodiode, IR detector, RF sensor, touch sensor, etc)
    - Force sensor

Sensors

A Head

- Microsoft Kinect
- 5-Megapixel Global Shutter Color Gigabit Ethernet Camera (1-Megapixel **on SE**)
- Environment Stereo Camera: Wide-Angle Global Shutter Color Stereo Ethernet Camera (**NOT on SE**)
- Manipulation Stereo Camera: Narrow-Angle Global Shutter Monochrome Stereo Ethernet (**NOT on SE**)
- LED Texture Projector Triggered with Narrow-Angle Stereo Camera (**NOT on SE**)

B Above the Shoulders

- Tilting Hokuyo UTM-30LX Laser Scanner
- Microstrain 3DM-GX2 IMU

C Forearm

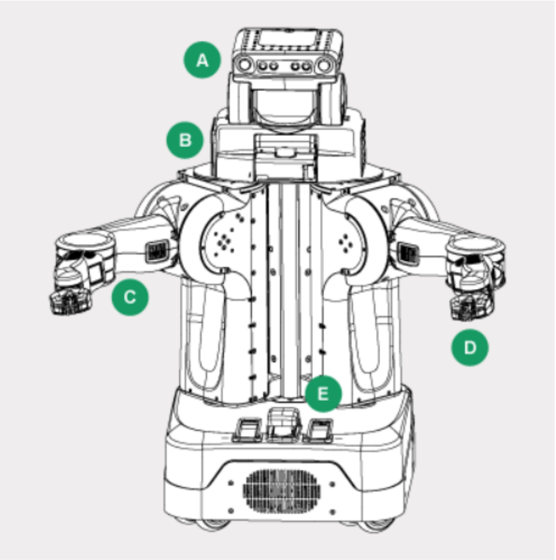
- Global Shutter Ethernet Camera

D Gripper

- Three-Axis Accelerometer
- Fingertip Pressure Sensor Arrays (**NOT on SE**)
- Calibration LED

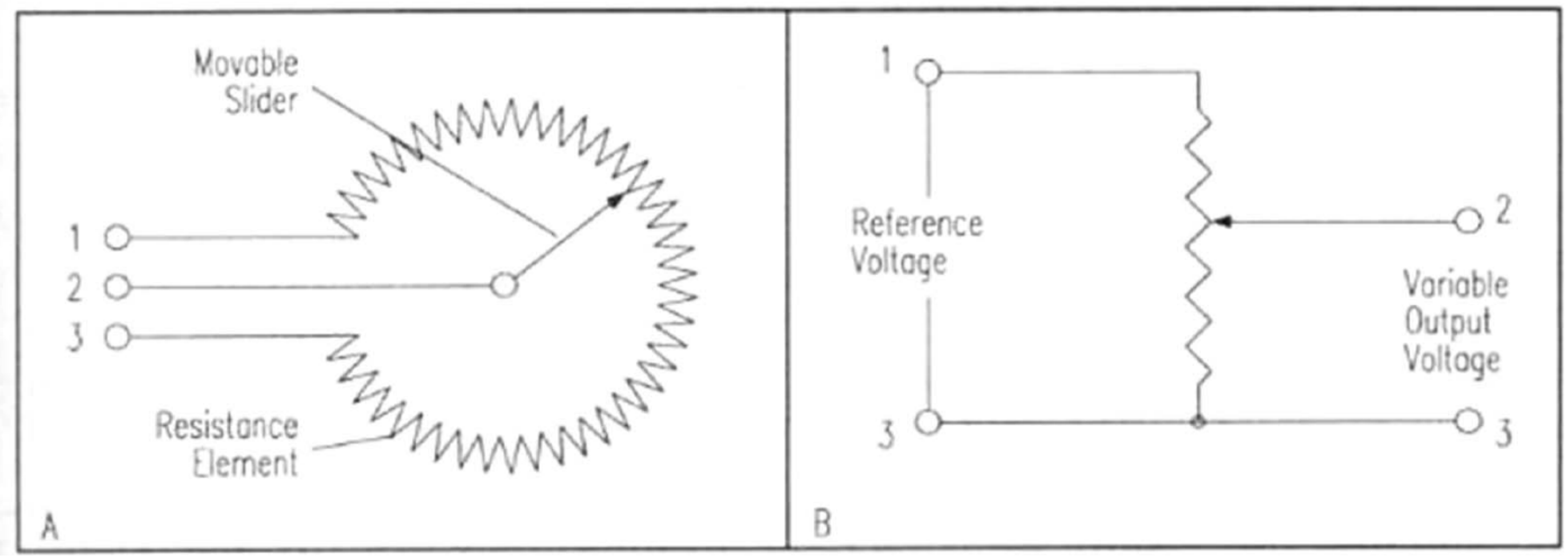
E Base

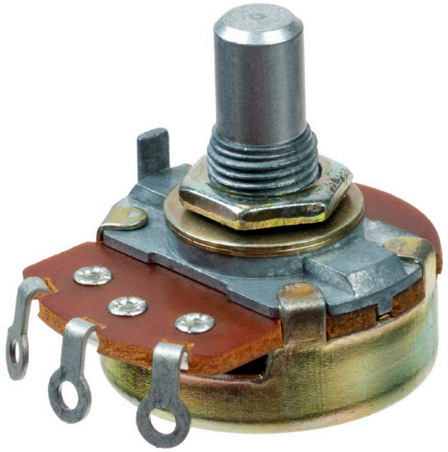
- Hokuyo UTM-30LX Laser Scanner



Position Sensor: Potentiometer

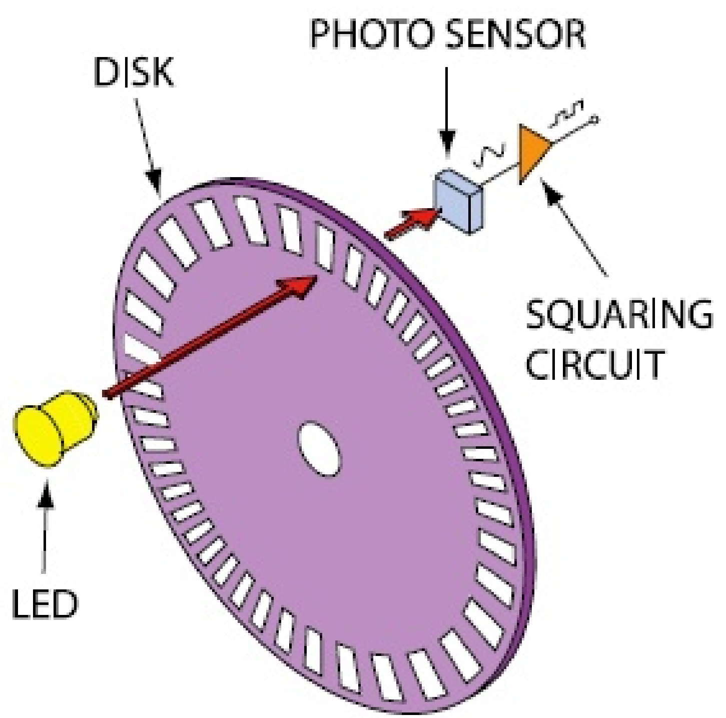
- A three-terminal resistor with a sliding or rotating contact that forms an adjustable voltage divider.
- Pros: Simple, cheap
- Cons: Frictions, noisy signal, nonlinearity





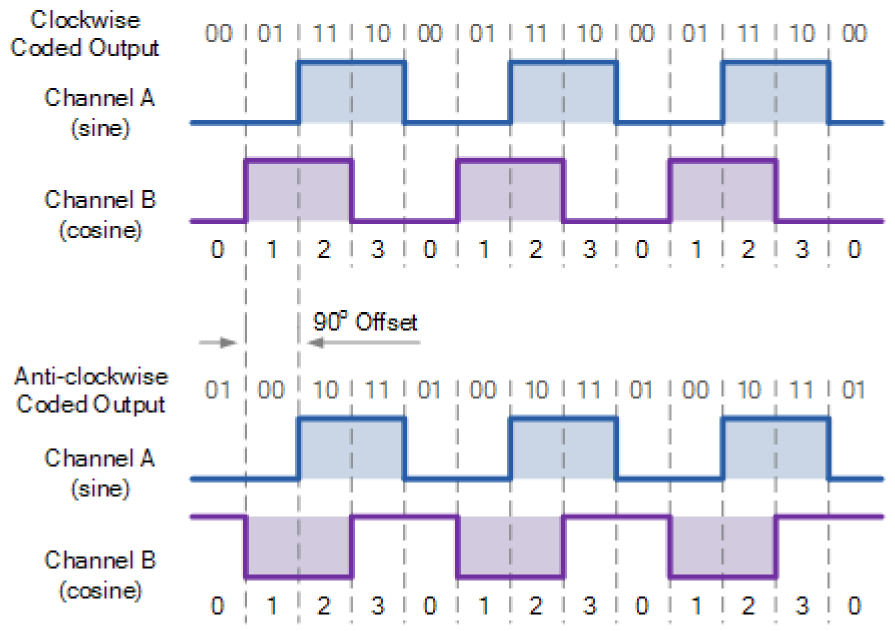
Position Sensor: Optical Encoder

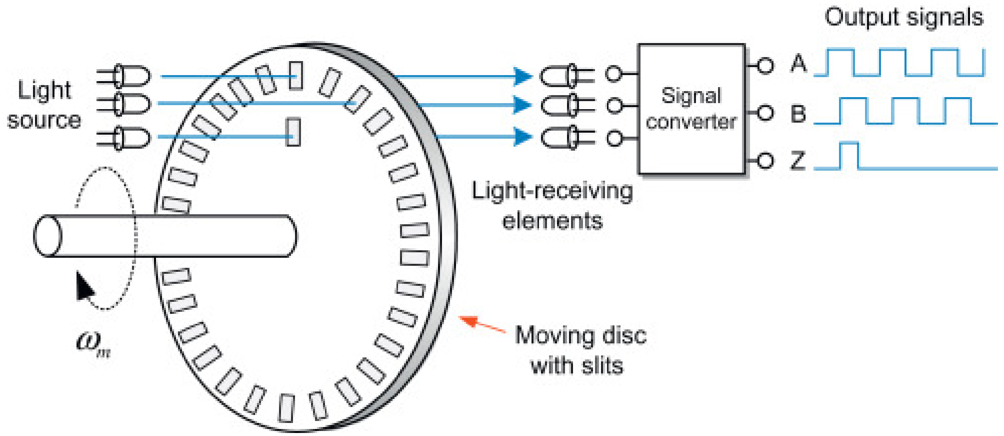
- An optical encoder is to measure the rotational position, speed and direction.
- It consists of a light beam, a light detector, and a rotating disc with slits.
- Optical encoder has become the most popular
  - Long life
  - Simple construction
  - Versatility
  - High accuracy and high resolution
- Typical resolutions of 2000 increments per revolution.
- Either relative or absolute

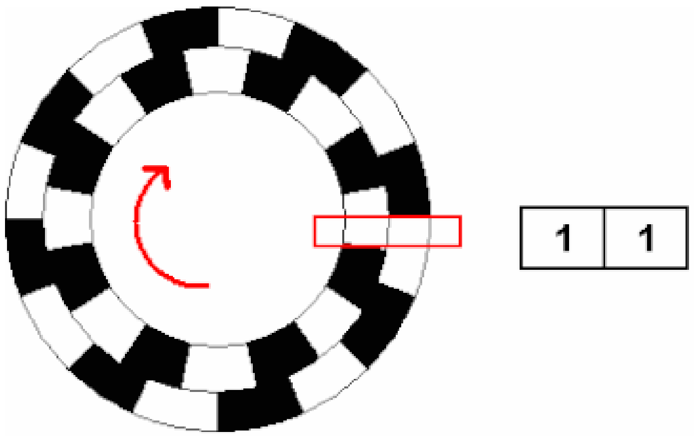


Incremental Encoder

- The rotary incremental encoder is the most widely used of all rotary encoders.
- An incremental encoder measures changes in position with two (or more) channels.
- The direction of rotation is determined by checking which phase of signals is leading.
  - If Phase A signals are leading, the rotation is in the clockwise direction.
  - If Phase B signals are leading, the rotation is the counterclockwise direction.





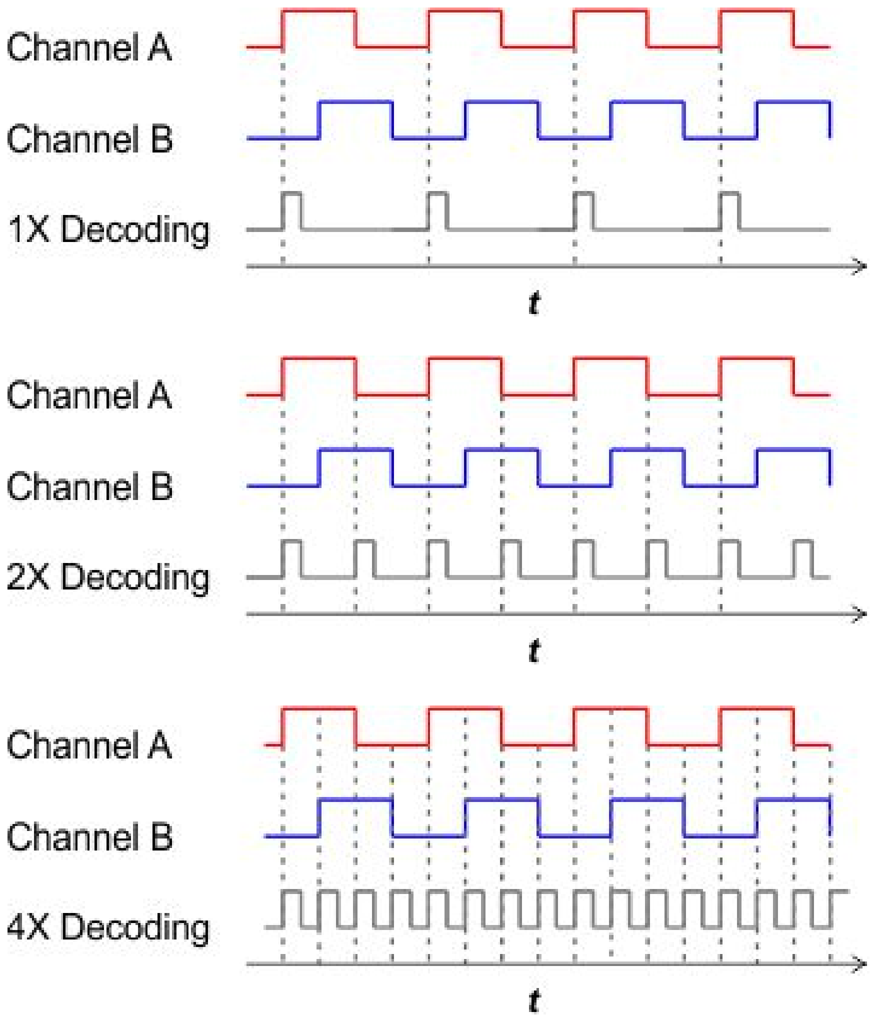


Incremental Encoder

- Resolution

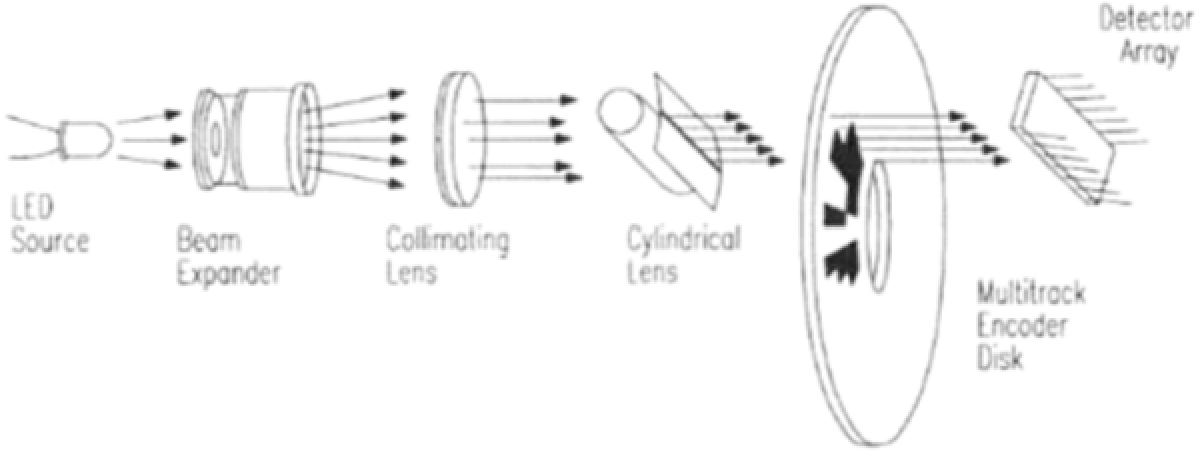
$$s = \frac{360^{\circ}}{Number\ of\ slits}$$

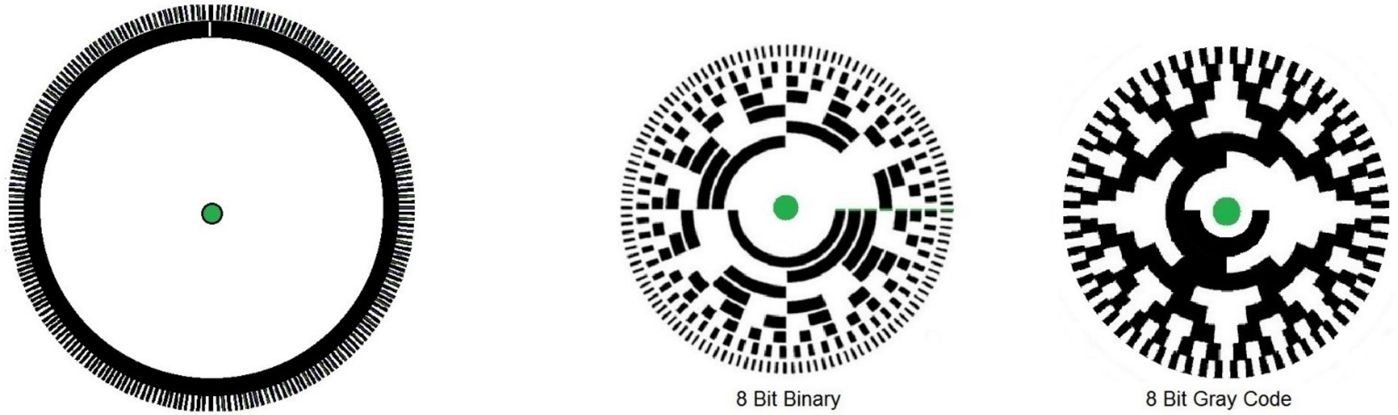
- The smaller is the resolution, the better is the measurement
- By counting the raising and falling edges, the resolution can be increased 4 times.



Absolute Optical Encoder

- Digital absolute encoders produce a unique digital code for each distinct angle of the shaft. An absolute encoder maintains position information when power is removed from the encoder.





Incremental Encoder

Absolute Encoder

Velocity Measurement

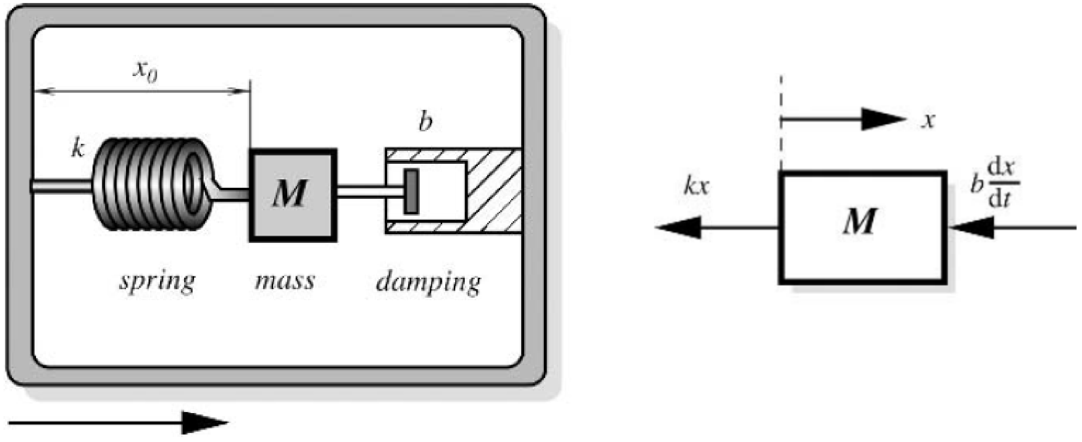
- Differentiate position

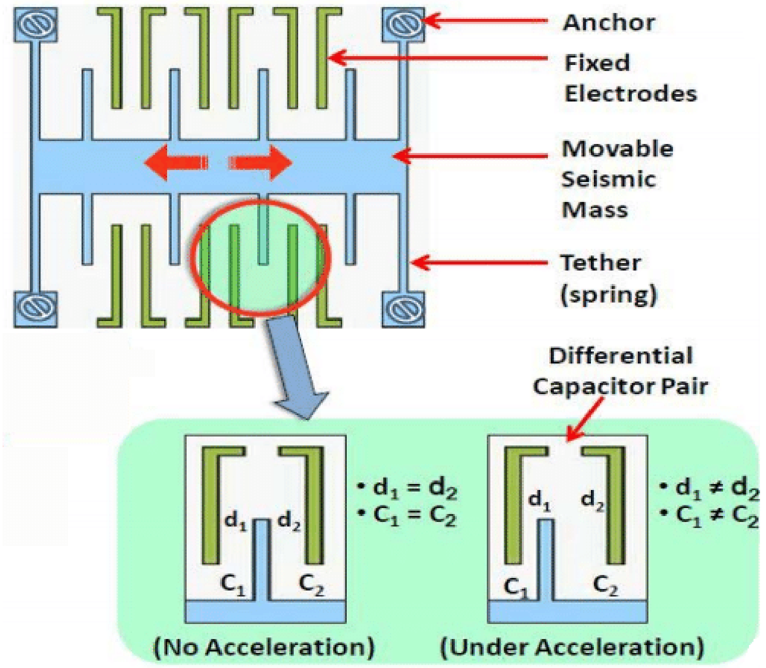
$$Velocity = \frac{\Delta Position}{\Delta Time}$$

- Advantages: measurement without additional sensors, simple calculation
- Problems: noisy signals
- Solution: filters (low-pass filter, Kalman filter, etc.)

Accelerometer

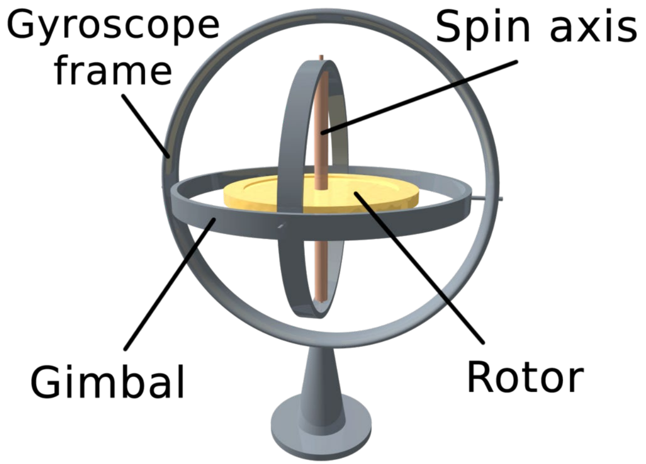
- Most of accelerometers are based on N ewton's second law. An accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced in the designed system. The displacement is then measured to give the acceleration.
- Sensing:
  - Piezoelectric
  - Capacitive
  - Magnetic
- Example: MEMS accelerometer

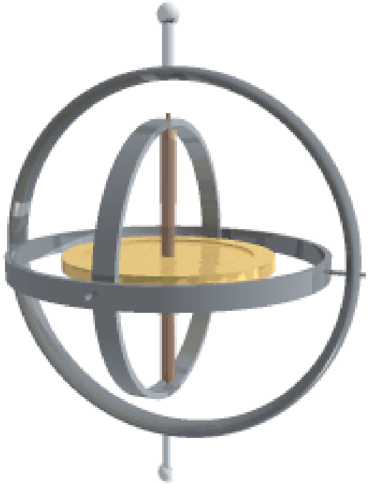




Gyroscopes

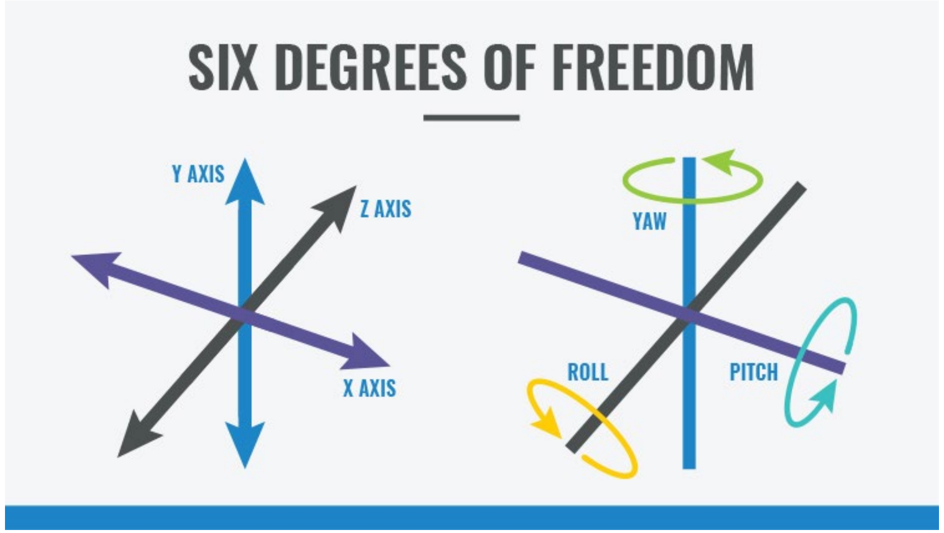
- A device used for measuring or maintaining orientation and angular velocity
- It is a spinning wheel or disc in which the axis of rotation (spin axis) is free to assume any orientation by itself. When rotating, the orientation of this axis is unaffected by tilting or rotation of the mounting, according to the conservation of angular momentum.
- Absolute measure for the heading of a mobile system

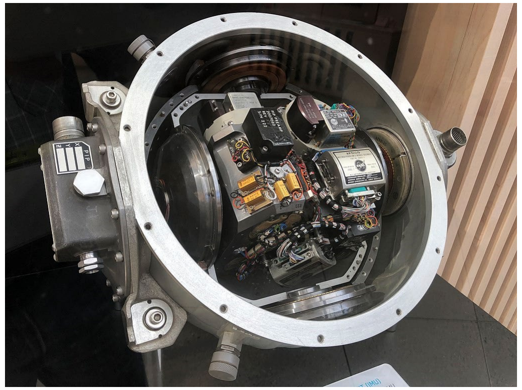


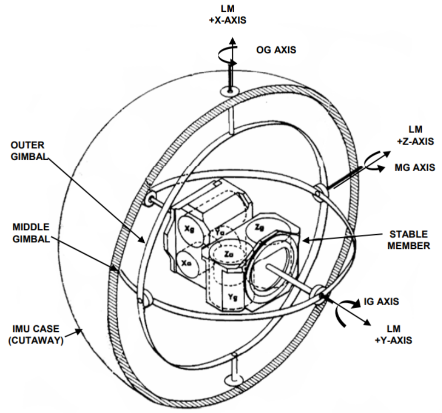


Inertial measurement unit (IMU)

- An electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers.



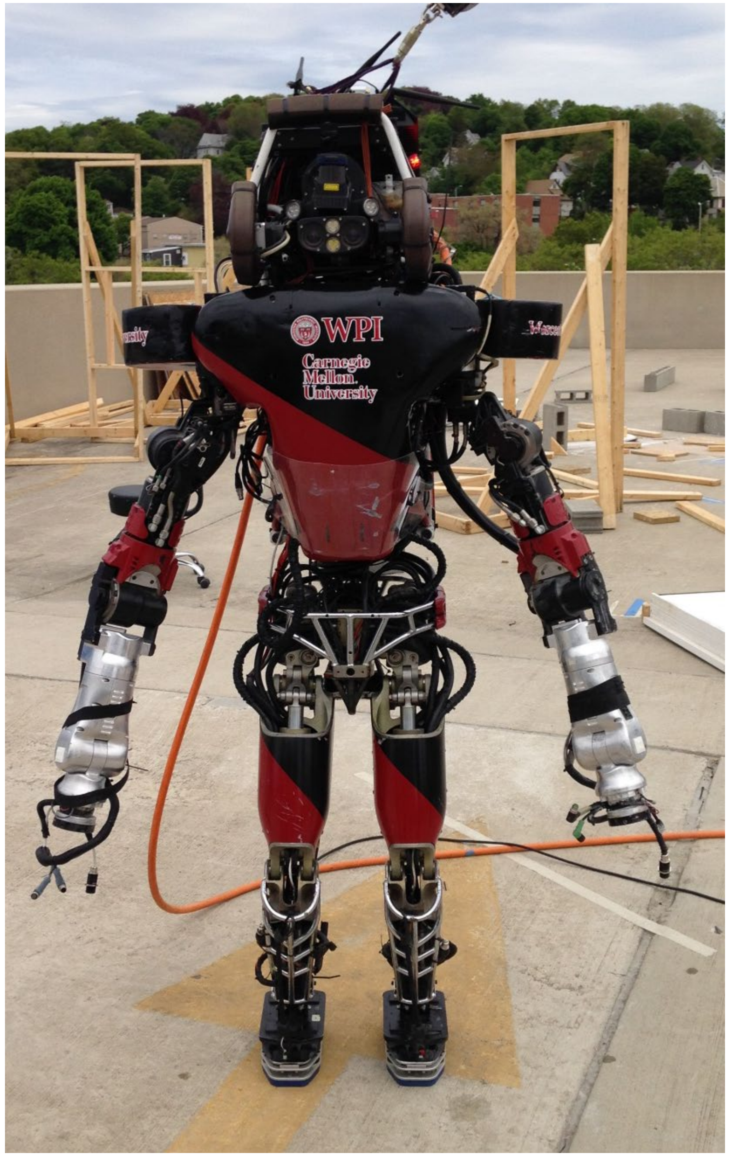




Robot Applications

The Atlas robot

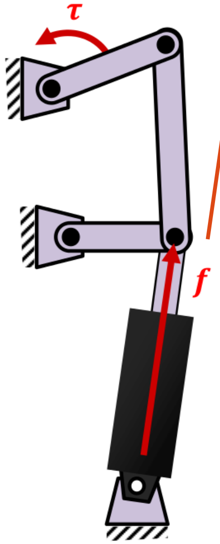
- Human size, 185 kg
- 30 DoF
  - 6 for each leg, 7 for each arm, 3 for the spine, 1 for neck pitch
- Mostly hydraulic actuators, electric forearms
- Onboard power and computing
- Joint servos controlled at 1 kHz



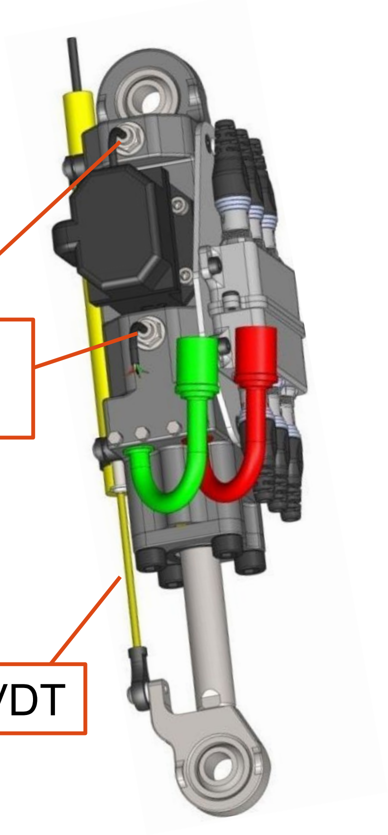
Onboard sensors

LiDAR
Stereo vision

Pelvis
IMU



Pressure
Sensors (2X)



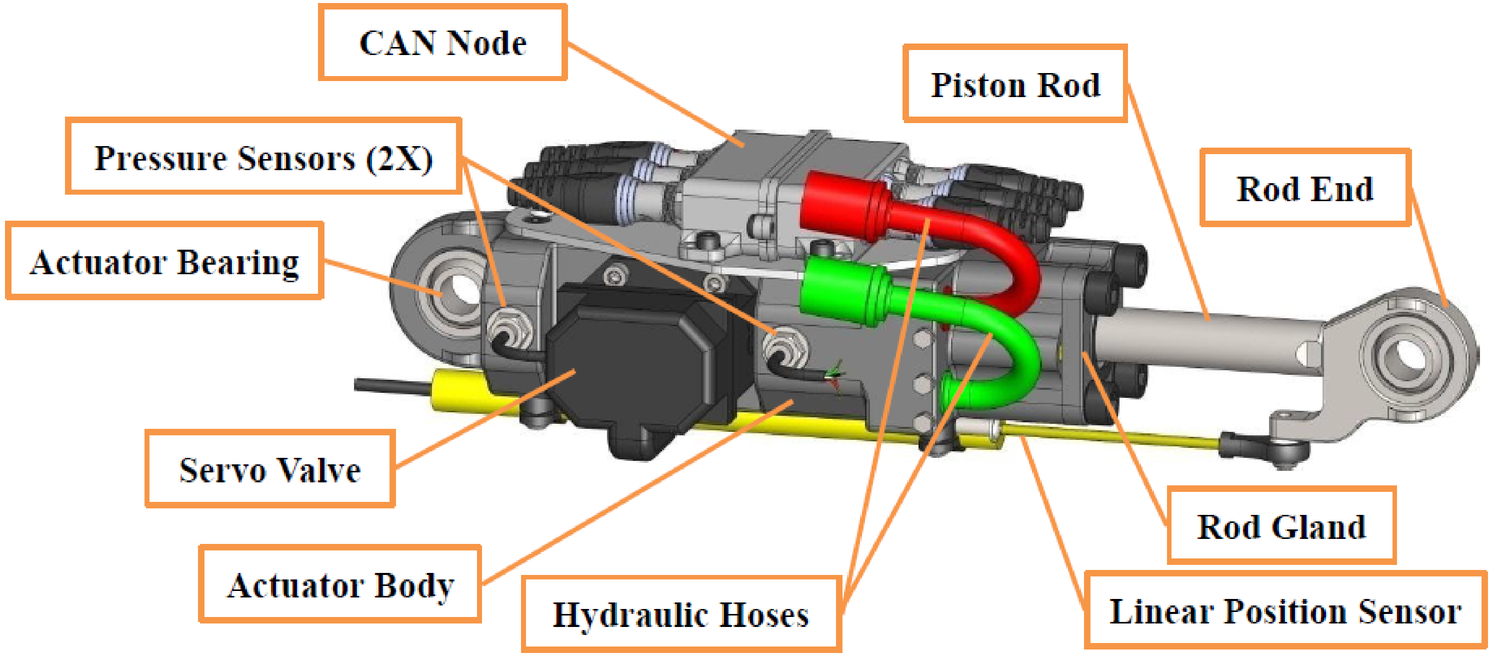
LVDT

3-axis F/T

F_z, M_x, M_y

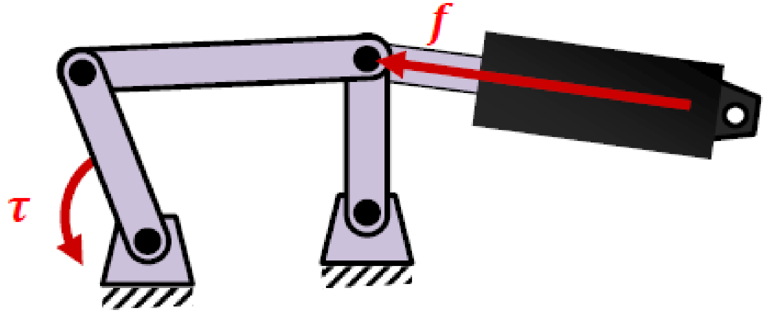
Actuator

- 15 linear actuators
- 13 rotary actuators (arms and Back Z)
- All hydraulic

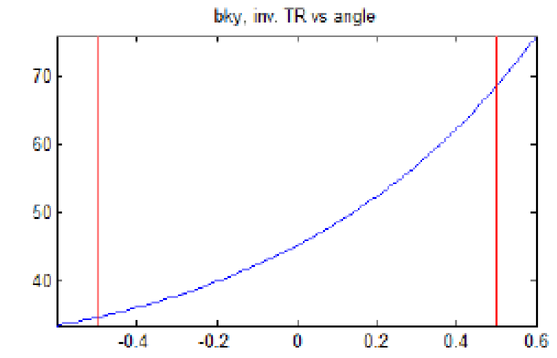


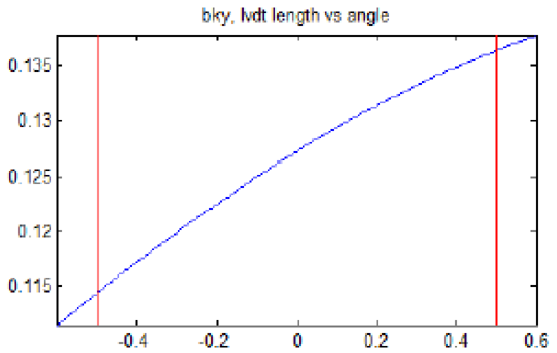
Joint Mechanism

- Linear actuators + mechanical transmission for most joints
  - Back z degree of freedom has rotary actuator
- High performance electrohydraulic servovalves
- Position sensing:
  - Linear variable differential transformer (LVDT)
  - MR encoder (back z)
  - Potentiometer (arms)
- Force sensing
  - Pressure sensors



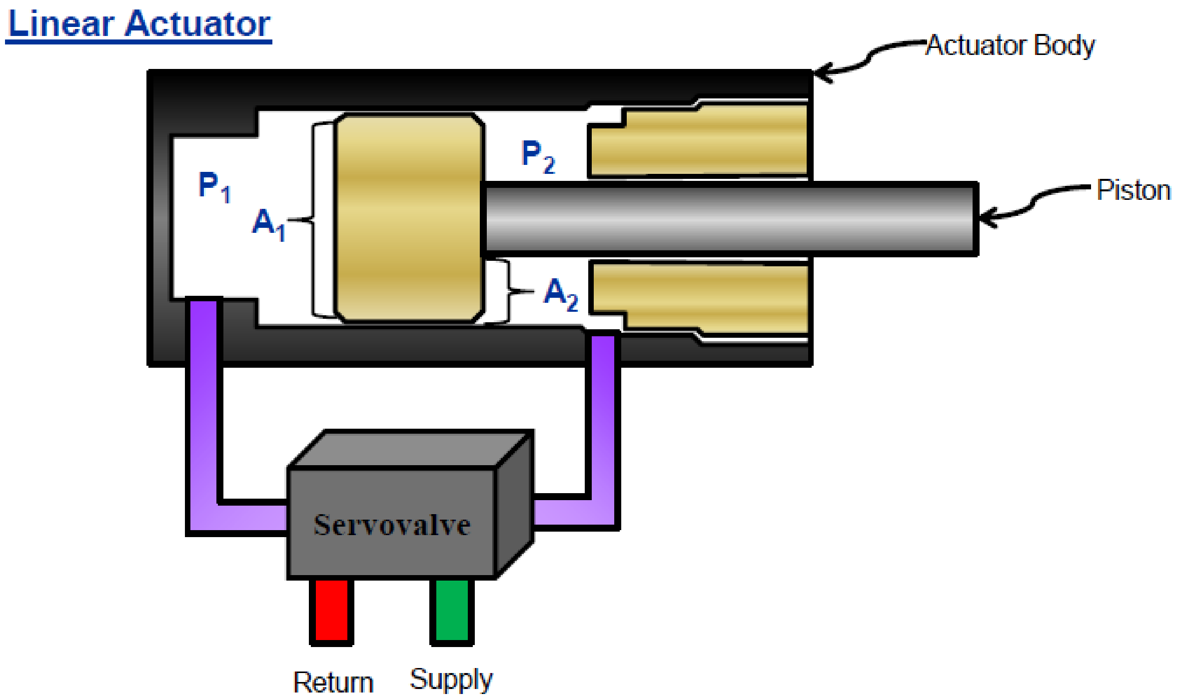
Typical 1 DoF joint





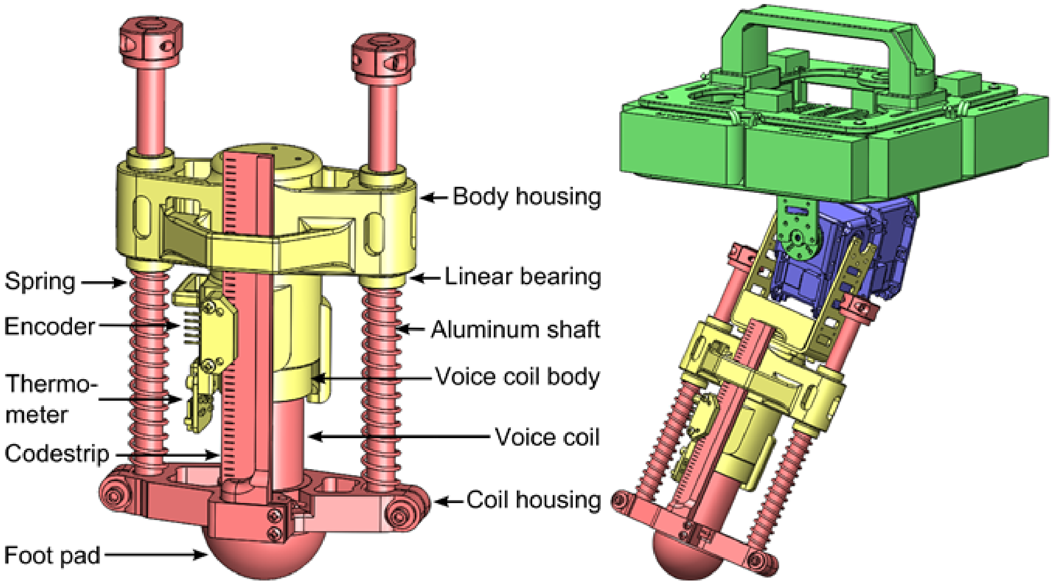
Joint Torque

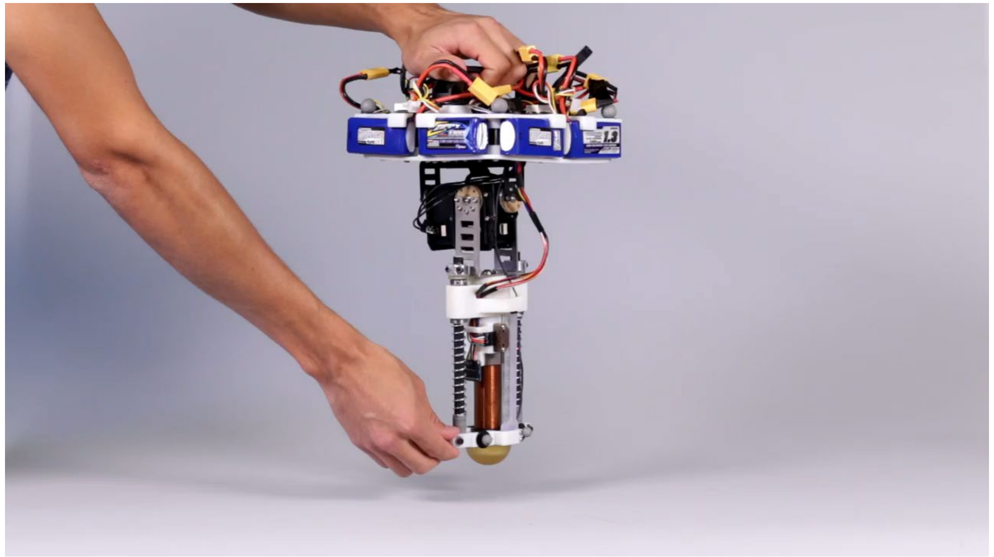
- Linear force, f, estimated via pressure sensors ($P_1 * A_1 - P_2 * A_2$)
  - $A_1 \neq A_2$, max. force is asymmetric
- Torque given by $\tau = f * TR$, where TR is the transmission ratio of the linkage
  - Max. torque is configuration dependent
  - Torque estimates do not take into account friction



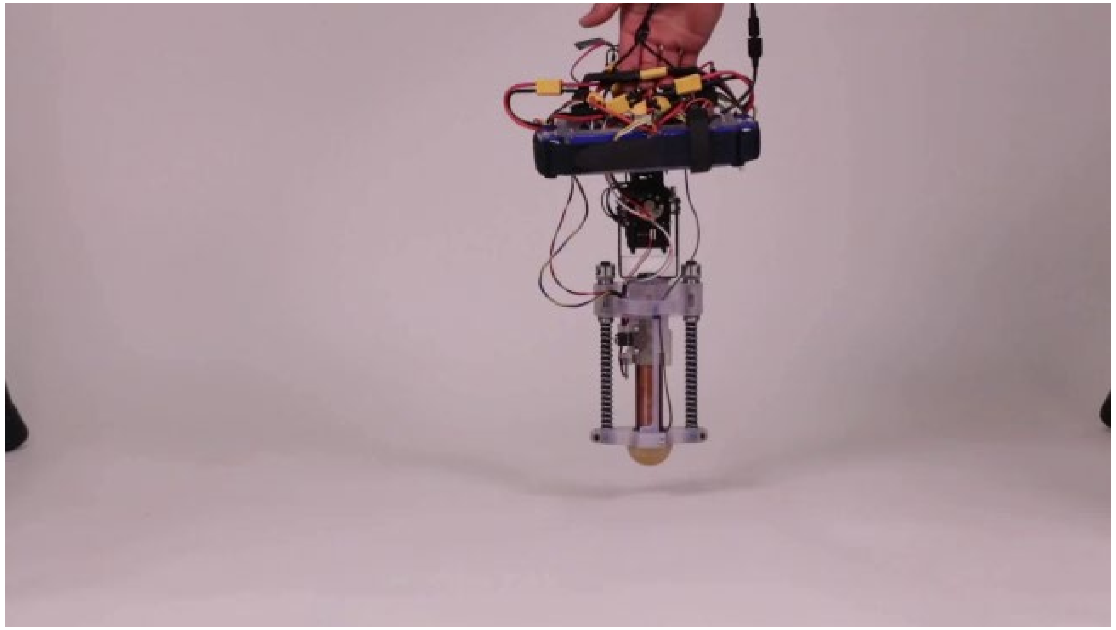
Hopping Robot

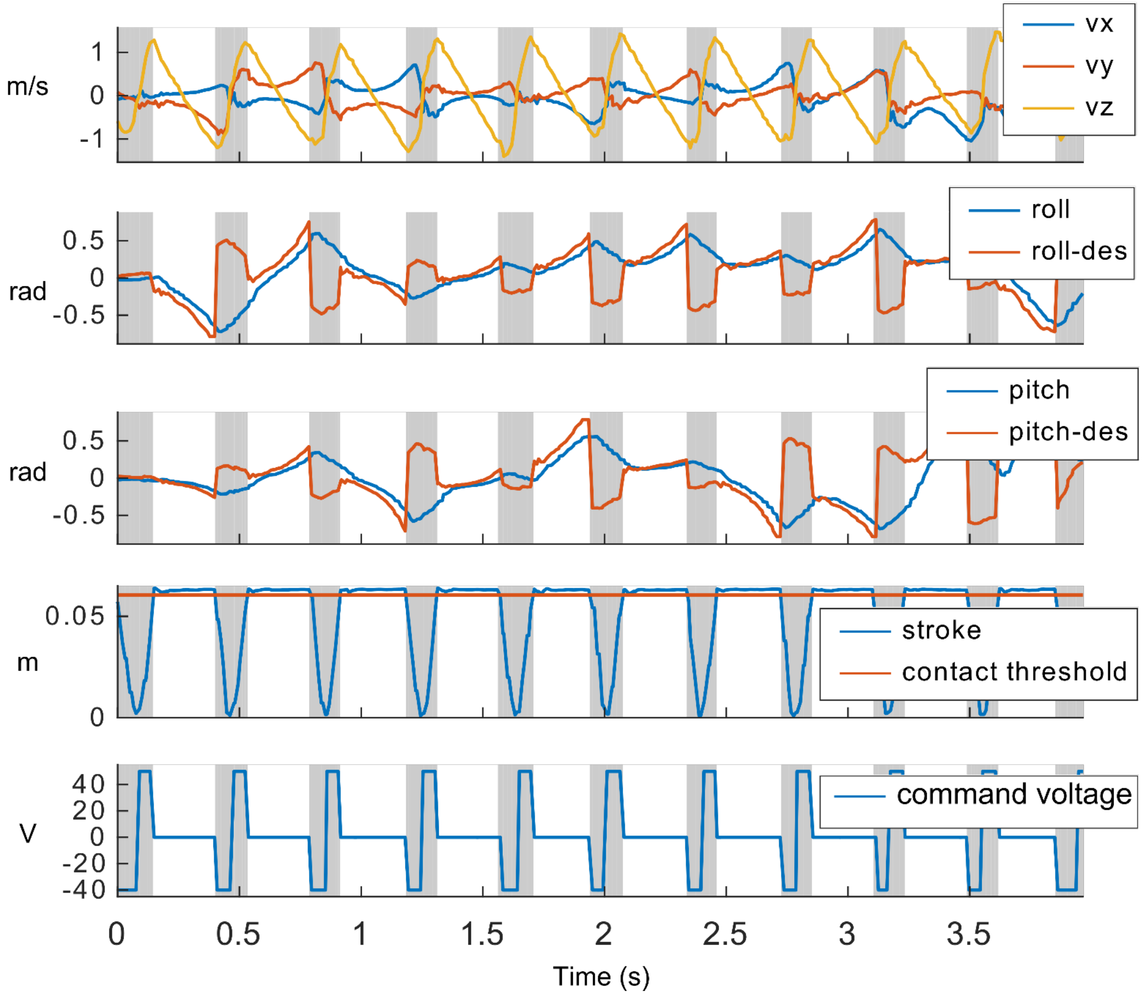
- LEAP mechanism
  - Stiffness (2060 N/m)
  - Increase input voltage (48V)
  - Temperature sensor
- Actuated gimbal hip
  - Two servo motors
- Components in “Torso”
  - Seven 11.1 V Li-Po Batteries
  - Microcontroller (TI LAUNCHXL-F28377S)
  - IMU (Xsens MTi-3- 8A7G6-DK)





Results





- Up to 11 hops
- Problems
  - Ignoring mass distribution
  - No “ground truth”

Difficulties in state estimation

- Data acquired
  - Vicon MX series (16 cameras, 120 fps)
  - Hand-held
  - Robot hopping