KTH ROYAL INSTITUTE OF TECHNOLOGY

Introduction to Robotics

DD2410

Lecture 5 - Actuators, Sensors I

Schedule - Lectures

Sep 02 - 1. Intro, Course fundamentals, Topics, What is a Robot, History, Applications.

Sep 03 - 2 ROS Introduction (Scheduled as lab, will be in zoom only)

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Oct 04 - 12. Navigation (how do I get from A to B?)

Oct 06 - Q/A - Open questions to your teachers.

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- Virtual work must be same independent of coordinates

$$\mathcal{F}^T \delta\chi = \tau^T \delta\Theta$$

- We remember that:

$$\delta\chi = J\delta\Theta$$

- Which gives us:

$$\mathcal{F}^T J = \tau^T$$

$$\tau = J^T \mathcal{F}$$

Jacobians for static forces

$$\tau = J^T \mathcal{F}$$

- We can now see that for singular configurations, there will be directions where the required torque for a given force goes to zero, or inversely, **the forces generated by a given torque tend to infinity**. This may cause damage to the robot or the environment.

Jacobians for static forces

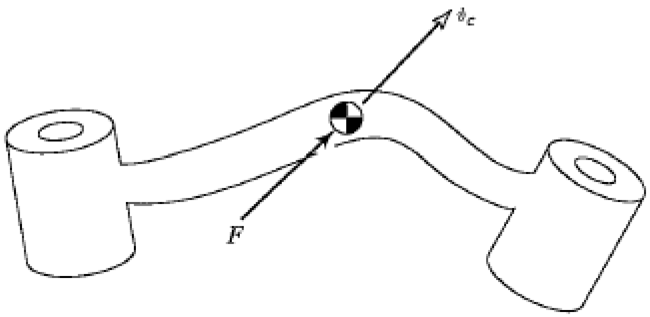
$$\tau = J^T \mathcal{F}$$

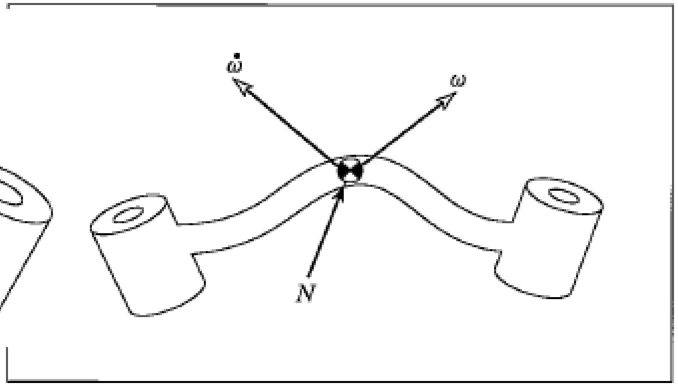
- We can also calculate inverse kinematics by virtual forces and torques. We apply a "force" correcting the end effector position, calculate the torques this would generate, and move the robot accordingly. This gives us the update step:

$$\epsilon_{\Theta} = J^T(\hat{\Theta})\,\epsilon_x$$

- This is useful when inverse of J does not exist, but typically converges slower.

Dynamics (R-MPC Chapter 7)





$$F = m\dot{v}_C,$$

$$N = {}^{C}I\dot{\omega} + \omega \times {}^{C}I\omega,$$

$${}^{A}I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix},$$

$$I_{xx} = \iiint_V (y^2 + z^2)\rho dv,$$

$$I_{yy} = \iiint_V (x^2 + z^2)\rho dv,$$

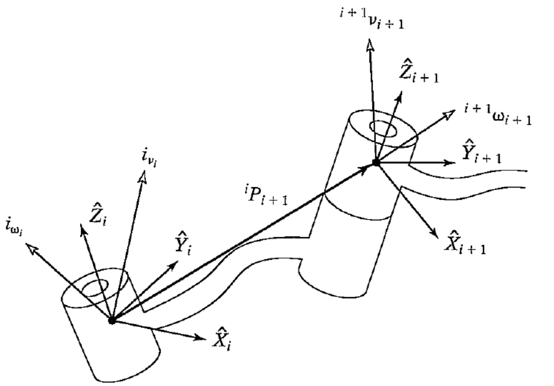
$$I_{zz} = \iiint_V (x^2 + y^2)\rho dv,$$

$$I_{xy} = \iiint_V xy\rho dv,$$

$$I_{xz} = \iiint_V xz\rho dv,$$

$$I_{yz} = \iiint_V yz\rho dv,$$

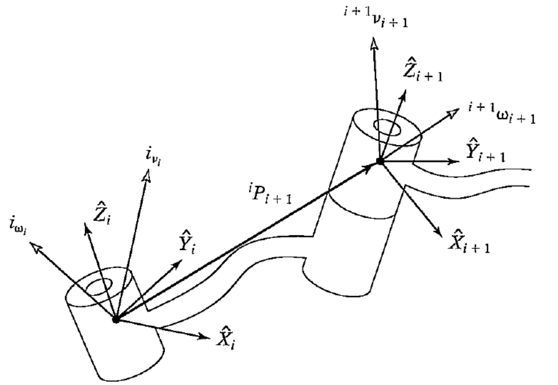
Dynamics (R- MPC chapter 7) - Rotational joints



$$^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_i + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}$$

$$^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_i + {}^{i}\omega_i \times {}^{i}P_{i+1})$$

Dynamics (R- MPC chapter 7) - Rotational joints



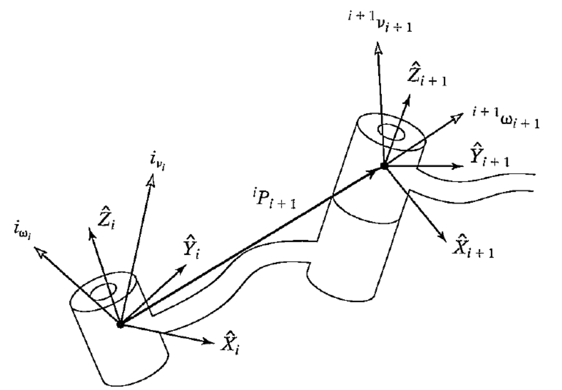
$${}^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_{i} + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}$$

$${}^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1})$$

$${}^{i+1}\dot{\omega}_{i+1} = {}^{i+1}_{i}R\,{}^{i}\dot{\omega}_{i} + {}^{i+1}_{i}R\,{}^{i}\omega_{i} \times \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} + \ddot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}.$$

$${}^{i+1}\dot{v}_{i+1} = {}^{i+1}_{i}R[{}^{i}\dot{\omega}_{i} \times {}^{i}P_{i+1} + {}^{i}\omega_{i} \times ({}^{i}\omega_{i} \times {}^{i}P_{i+1}) + {}^{i}\dot{v}_{i}]$$

Dynamics (R-MPC chapter 7) - Prismatic joints



$$ {}^{i+1}\omega_{i+1} = {}^{i+1}_{i}R\,{}^{i}\omega_{i}, $$

$$ {}^{i+1}v_{i+1} = {}^{i+1}_{i}R({}^{i}v_{i} + {}^{i}\omega_{i} \times {}^{i}P_{i+1}) + \dot{d}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} $$

$$ {}^{i+1}\dot{\omega}_{i+1} = {}^{i+1}_{i}R\,{}^{i}\dot{\omega}_{i}. $$

$$ \begin{aligned} {}^{i+1}\dot{v}_{i+1} = {}^{i+1}_{i}R({}^{i}\dot{\omega}_{i} \times {}^{i}P_{i+1} + {}^{i}\omega_{i} \times ({}^{i}\omega_{i} \times {}^{i}P_{i+1}) + {}^{i}\dot{v}_{i}) \\ + 2\,{}^{i+1}\omega_{i+1} \times \dot{d}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} + \ddot{d}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} \end{aligned} $$

$$ {}^{i}\dot{v}_{C_i} = {}^{i}\dot{\omega}_{i} \times {}^{i}P_{C_i} + {}^{i}\omega_{i} \times ({}^{i}\omega_{i} + {}^{i}P_{C_i}) + {}^{i}\dot{v}_{i} $$

Newton - Euler approach:

- Find the acceleration and velocity of each joint, working outwards

- Find the necessary torque/force to generate that acceleration, adding the external forces and torques, working inwards

Dynamics

Outward iterations: $i : 0 \rightarrow 5$

$$
\begin{aligned}
{}^{i+1}\omega_{i+1} &= {}^{i+1}_{i}R\,{}^{i}\omega_i + \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}, \\
{}^{i+1}\dot{\omega}_{i+1} &= {}^{i+1}_{i}R\,{}^{i}\dot{\omega}_i + {}^{i+1}_{i}R\,{}^{i}\omega_i \times \dot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1} + \ddot{\theta}_{i+1}\,{}^{i+1}\hat{Z}_{i+1}, \\
{}^{i+1}\dot{v}_{i+1} &= {}^{i+1}_{i}R({}^{i}\dot{\omega}_i \times {}^{i}P_{i+1} + {}^{i}\omega_i \times ({}^{i}\omega_i \times {}^{i}P_{i+1}) + {}^{i}\dot{v}_i), \\
{}^{i+1}\dot{v}_{C_{i+1}} &= {}^{i+1}\dot{\omega}_{i+1} \times {}^{i+1}P_{C_{i+1}} \\
&\quad + {}^{i+1}\omega_{i+1} \times ({}^{i+1}\omega_{i+1} \times {}^{i+1}P_{C_{i+1}}) + {}^{i+1}\dot{v}_{i+1}, \\
{}^{i+1}F_{i+1} &= m_{i+1}\,{}^{i+1}\dot{v}_{C_{i+1}}, \\
{}^{i+1}N_{i+1} &= {}^{C_{i+1}}I_{i+1}\,{}^{i+1}\dot{\omega}_{i+1} + {}^{i+1}\omega_{i+1} \times {}^{C_{i+1}}I_{i+1}\,{}^{i+1}\omega_{i+1}.
\end{aligned}
$$

Inward iterations: $i : 6 \rightarrow 1$

$$
\begin{aligned}
{}^{i}f_i &= {}^{i}_{i+1}R\,{}^{i+1}f_{i+1} + {}^{i}F_i, \\
{}^{i}n_i &= {}^{i}N_i + {}^{i}_{i+1}R\,{}^{i+1}n_{i+1} + {}^{i}P_{C_i} \times {}^{i}F_i \\
&\quad + {}^{i}P_{i+1} \times {}^{i}_{i+1}R\,{}^{i+1}f_{i+1}, \\
\tau_i &= {}^{i}n_i^T\,{}^{i}\hat{Z}_i.
\end{aligned}
$$

The resulting dynamic equations can be written on the form (state-space equation):

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) + J^T f$$

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Oct 06 - Q/A - Open questions to your teachers.

- Actuation
  - Motors, other types
  - Geometry, transmissions
  - Electronics
- Sensing
  - Proprioception
  - Forces/torques, tactile
  - Sensorless estimation

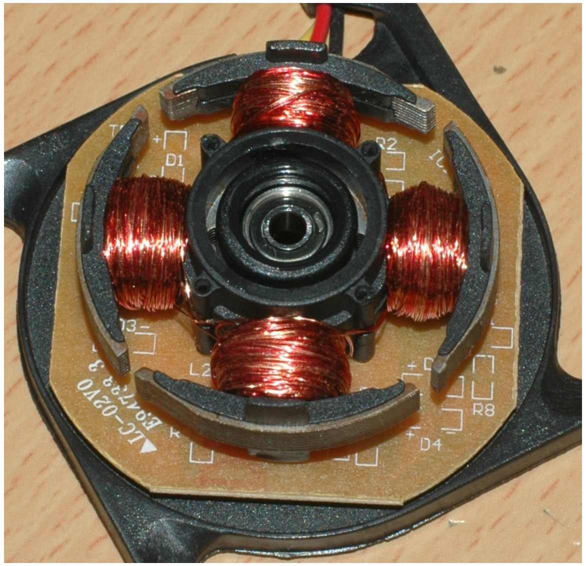
Actuation types

- Electric motors
  - Easy to control, very precise
  - Most common in robotic manipulators
- Pneumatics
  - Inherently compliant
  - Silent, non-magnetic
- Hydraulics
  - Very powerful
  - Good at static forces/torques

Actuation types

- Simple servo motors
- Cheap
- Go to commanded position

- Brushless motors
  - Good static torque, but may overheat
  - Torque decreases approx. linearly with rotational velocity
  - Available in wide range of power ratings, for a given design, peak output power is limited by heat.
  - Torque is proportional to current
  - 1~10 kW/kg



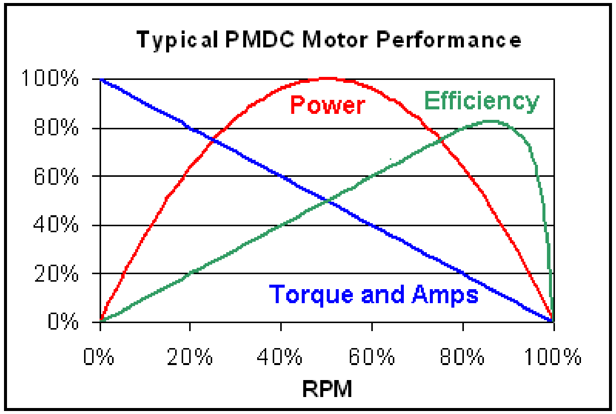
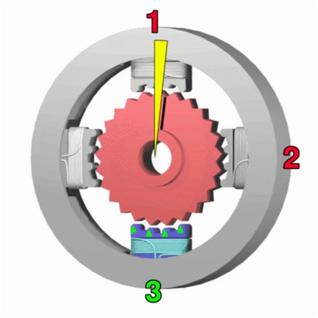


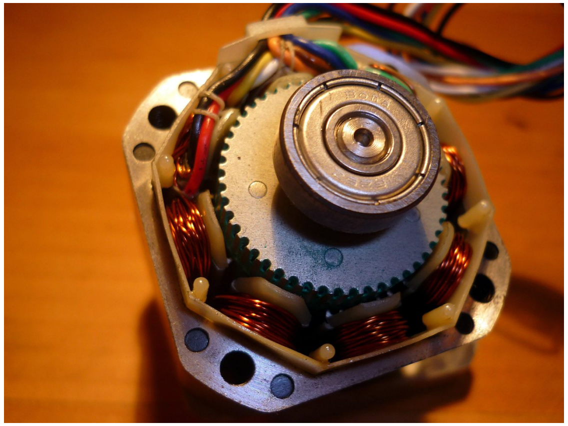
Image credit: The Electric Chronicles
https://evmc2.wordpress.com/2014/07/21/electric-motor-power-really-simple-and-hp-ratings/

Actuation - electric motors

- Brushless motors + water cooling

- Stepper motors
  - Can be advanced in "ticks"
  - Typically makes a characteristic noise





- Hardware:
  - Each motor is driven by analog signals, and must be powered by a motor driver unit.

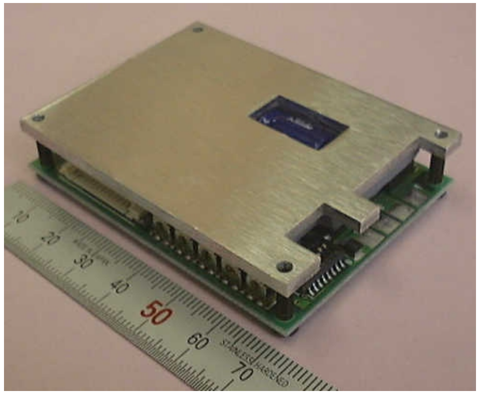
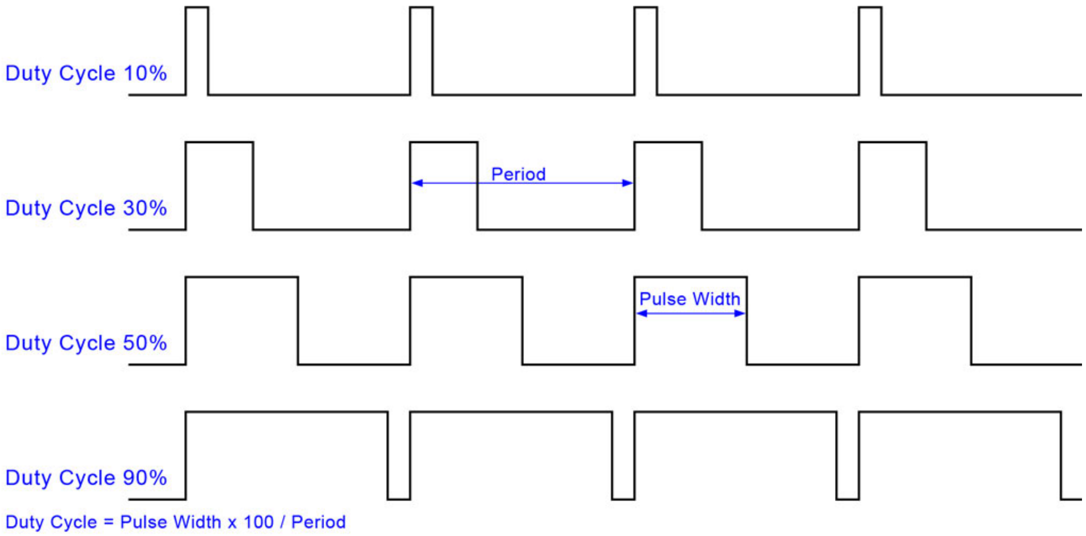


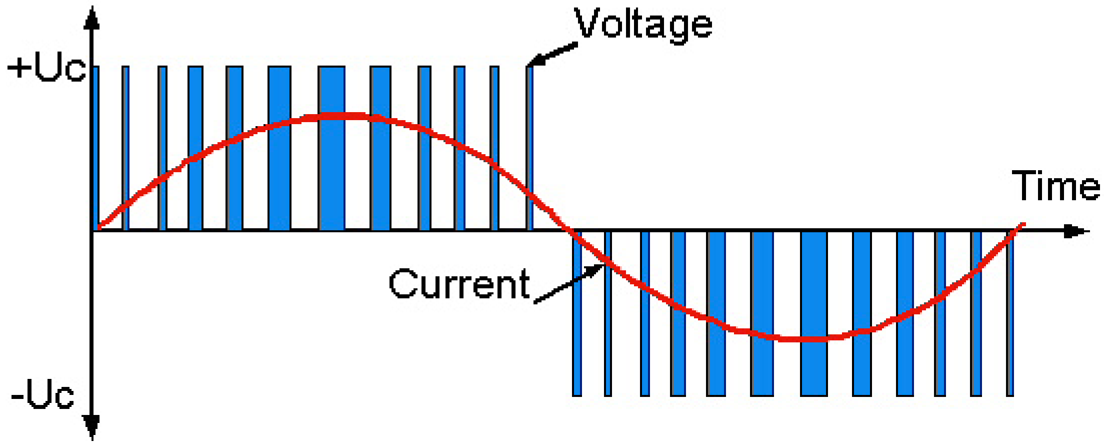
Image: TiTech motor driver v.2

Actuation - electric motors

- Pulse width modulation - PWM



- Pulse width modulation - PWM
  - Typical frequencies for motors are in the 1~10 kHz range.
  - Motor acts as low-pass filter (inductor coil + mass)



Actuation - transmission

- Direct drive is not always possible - we need transmissions
- Typical reduction ratios are 50:1 ~ 300:1

- Transmission issues:
  - Motor inertia is multiplied by square of ratio, potentially largest dynamic factor

If gear ratio is **a,** and motor inertia around axis is $\mathbf{I_a}$, the inertia $\mathbf{I_l}$ in the link frame will be

$$\mathbf{I_l = a^2 * I_a}$$

- Transmission issues:
  - Backlash

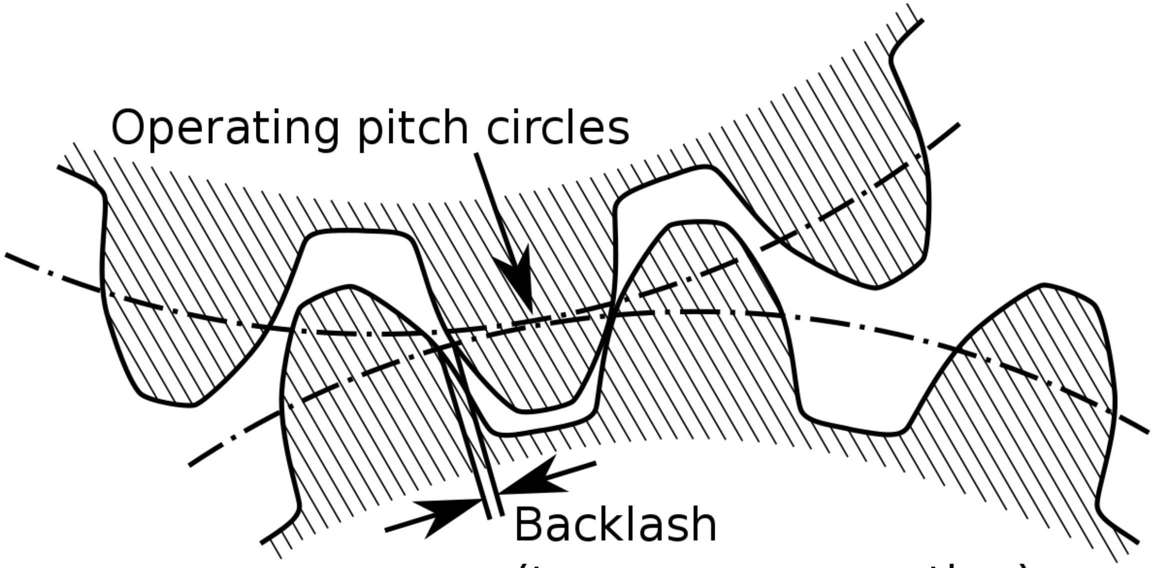
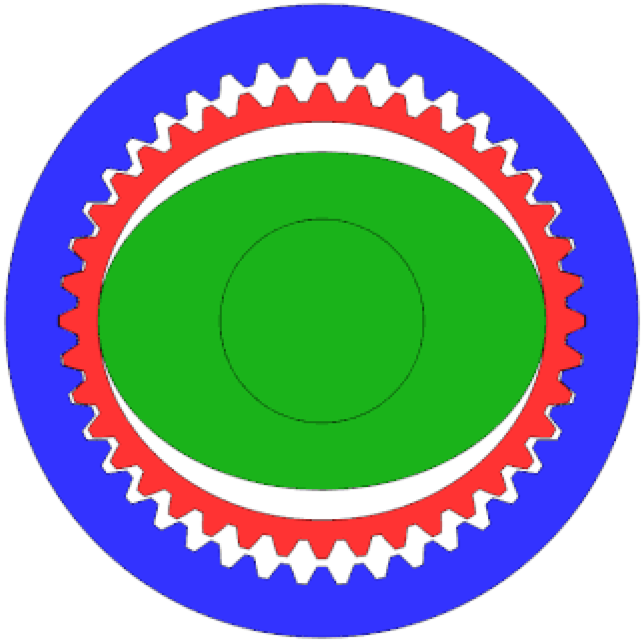


Image: Wikimedia - user Slashme

- Harmonic Drive - strain wave gearing (SWG)



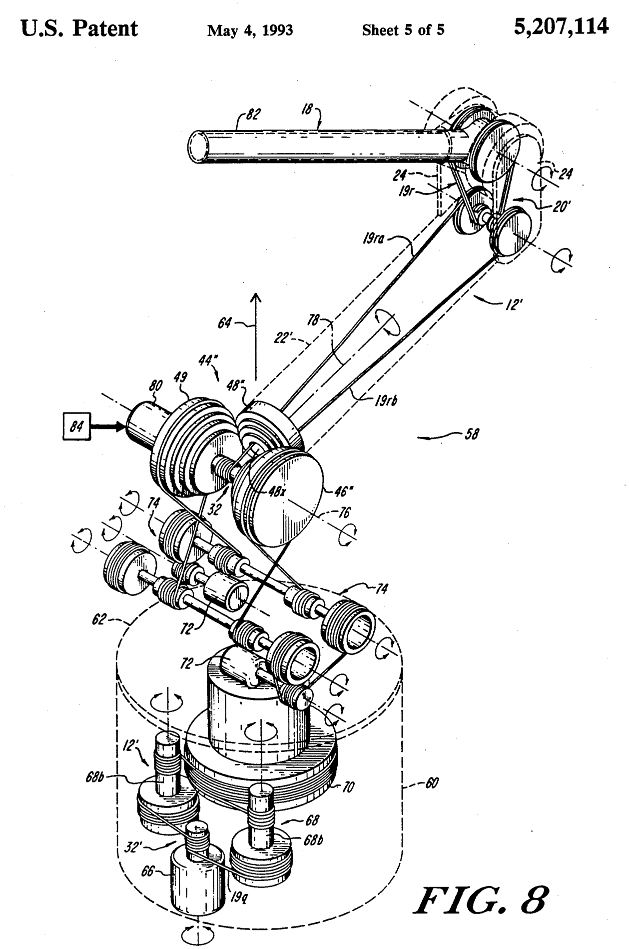
- Geometric design issues, placement of motors and drivers
  - Motors (+ gears) place mass further out in kinematic chain, requiring more power.
  - Cables
    - Each motor requires min. 2 cables (power)
    - Each driver requires min. 4 cables (power + data), but these can be shared
    - Difficult to pass multiple cables through joints

Motor and driver placements

Image: ABB

Image: KUKA

Motor and driver placements



- Torques can be measured as cable load.
- Cable may need retightening frequently

Image: Barrett Technology

- Pneumatics
  - Inherently compliant
  - Silent
  - Compressor and/or tank can be located far from actuator cylinder
  - High power per weight at actuator
  - Non-electric, non-magnetic
  - Cheap and simple

Actuation - Fluids

- Pneumatics

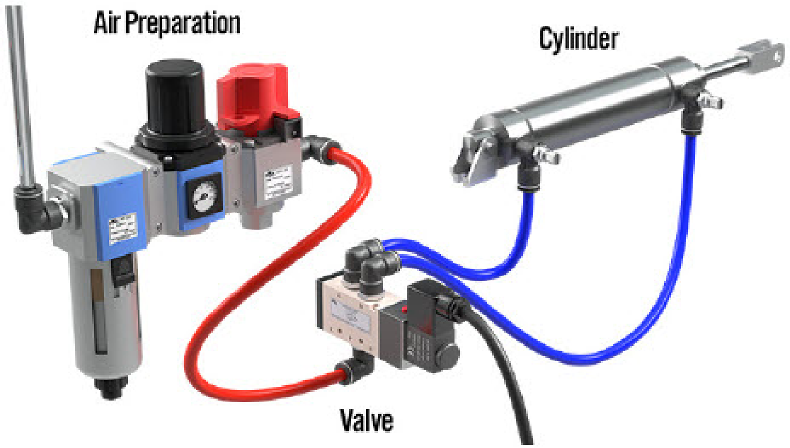


Figure 1C : Basic pneumatic system

Actuation - Pneumatics

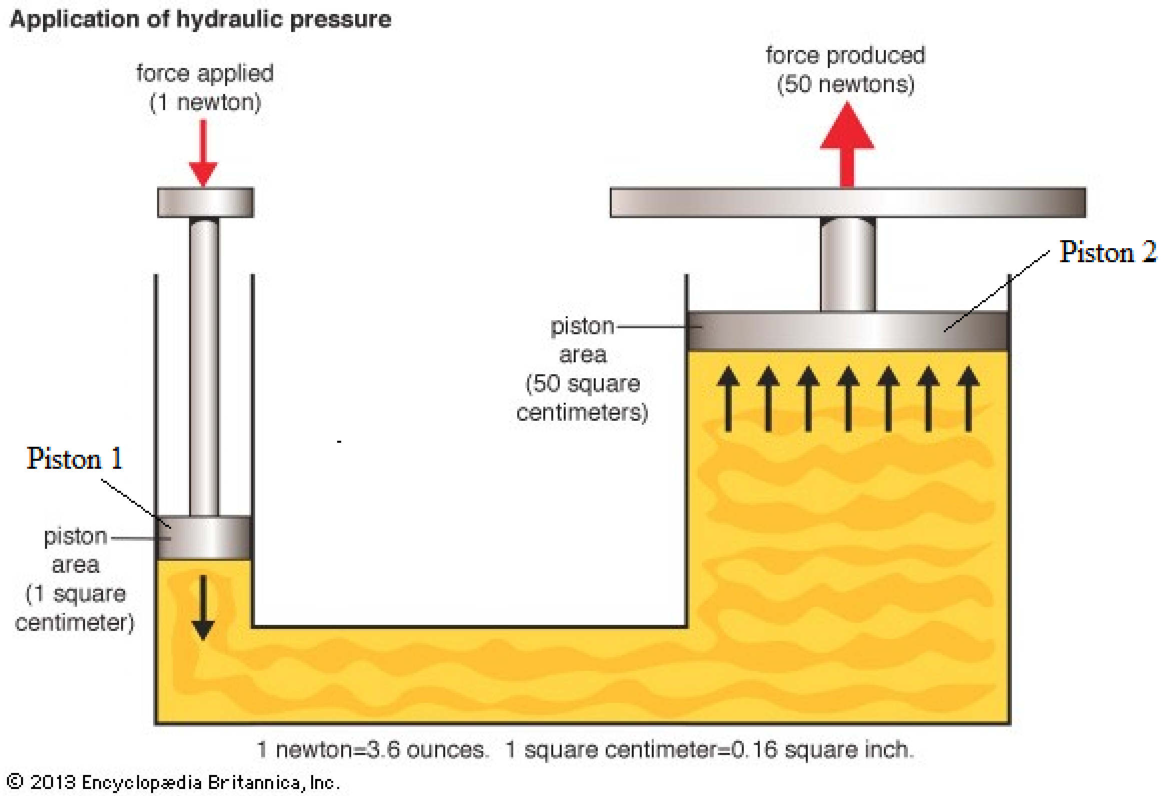
Video: Kokoro LTD

Actuation - Fluids

- Hydraulics
  - Very powerful per mass
  - Good for static loads
  - Dirty
  - Slow
  - Challenging to control

Actuation - Hydraulics

Actuation - Hydraulics

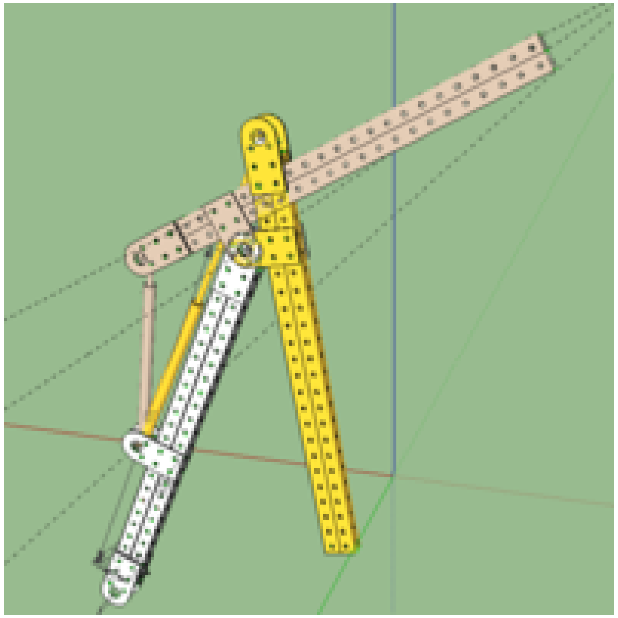


Up to 3 kN per cm^2 in actual systems

Actuation - Hydraulics

Applicable torque depends on the configuration

$\boldsymbol{\tau} = \mathbf{F} \times \mathbf{r}$



Actuation - Hydraulics

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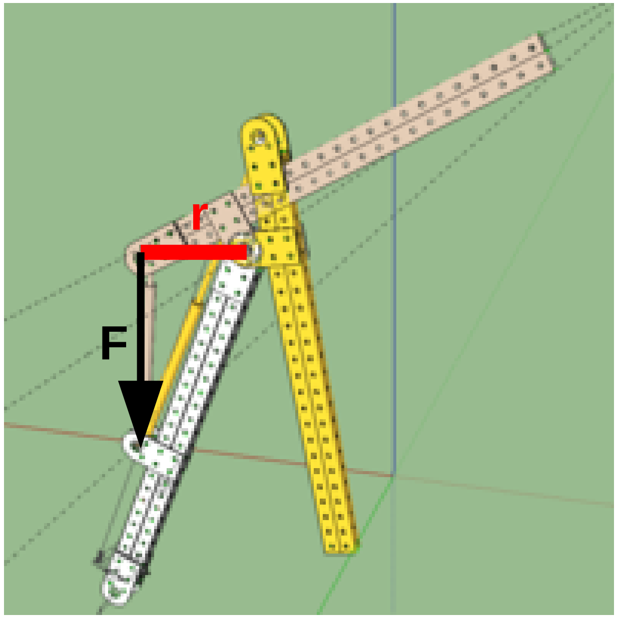

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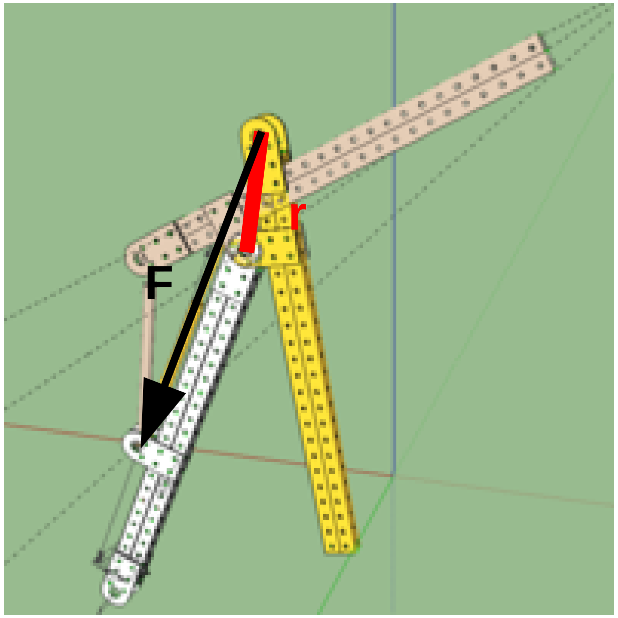


Actuation

Characteristics	Pneumatic	Hydraulic	Electric
Complexity	Simple	Medium	Medium/High
Peak power	High	Very high	High
Size	Low size/force	Very low size/force	Medium size/force
Control	Simple valves	Simple valves	Electronic controller
Position accuracy	Good	Good	Better
Speed	Fast	Slow	Fast
Purchase cost	Low	High	High
Operating cost	Medium	High	Low
Maintenance cost	Low	High	Low
Utilities	Compressor/power/ pipes	Pump/power/ pipes	Power only
Efficiency	Low	Low	High
Reliability	Excellent	Good	Good
Maintenance	Low	Medium	Medium

Table 1A: Linear Power Transmission Comparison

Actuation - others

- Actuation
  - artificial muscle
  - passive actuation (only braking)

Actuation - others

- Artificial muscles
  - piezo
  - pneumatic

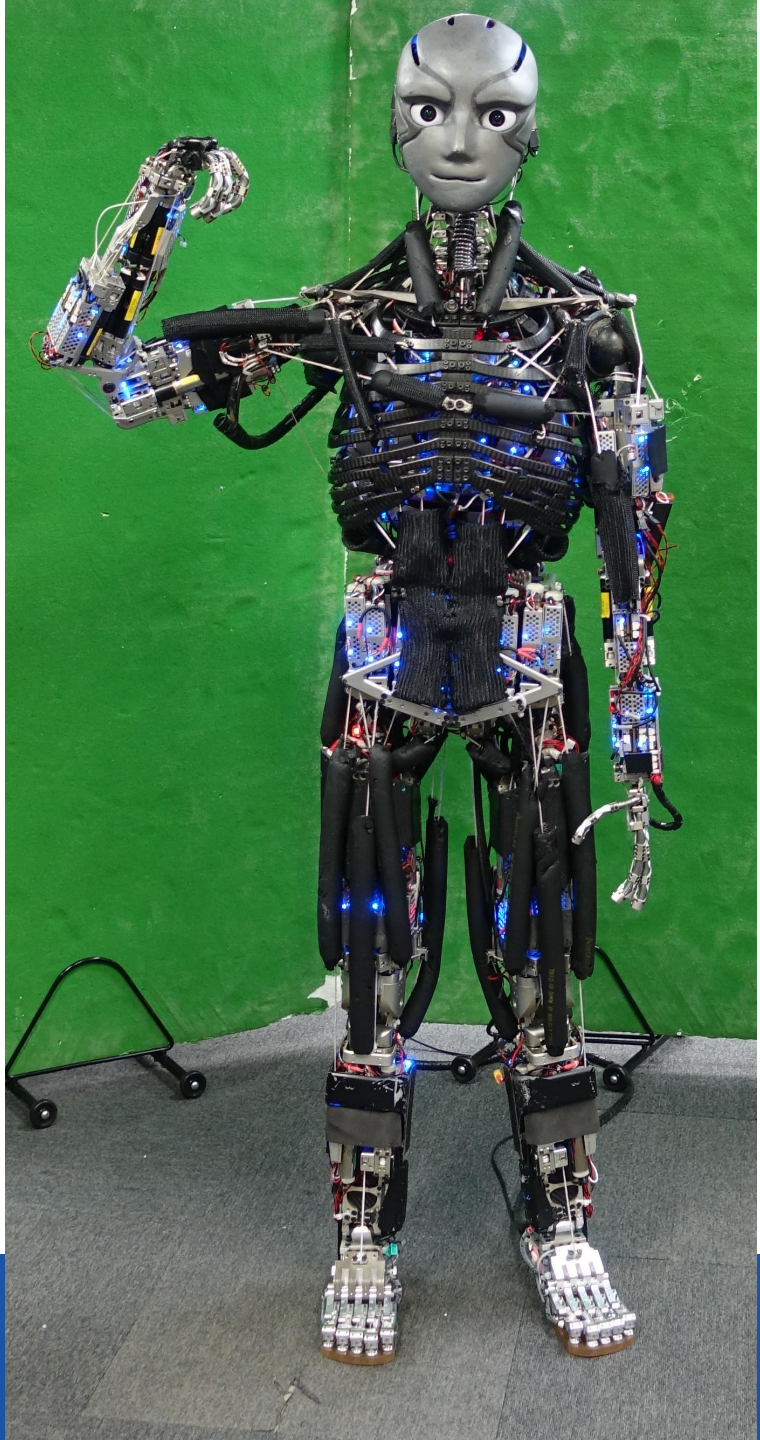
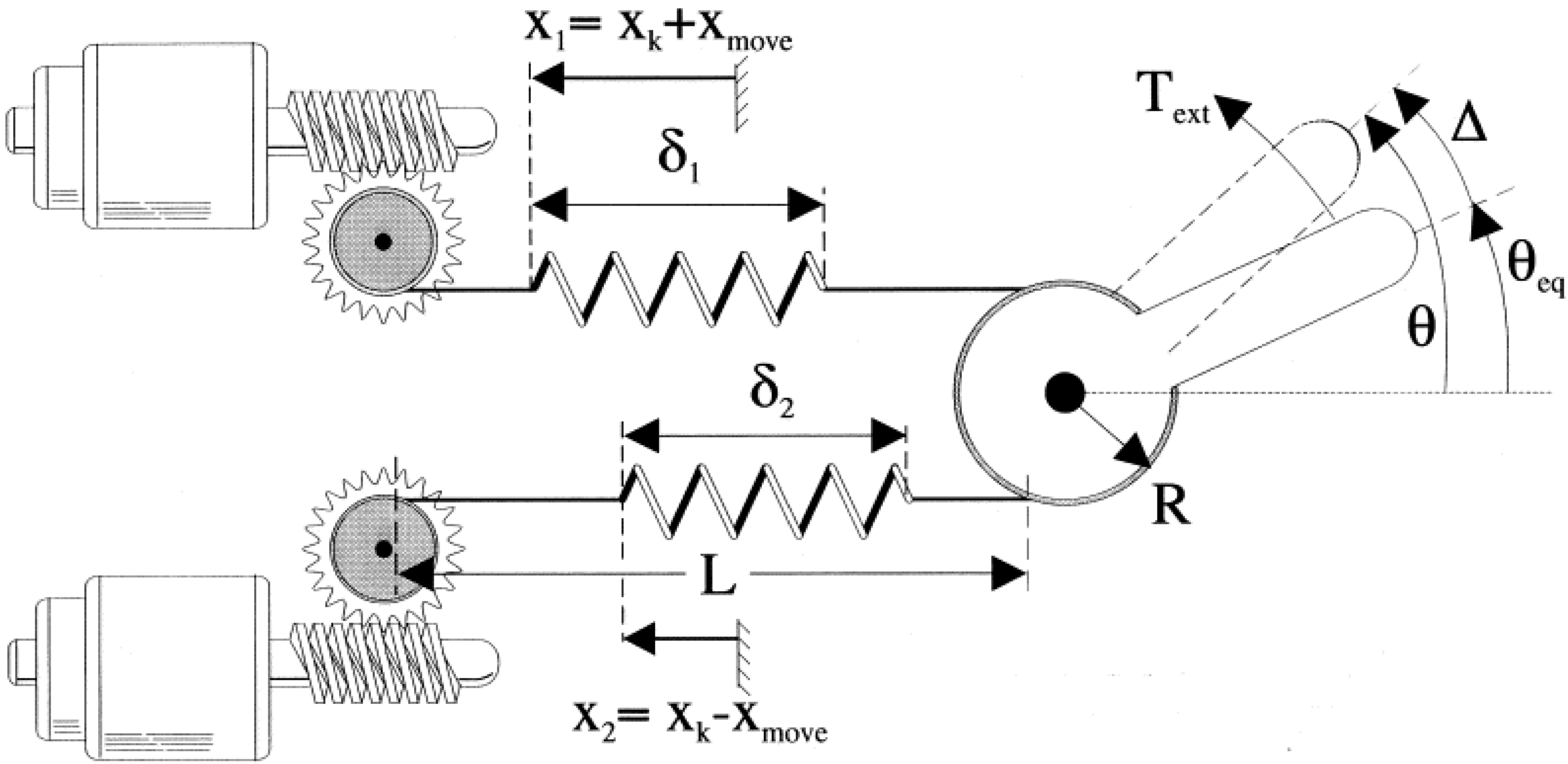


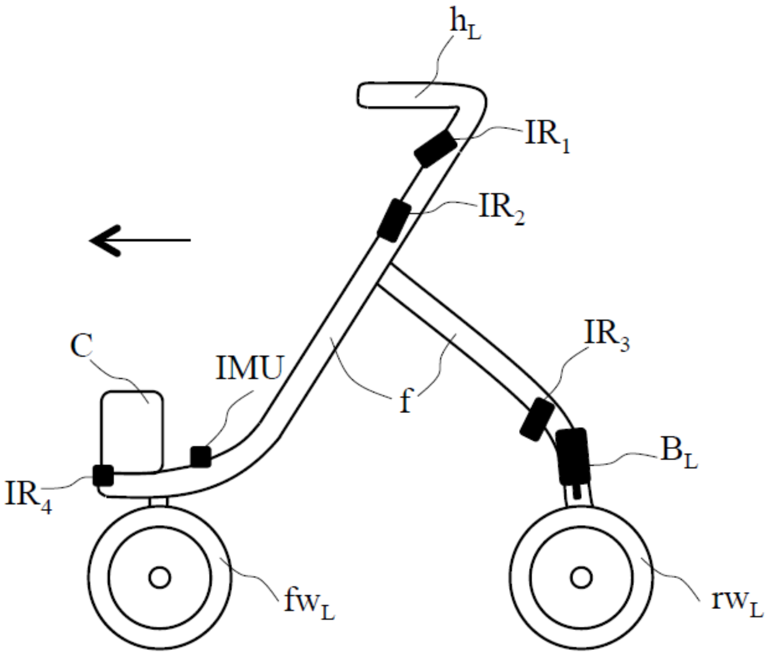
Image: Kengoro

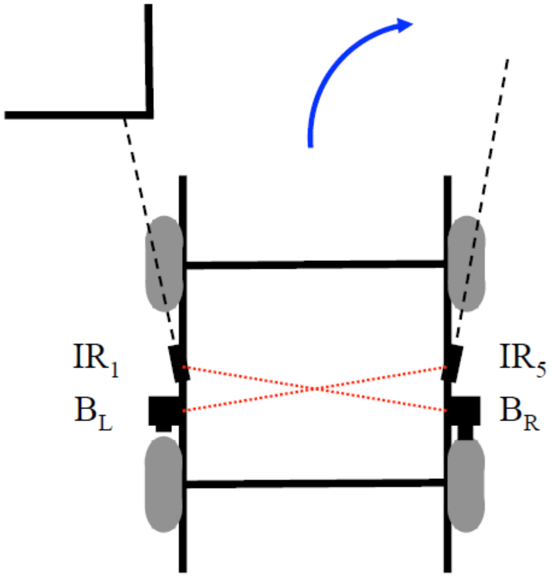
Antagonistic actuators



Antagonistic actuators

Steering by braking





Thomas Hellström, *An intelligent rollator with steering by braking*, Department of Computing Science Umeå University

Sensing

- Proprioceptive sensing
  - Pose
  - Force/torque
  - Effort, Voltage, Current
  - Tactile
  - Temperature

Sensing

- Encoders
  - Sense joint position/angle

Encoders

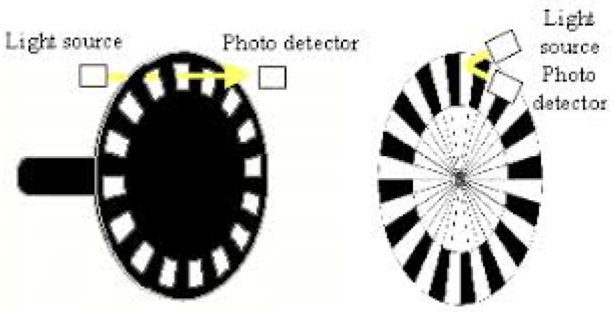
- Potentiometer
  - Resistance is function of position

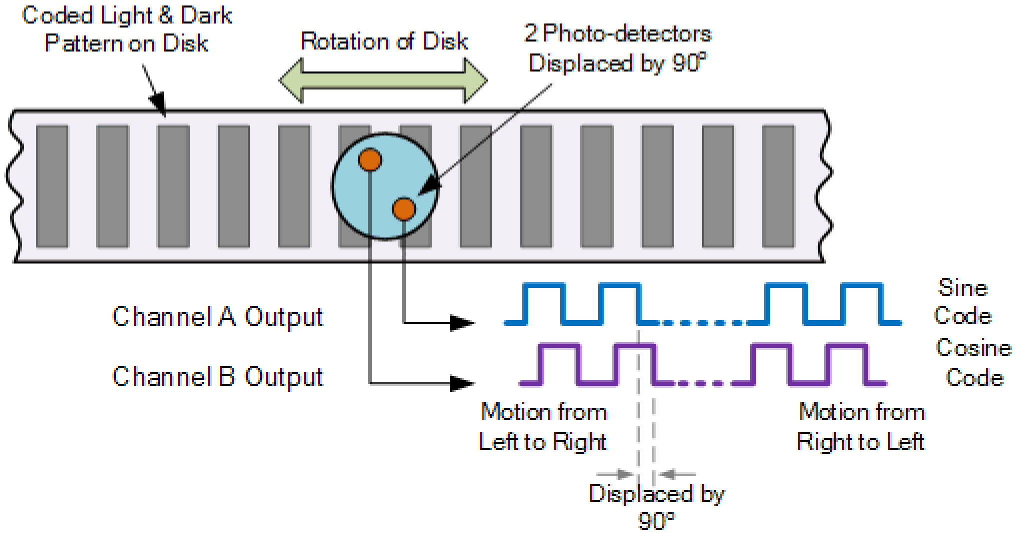
Potentiometer

Encoders

- Optical encoders

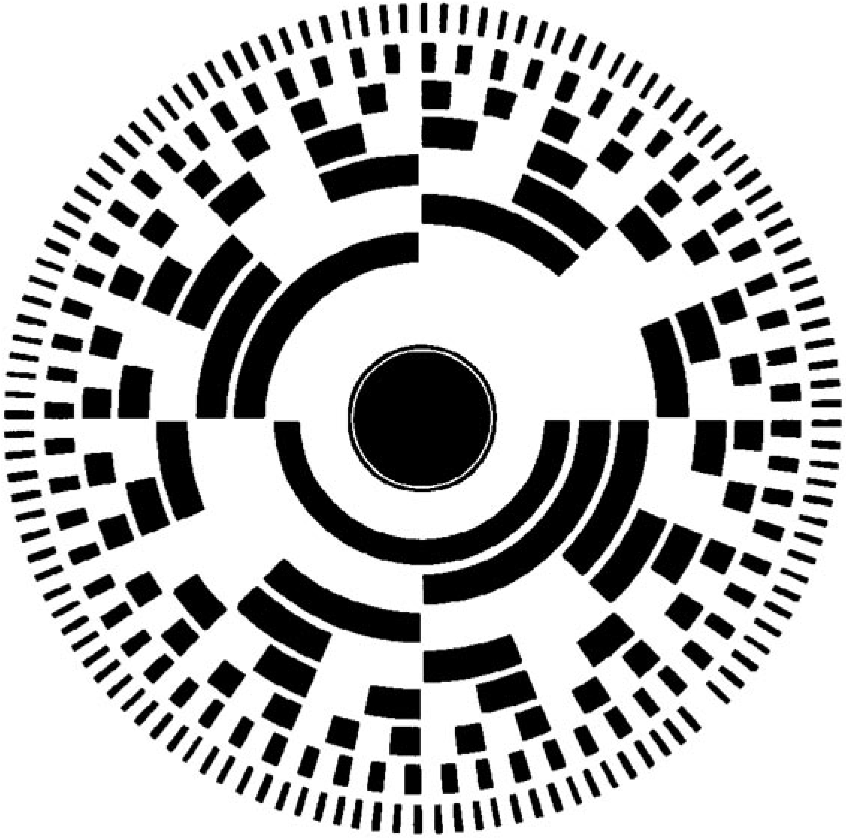
- Optical encoders
- Incremental patterns
- Needs resetting to determine zero position





Encoders

- Optical encoders
- Absolute position patterns
- Needs resetting to determine zero position



Encoders

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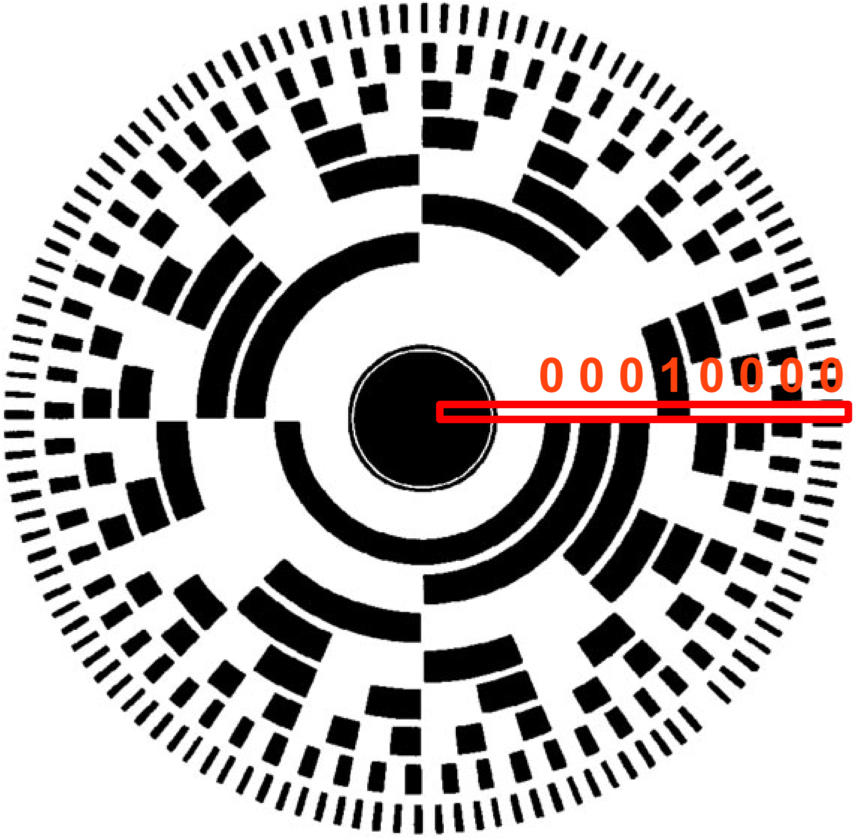
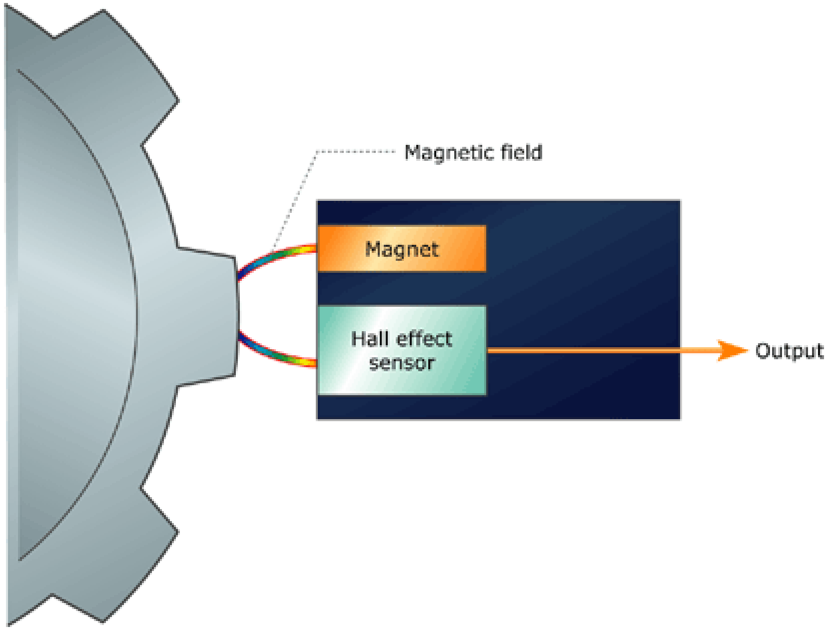
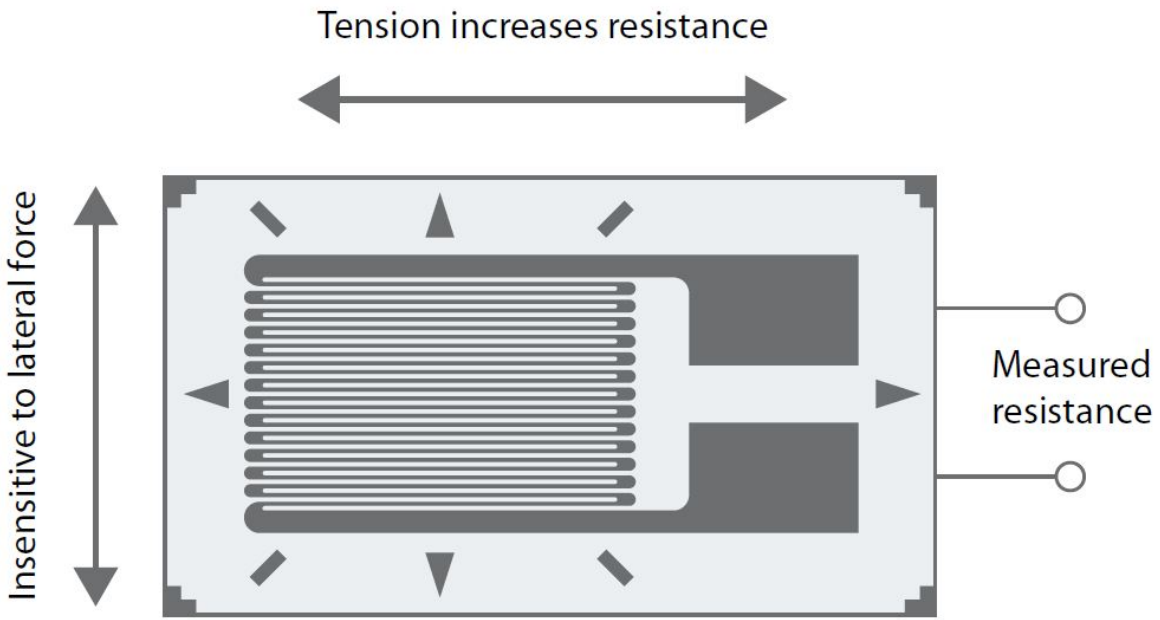


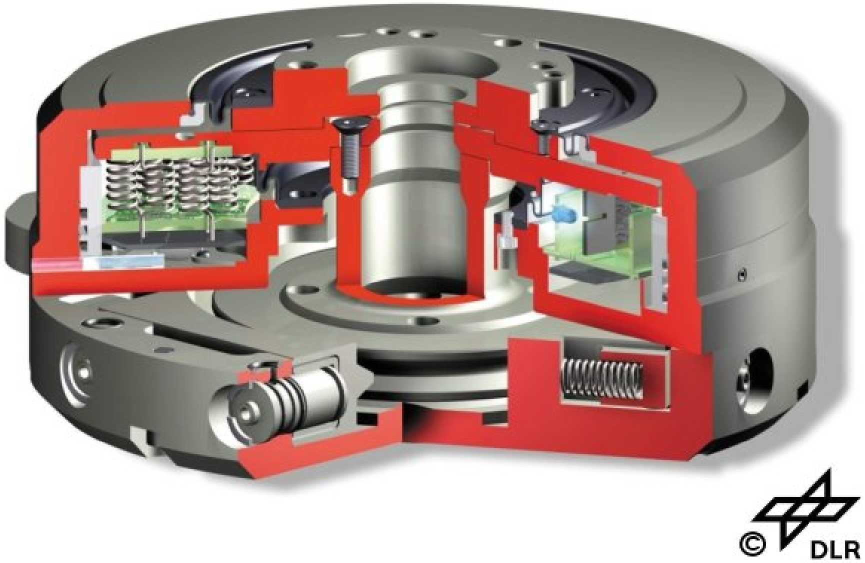
- Hall effect sensors
- Needs resetting to determine zero position
- Uses Hall effect
  The difference in magnetic field strength causes voltage differences in the sensor

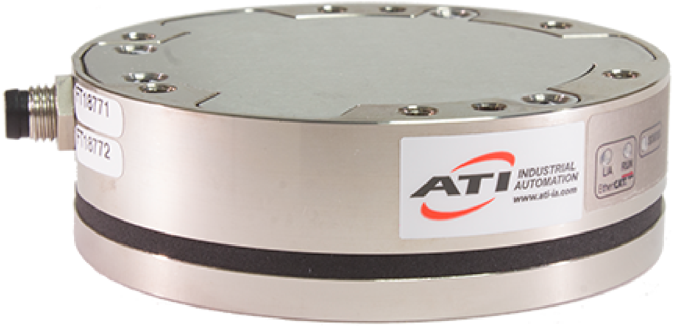


- Strain gauge

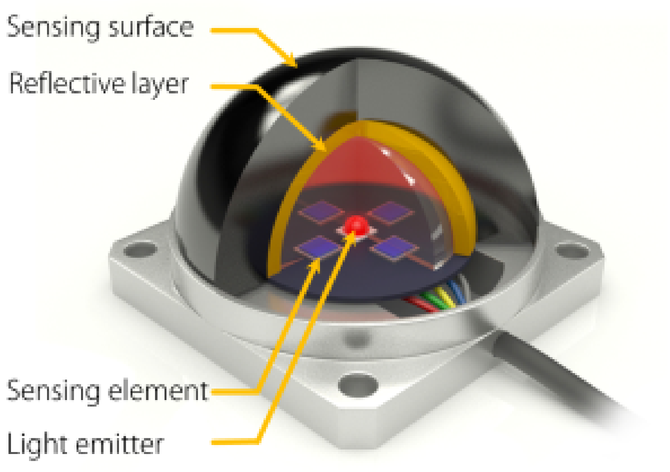


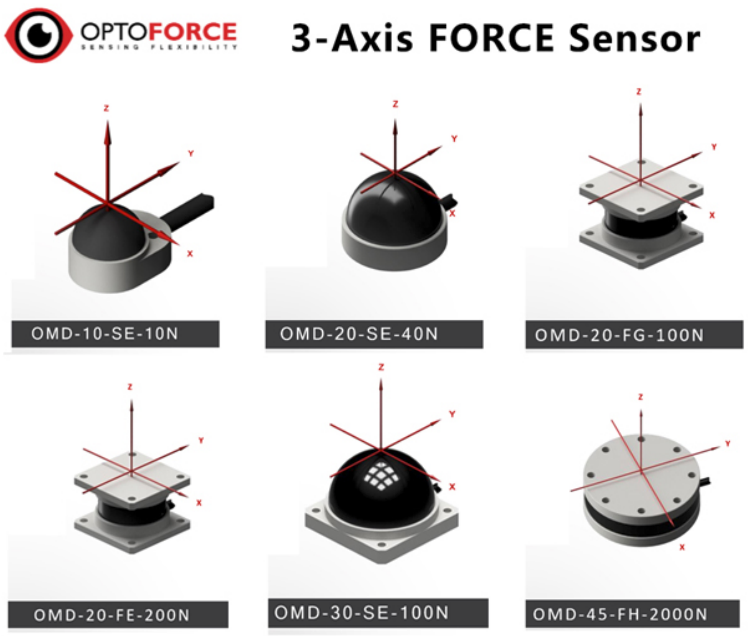
- Load cell
- Contains flexible metal parts with strain gauges attached
- Linear transformation between measured deformation and applied forces and torques

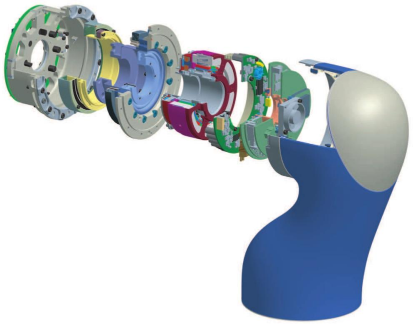




- Optoforce


Sensing surface
Reflective layer
Sensing element
Light emitter


OPTOFORCE
3-Axis FORCE Sensor
OMD-10-SE-10N
OMD-20-SE-40N
OMD-20-FG-100N
OMD-20-FE-200N
OMD-30-SE-100N
OMD-45-FH-2000N

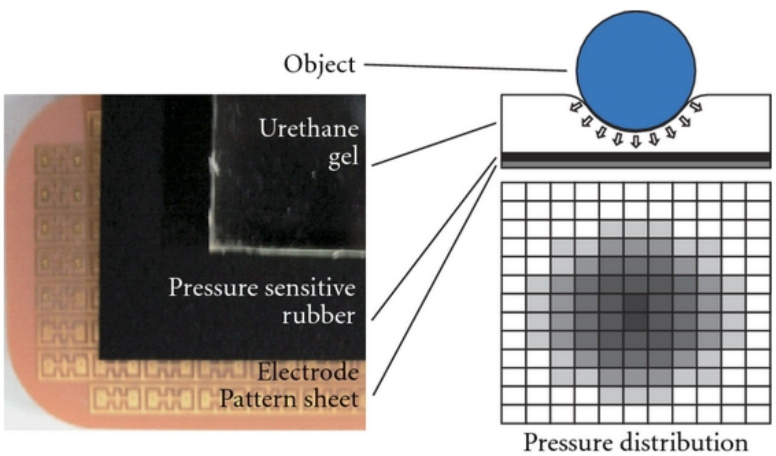


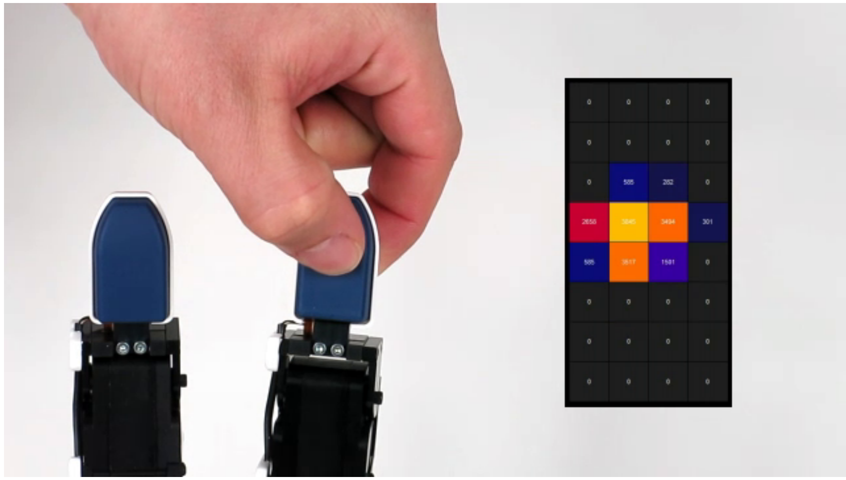
- Placement of sensors
  - Sensors at joints gives us the actual torque at each joint, which enables advanced feedback control for arm dynamics
  - Sensors at end effector gives us interaction forces and torques, which enables advanced feedback control for the task
  - End effector forces/torques are related to joint torques by Jacobian

$$\tau = J^T \mathcal{F}$$

Sensing

- Tactile
  - Sense (distribution of) contact forces from the environment
  - Ideally, integral of taxels should give normal force...

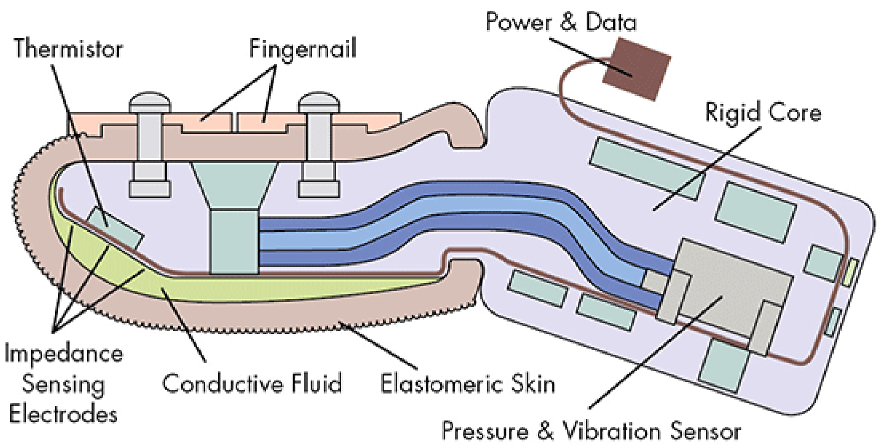




Weiss tactile sensor

Sensing

- Tactile sensing for higher frequencies



Syntouch BioTac

Effort

- Sensorless sensing
  - We know that

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) + J^T F$$

  - If we know the current flowing through the motors, and the torque each motor produces at a given current, we can solve for **F**
  - Sensitive to modelling errors