Implementing Control Strategies for Manipulation

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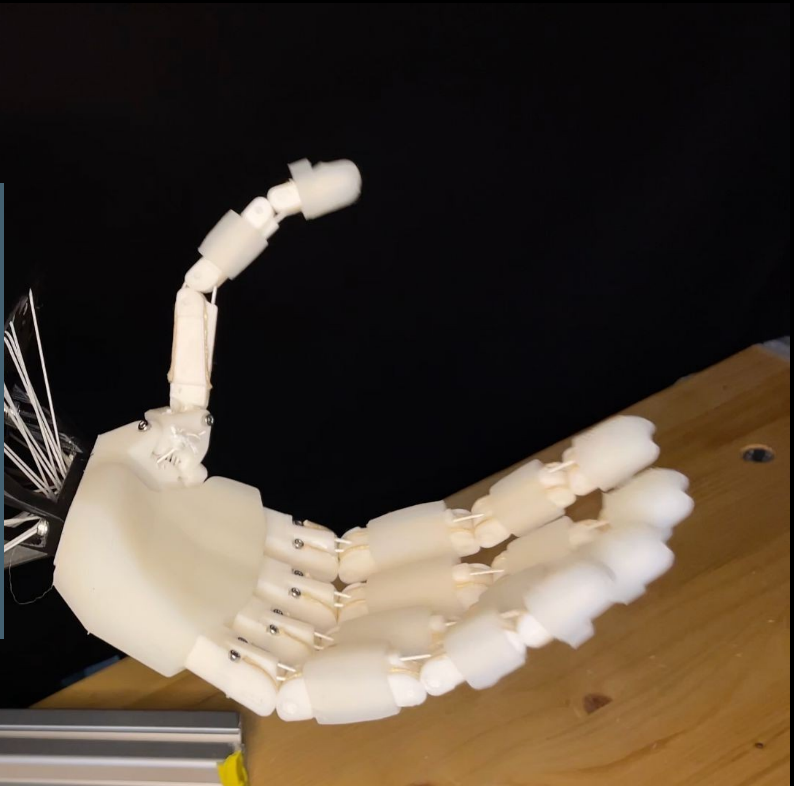
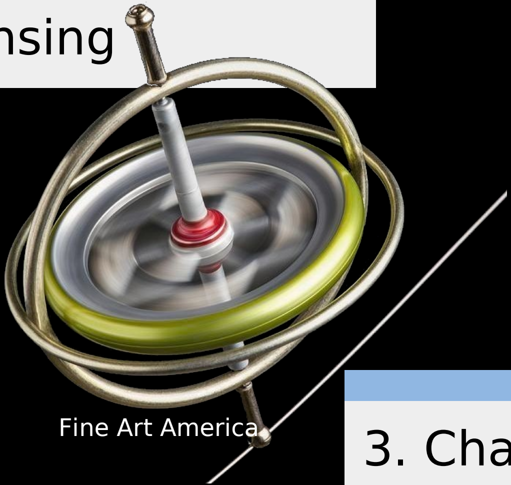


Toshimitsu et al., Getting the ball rolling (2023)

Plan for Today

1. Sensing

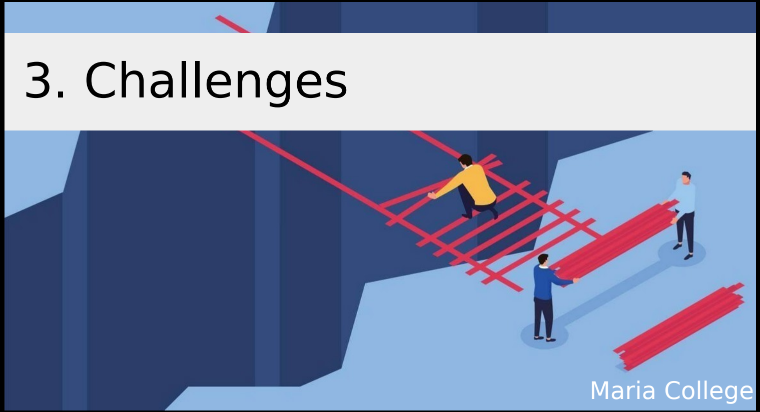


Fine Art America

2. Control

Wikimedia

3. Challenges



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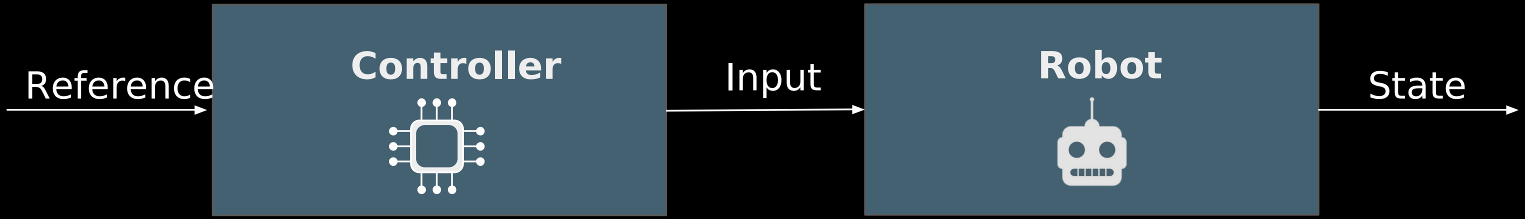
Control, but how?

Simplest controller possible: Open loop



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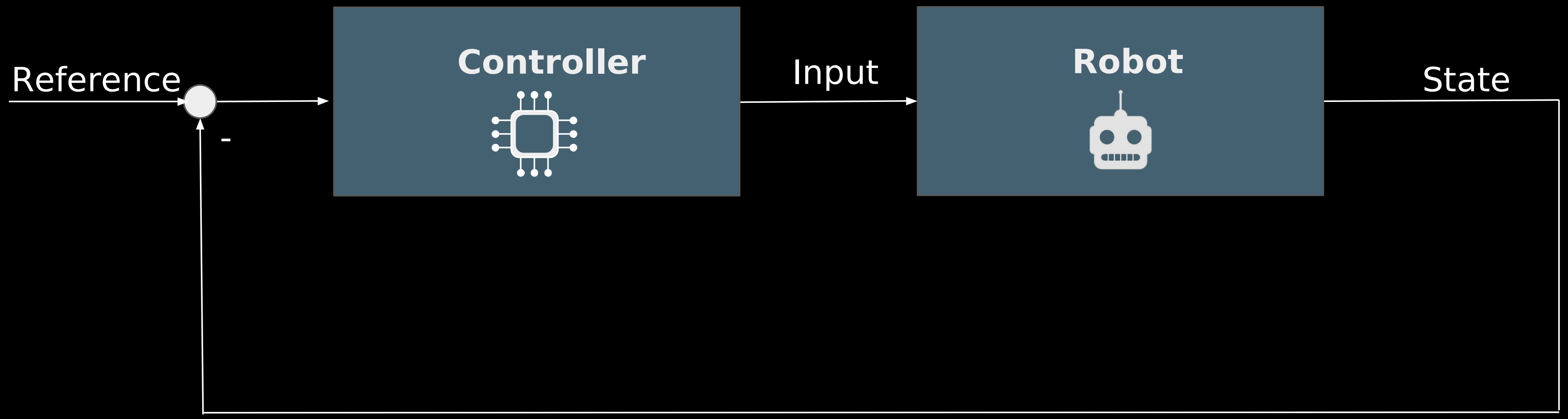
Closed Loop Controller



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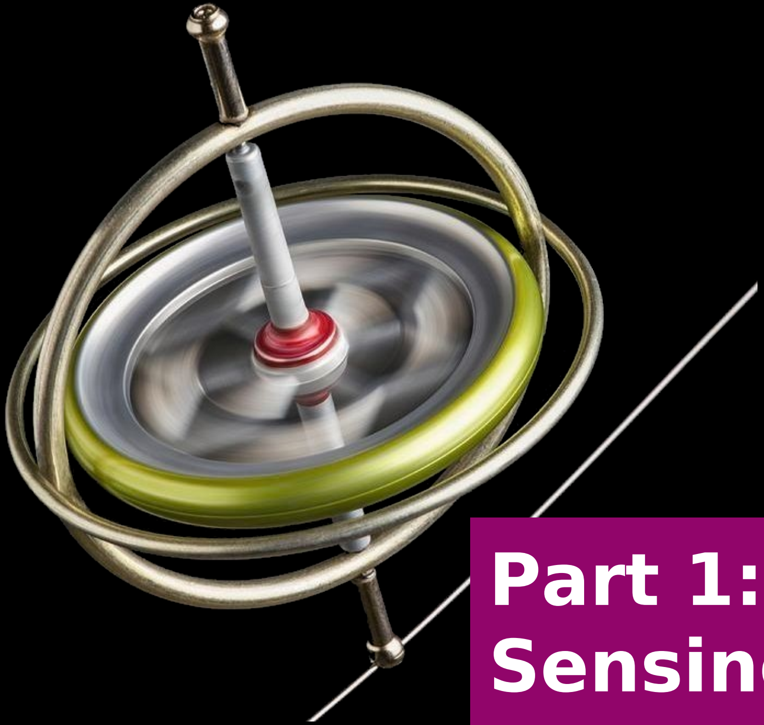

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Part 1: Sensing

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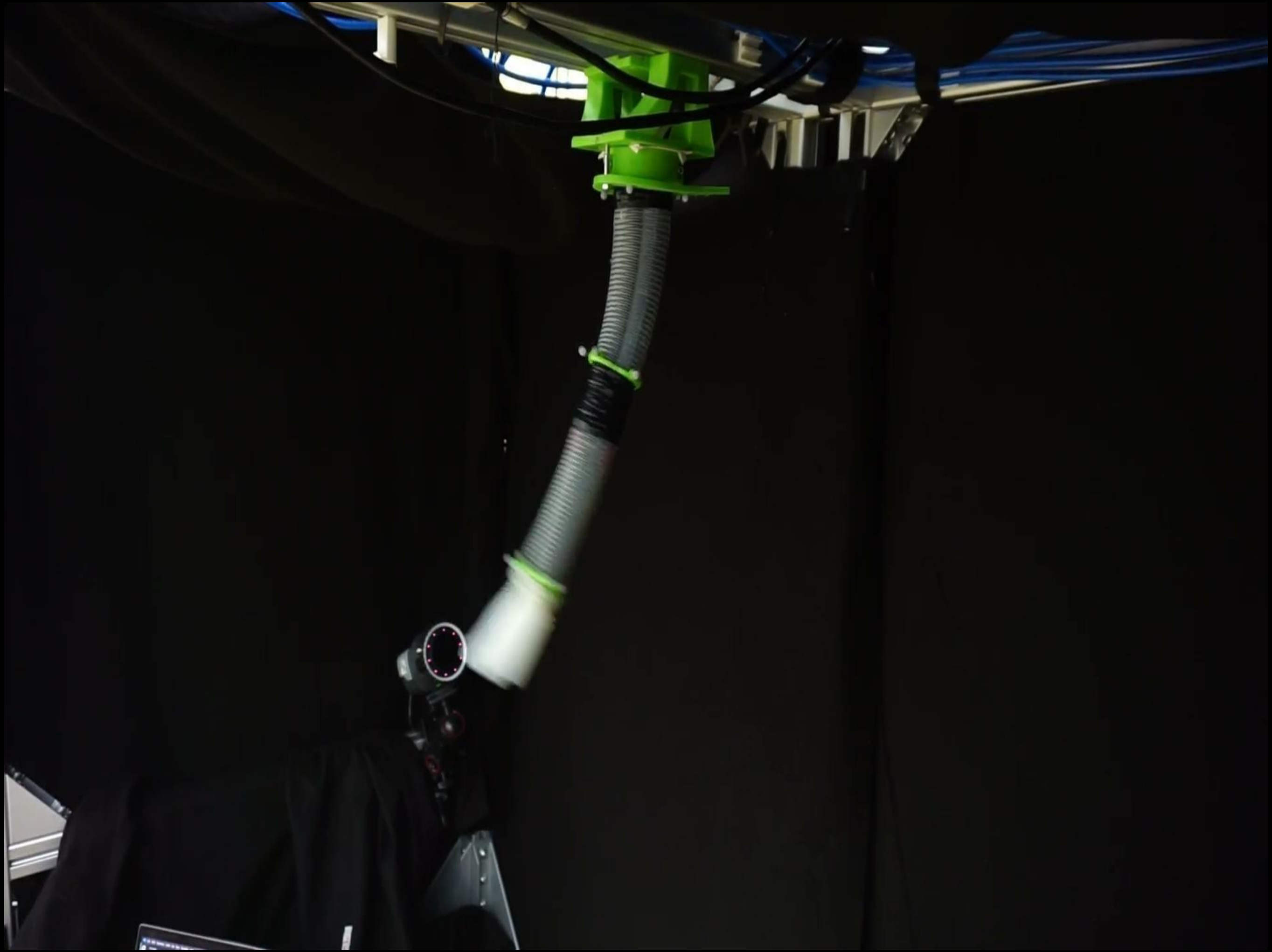
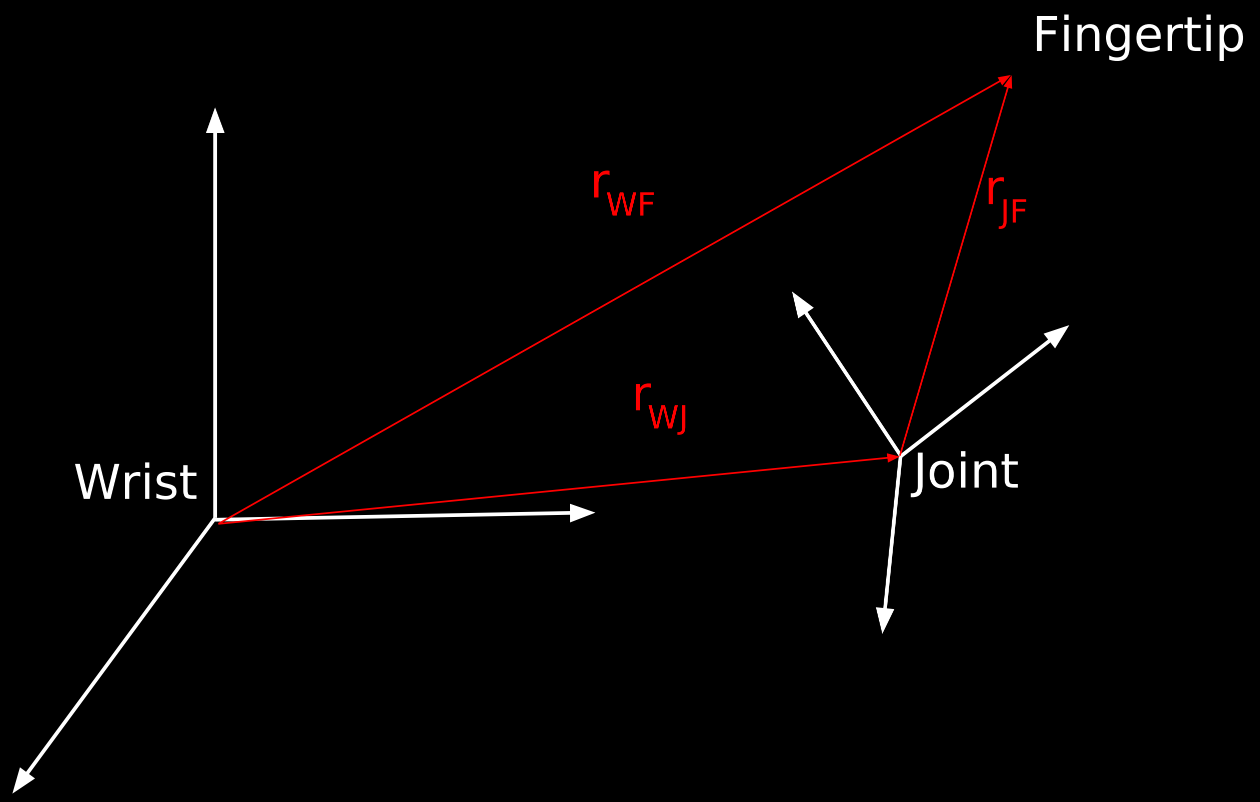
Sensing the pose: two methods

- Direct methods: Direct reference to the world reference frame
  - The sensors obtain the absolute value of the state we are measuring

- Indirect methods: Obtain a measurement with reference to a second fra
  - The sensors will estimate a relative measurement, that can be transformed into an absolute measurement

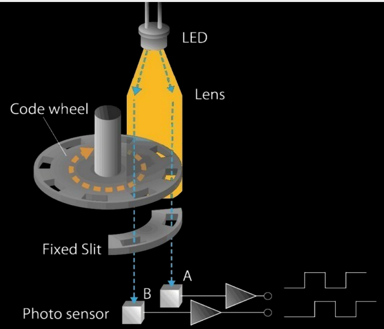


Second solution



What sensors you might find in the future?

- Motor Encoders



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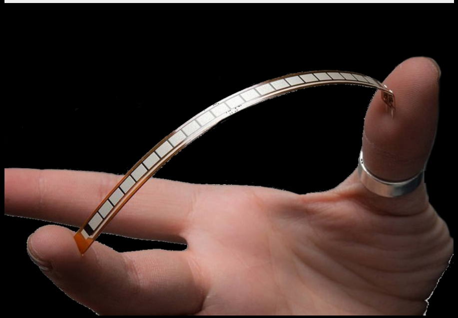
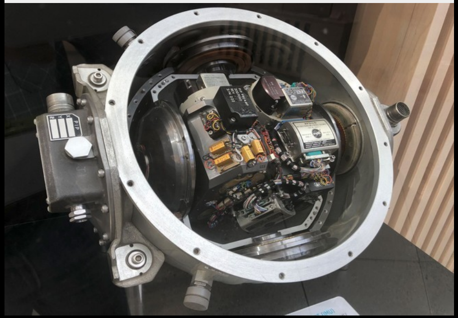
- Flex Sensors



AdaFruit

- IMU



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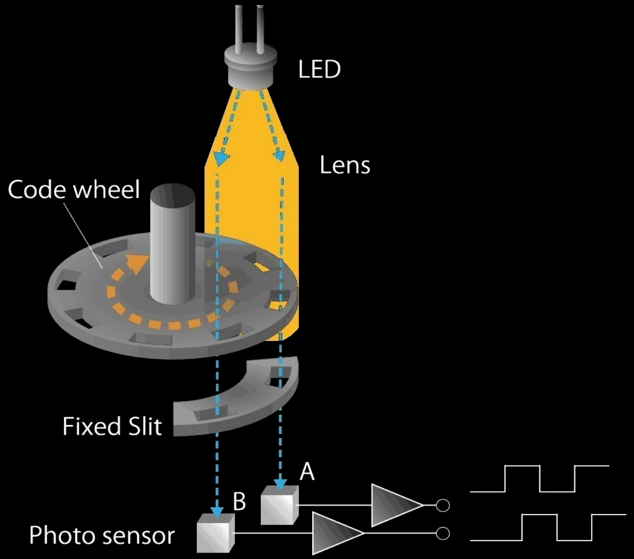
- Other principles?

?

1. Encoders



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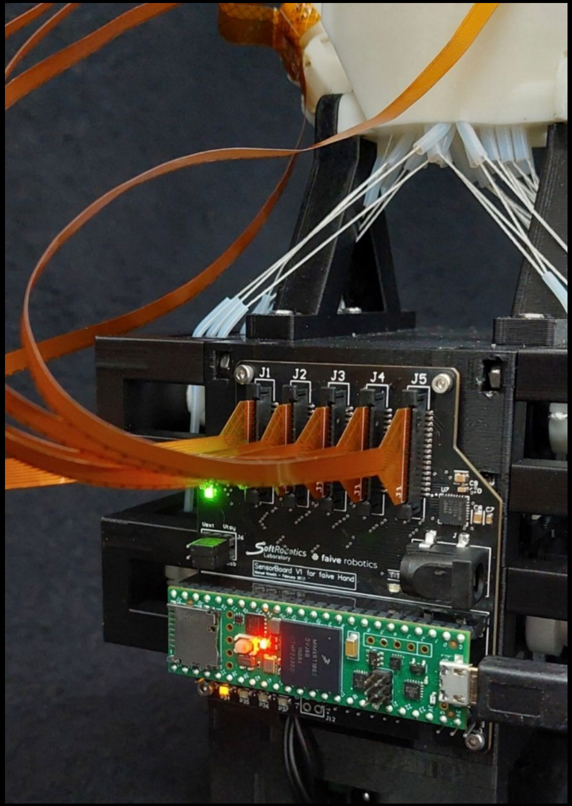
2. Flex Sensors



Knecht et al. *Actuation, Sensing and Control of the faive Robotic Hand*

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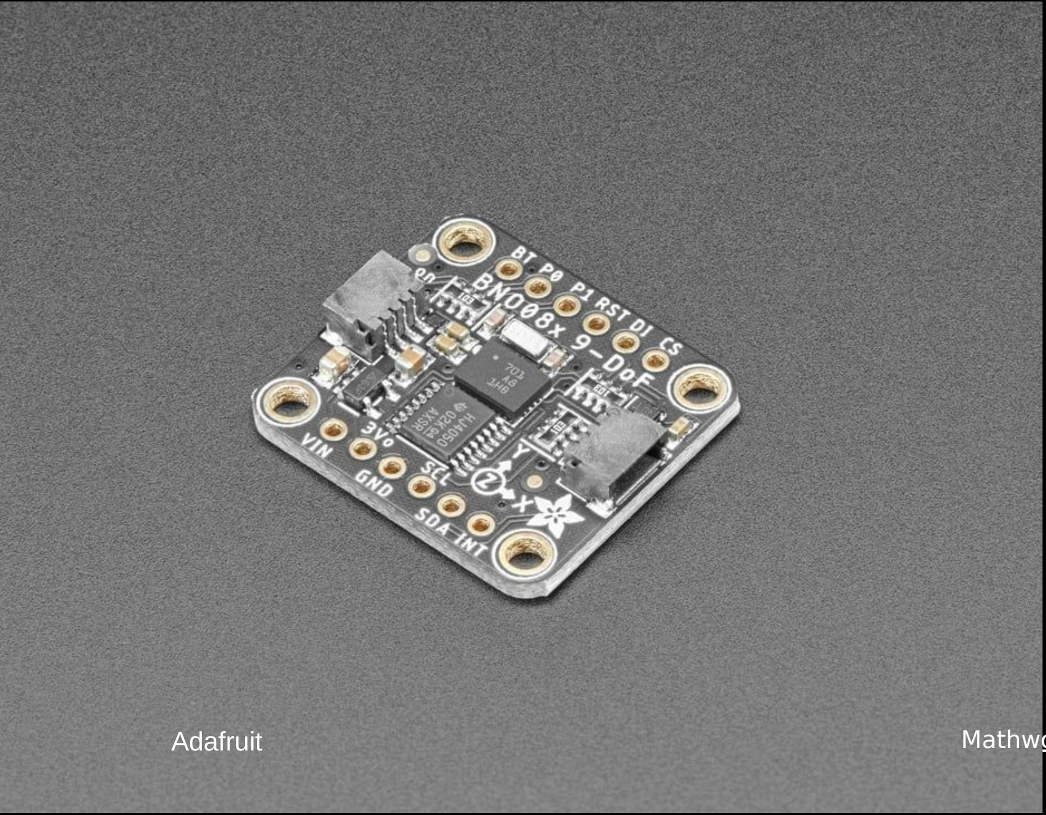
3. Inertial Measurement Unit



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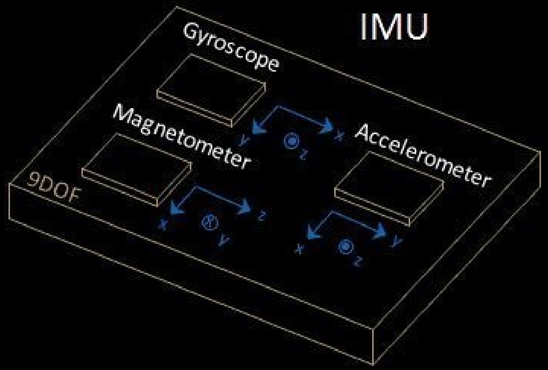
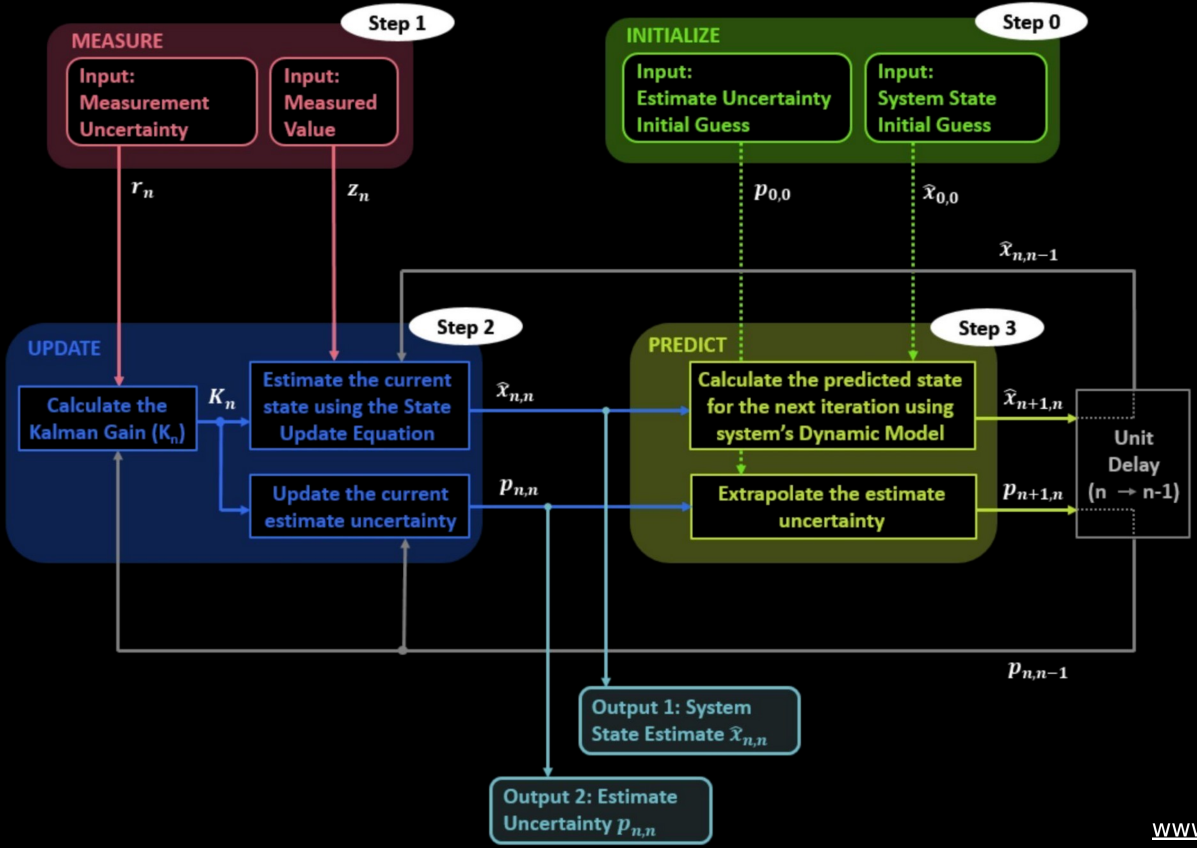


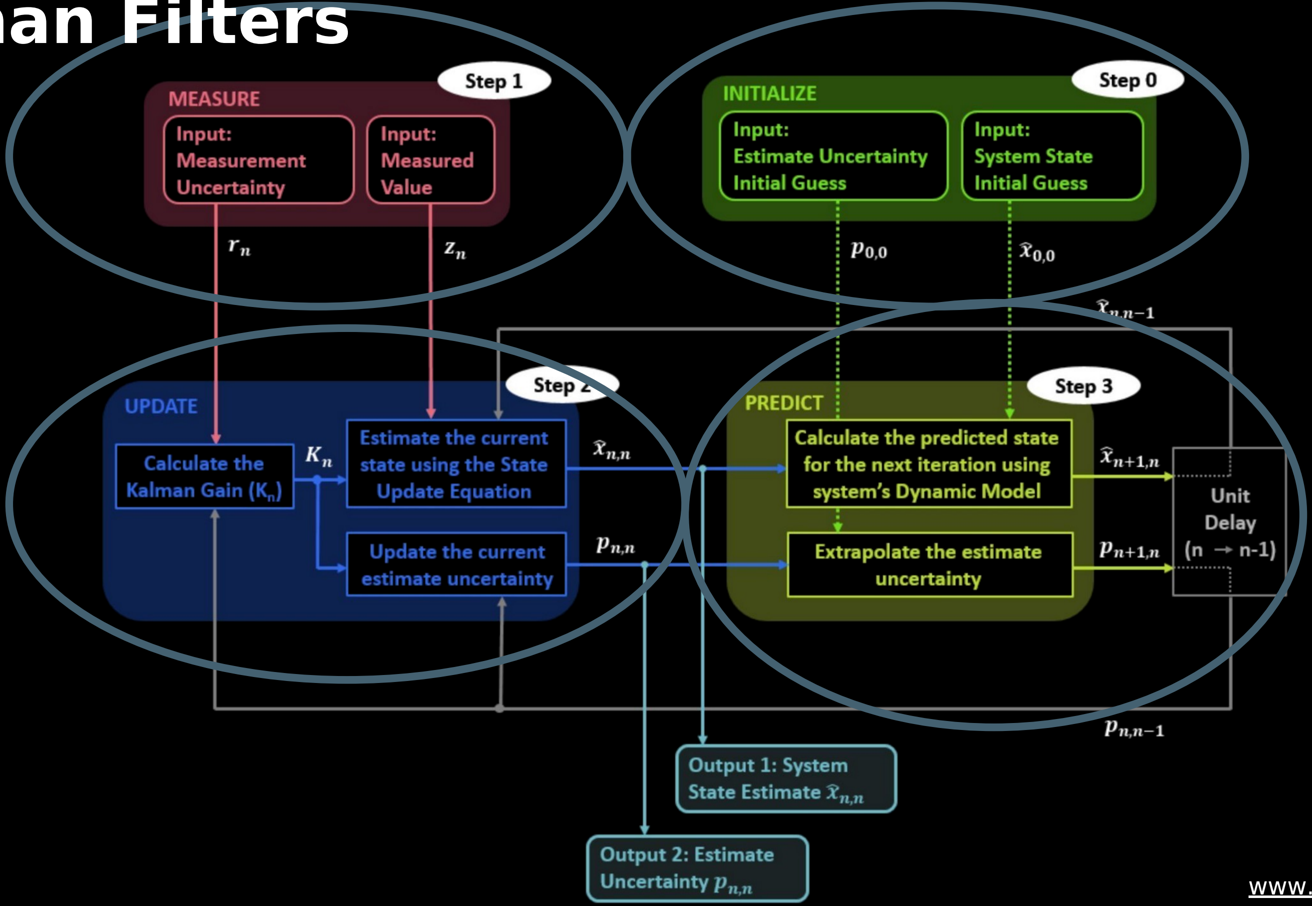
Mathworks

Kalman Filters



www.kalmanfilter.net

Kalman Filters



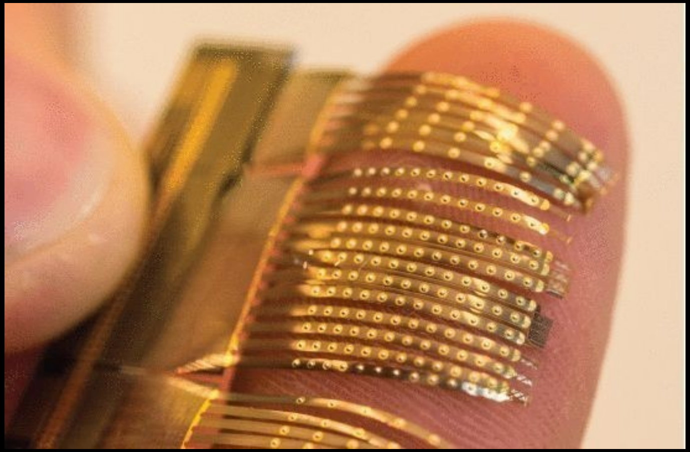
www.kalmanfilter.net

Sensing the touch:

- Force Sensing Resistors

Ohmite

- Artificial Skin



Weichart et al. *Tactile Sensing With Scalable Capacitive Sensor Arrays on Flexible Substrates (2021)*

Wrapping up

- Pose estimation
  - Directly measuring the absolute pose (6 DoF)
    - Camera triangulation
  - Measuring the pose with respect to the wrist
    - Encoders
    - Flex sensors
    - Inertial Measurement Unit
  - Kalman Filters
- Force estimation
  - Force Sensing Resistors
  - Artificial Skin

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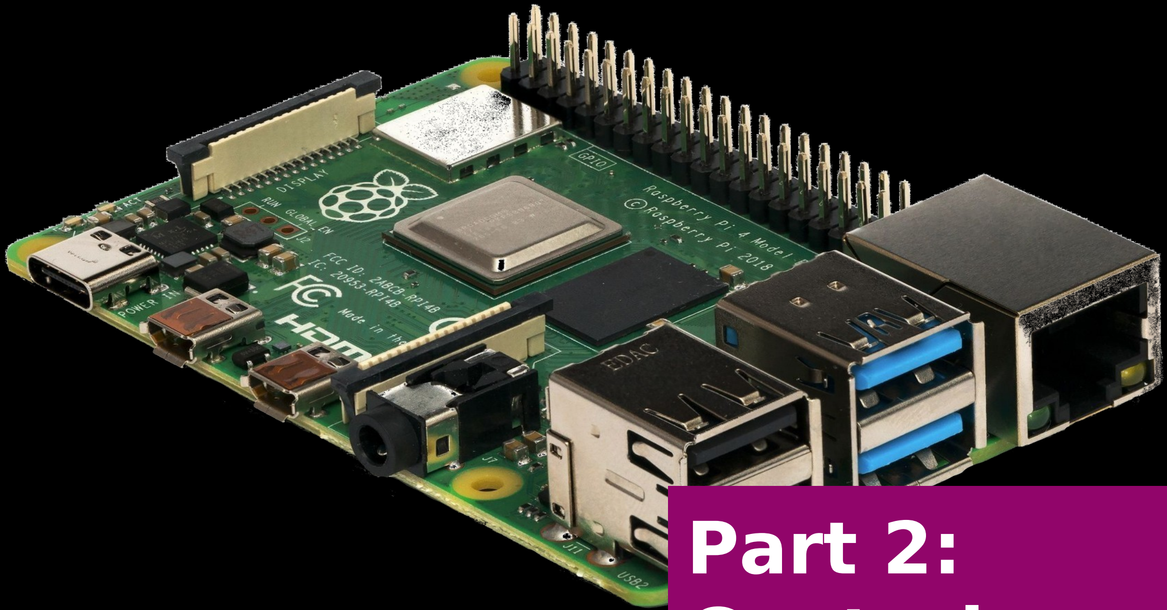

Part 2: Control

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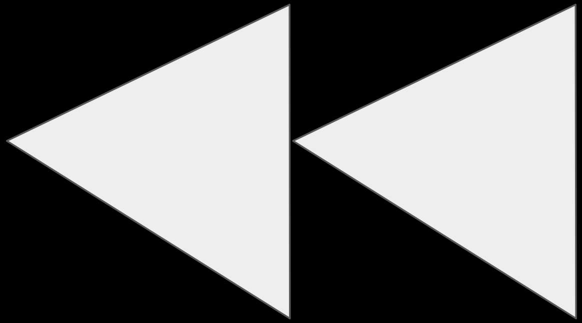


Inverse Kinematics

- From greek ***kinema*** = motion
- In the past units we learnt that:
  - $J(q)\dot{q} = \chi_e = \begin{bmatrix} \dot{p}_e \\ w_e \end{bmatrix}$
- If we invert it we obtain:
  - $\dot{q} = J^{+}\chi_e$ with $\mathrm{J}^{+} = J^{T}\left(JJ^{T}\right)^{-1}$
- And in a differential form:
  - $\Delta\chi_e = J^{+}\Delta q$

Algorithm 1 Numerical Inverse Kinematics

```
q ← q^0                                          ▷ Start configuration
while ||χ*_e − χ_e(q)|| > tol do                 ▷ While the solution is not reached
    J_eA ← J_eA(q) = ∂χ_e/∂q (q)                 ▷ Evaluate Jacobian for q
    J^+_eA ← (J_eA)^+                            ▷ Calculate the pseudo inverse
    Δχ_e ← χ*_e − χ_e(q)                         ▷ Find the end-effector configuration error vector
    q ← q + J^+_eA Δχ_e                          ▷ Update the generalized coordinates
end while
```

A possible inverse kinematics algorithm

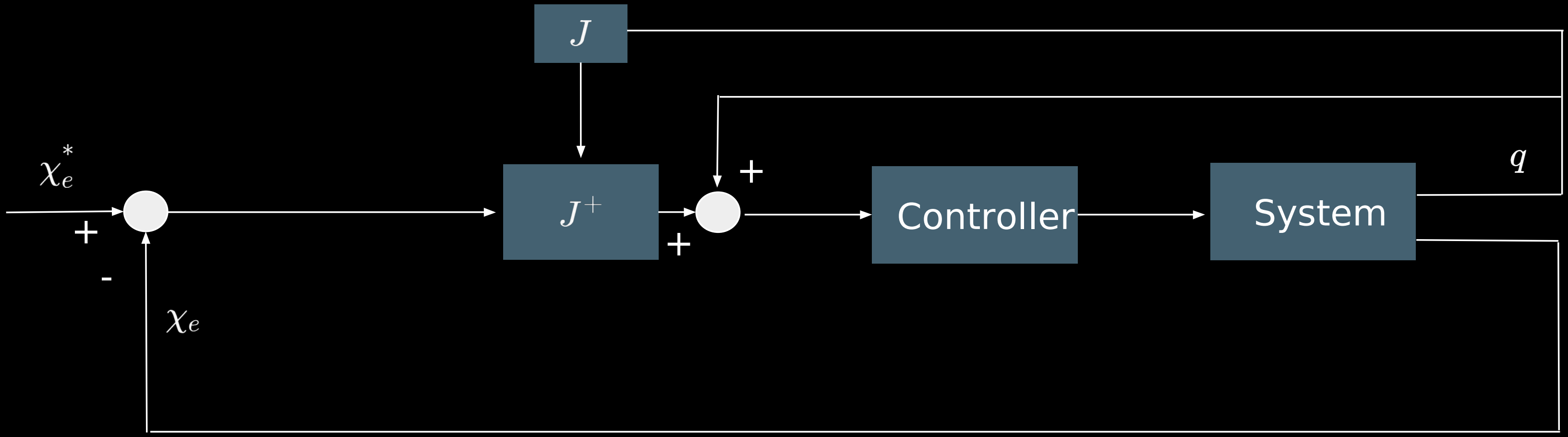
Marco Hutter, Roland Siegwart
Robot Dynamics Class ETH

To overcome stability issues the update can be scaled by a factor *k*

$q \leftarrow q + kJ_{eA}^{+}\Delta\chi_e$ with $k \in (0,1)$

However this leads to a slower convergence

Inverse Kinematics



Trajectory Control

We can use a closed loop controller, but we need to add a component for the desired velocities

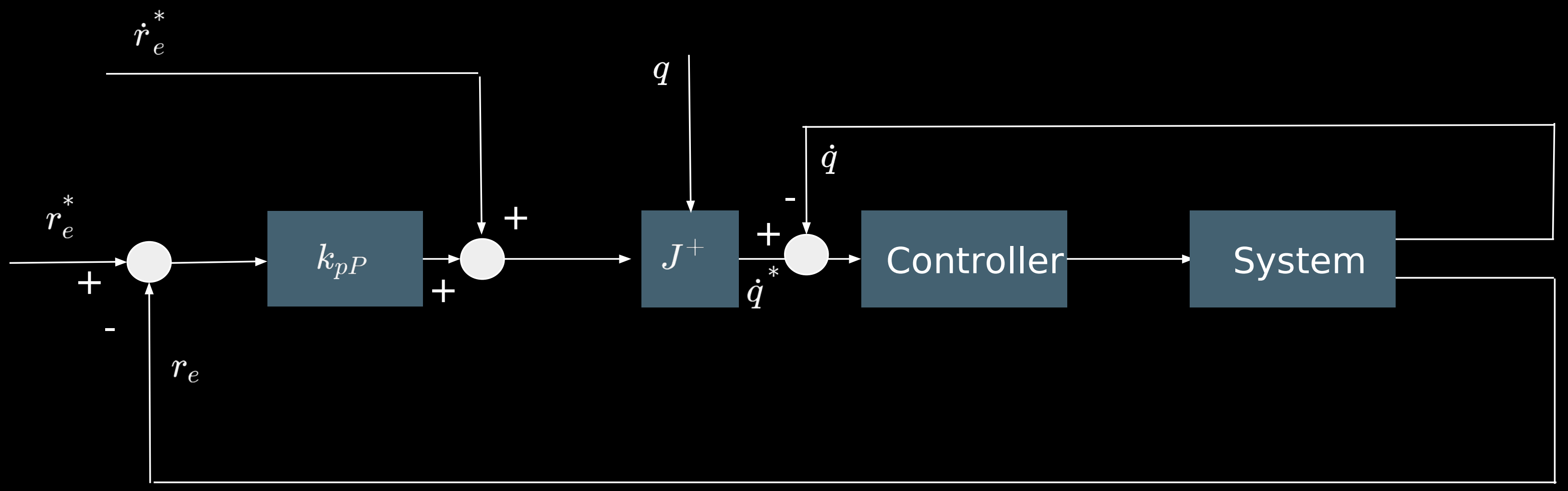
We define $\Delta r_e^t = r_e^*(t) - r_e(q^t)$

And the desired joint velocity $\dot{q}^* = J_{e0_P}^+(q^t) \cdot (\dot{r}_e^*(t) + k_{pP}\Delta r_e^t)$

If we have a desired rotation rate we write $\dot{q}^* = J_{e0_R}^+(q^t) \cdot (\omega_e^*(t) + k_{pR}\Delta\phi)$

Where ϕ are the angles used to represent the orientation of the end effector.

Trajectory Control



Dynamic control

The dynamic model is

$$M(q)\ddot{q} + b(q, \dot{q}) + g(q) = \tau + J_c(q)^T F_c$$

With:

$M(q)$: Generalized mass matrix

$q, \dot{q}, \ddot{q}$: Generalized position, velocity and acceleration vector

$b(q, \dot{q})$: Coriolis and centrifugal terms

$g(q)$: Gravitational terms

τ : External generalized forces

F_c : External Cartesian forces

$J_c(q)$: Geometric Jacobian corresponding to the external forces

Dynamic control

The dynamic model is

$$M(q)\ddot{q} + b(q, \dot{q}) + g(q) = \tau + J_c(q)^T F_c$$

If we know the desired generalized accelerations, velocities and poses we can write

$$\ddot{q}^* = k_p(q^* - q) + k_d(\dot{q}^* - \dot{q})$$

Thus the joint torques will be

$$\tau^* = M(q)\ddot{q}^* + b(q, \dot{q}) + g(q)$$

Task-space control

Remember that $J(q)\dot{q} = \chi_e = \begin{bmatrix} \dot{p}_e \\ w_e \end{bmatrix}$

If you derive that with respect to time: $\dot{\chi}_e = J(q)\ddot{q} + \dot{J}(q)\dot{q}$

And if we solve the dynamics equation for the joint acceleration and substitute in the equation ab
get: $\dot{\chi}_e = JM^{-1}(\tau - b - g) + \dot{J}\,\dot{q}$

Finally, remembering that $\tau = J_e^T F_e$

We can write $\Lambda_e \dot{\chi}_e + \mu + p = F_e$

$$\Lambda_e = (J_e M^{-1} J_e^T)^{-1}$$
$$\mu = \Lambda_e J_e M^{-1} b - \Lambda_e \dot{J}_e \dot{q}$$
$$p = \Lambda_e J_e M^{-1} g$$

Task-space control

Defining the dynamics uniquely depending on the state of the end effector allows us to design a c
loop

$$\dot{\chi}_e^* = \begin{pmatrix} r_e^* - r_e \\ \Delta\phi_e \end{pmatrix} + k_d(\chi_e^* - \chi_e)$$

Part 3: Challenges

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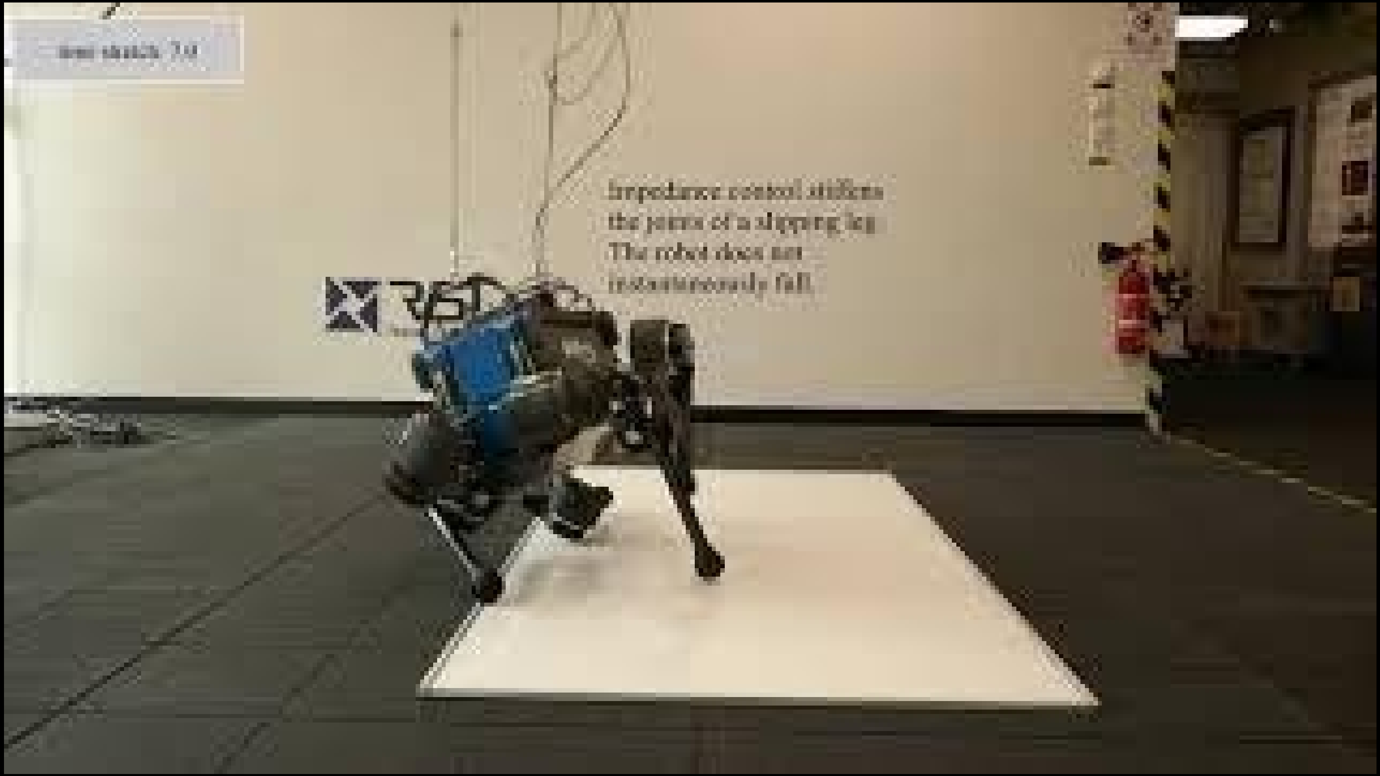
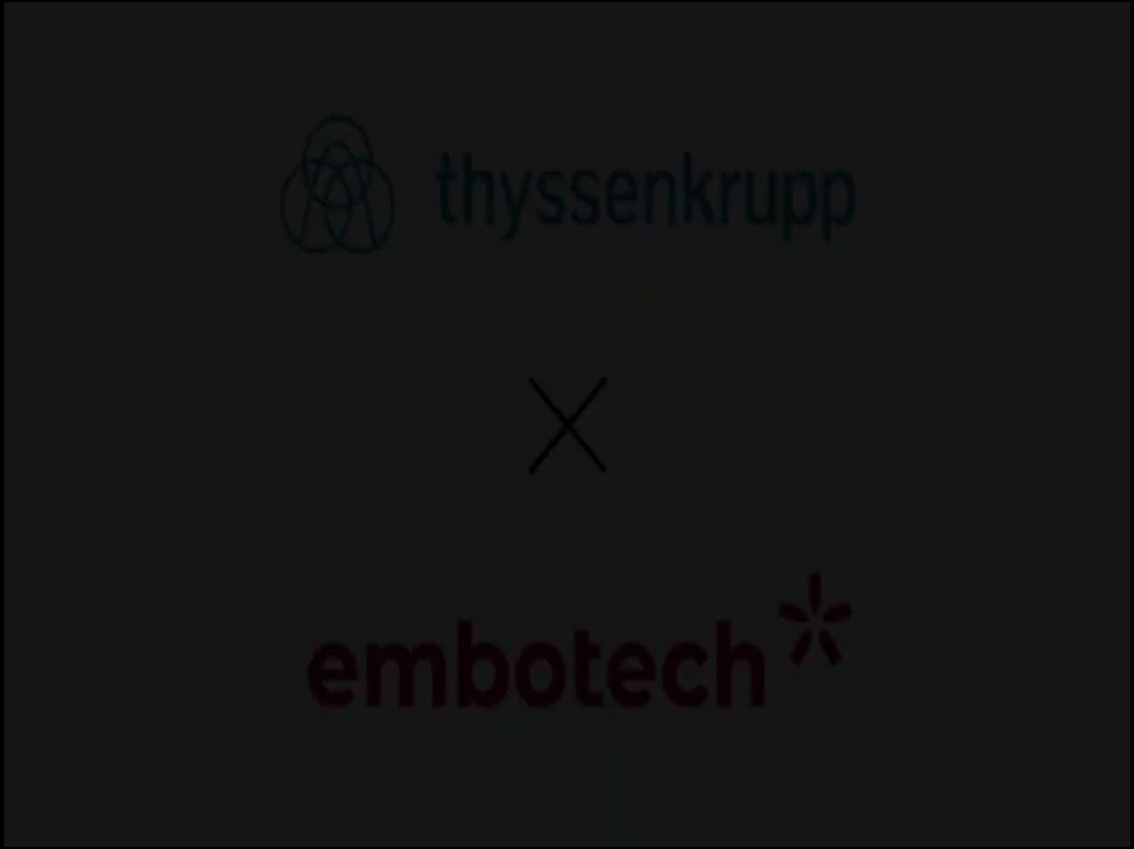
What should you expect?

- Uncertainty and Partial Observability
- Long Horizon
- Under/Over actuation
- Sim-to-real gap
- Tendon strain
- Skin non-linearity
- Encoder's sensibility

Uncertainty and Partial Observability

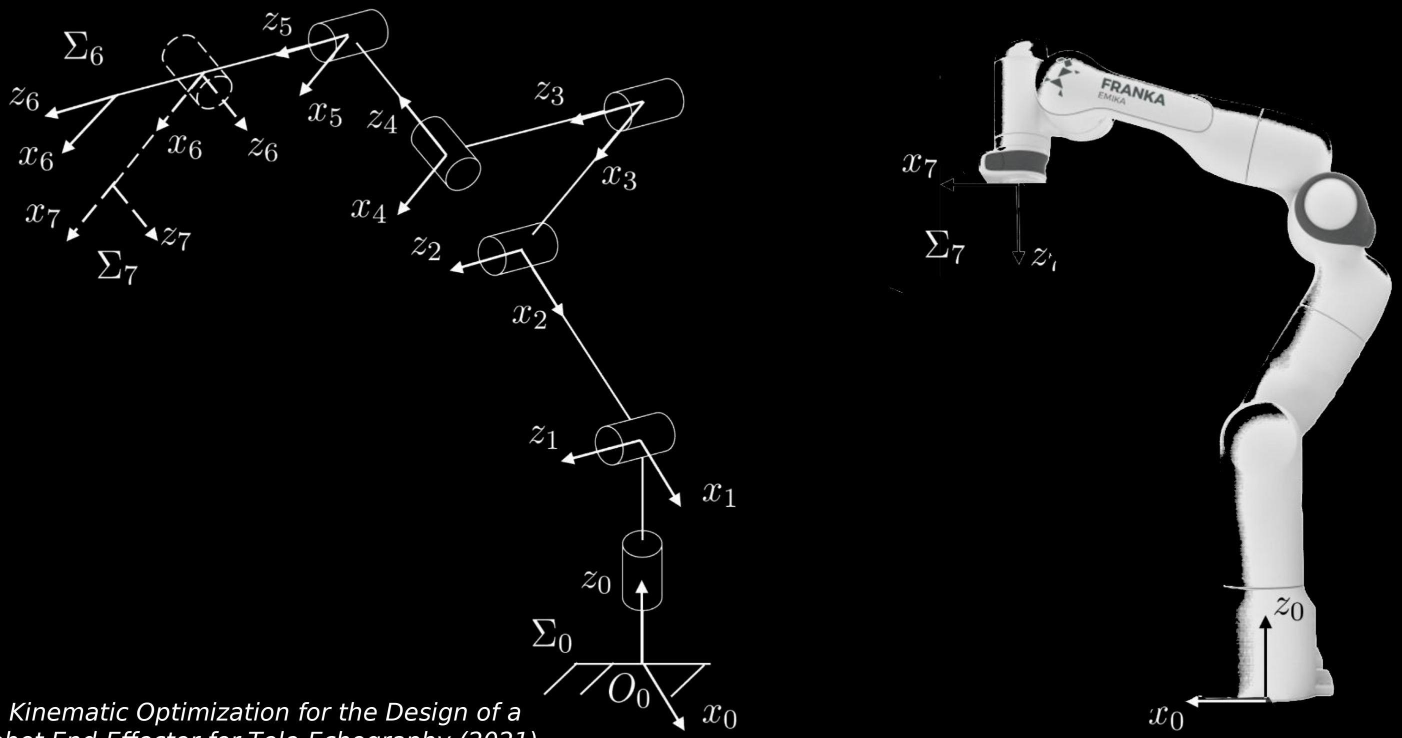


Long Horizon



Tyssenkrupp X Embotech

Underactuation and Overactuation

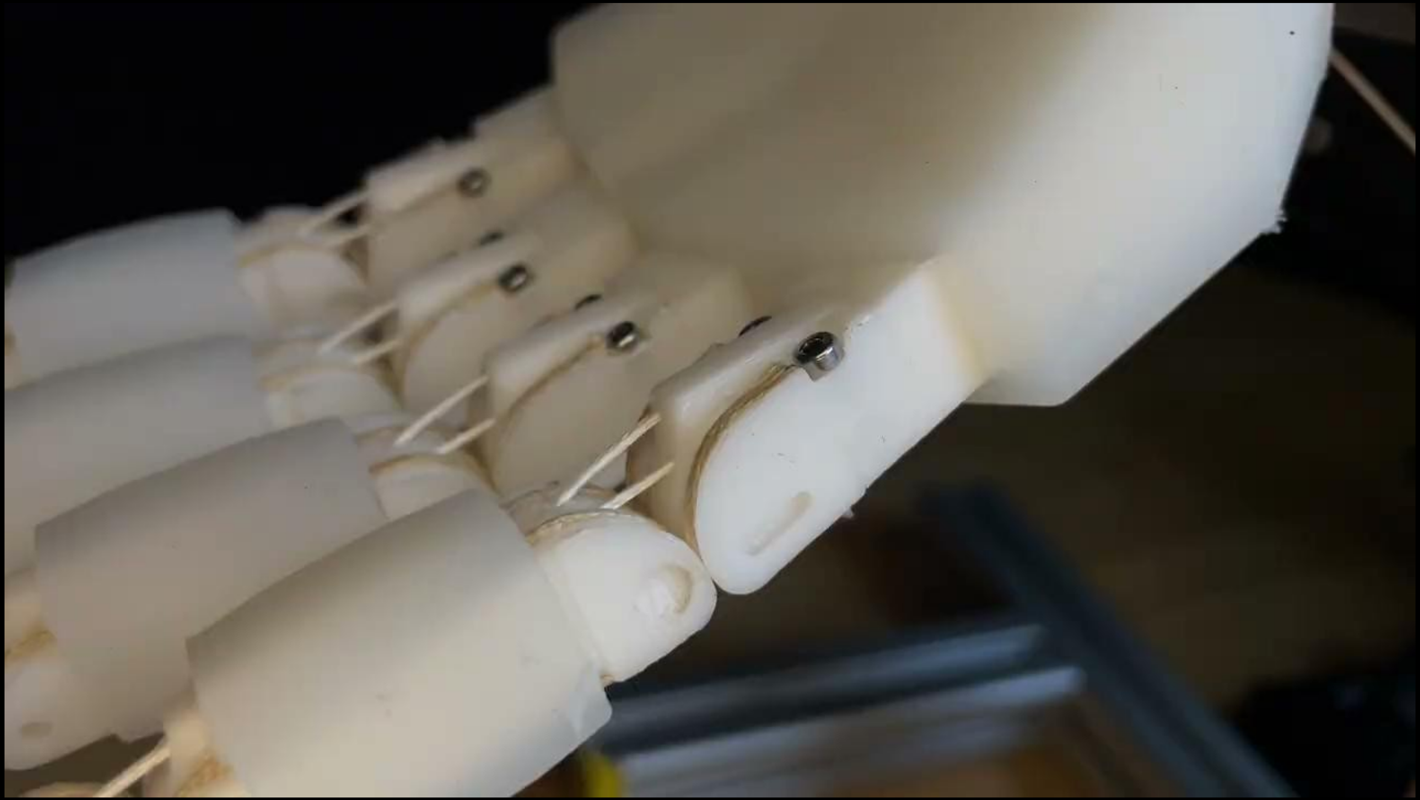


Filippeschi et al. *Kinematic Optimization for the Design of a Collaborative Robot End-Effector for Tele-Echography (2021)*

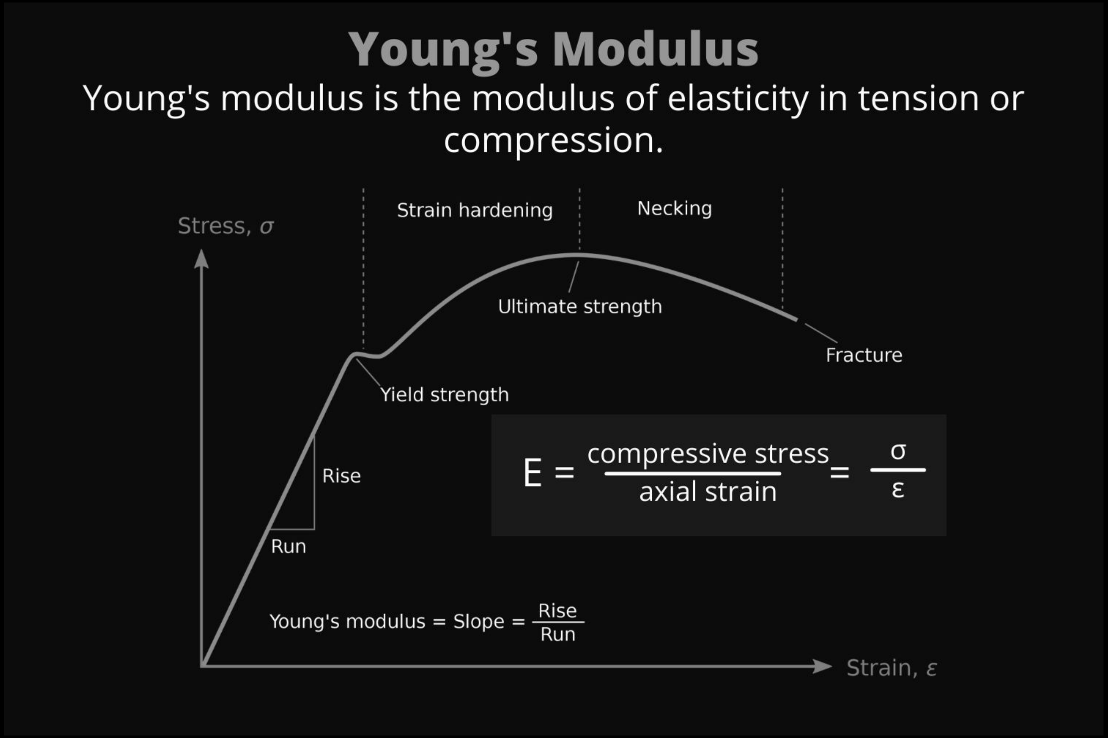
(a) (b)

Sim-to-real gap

Tendon strain

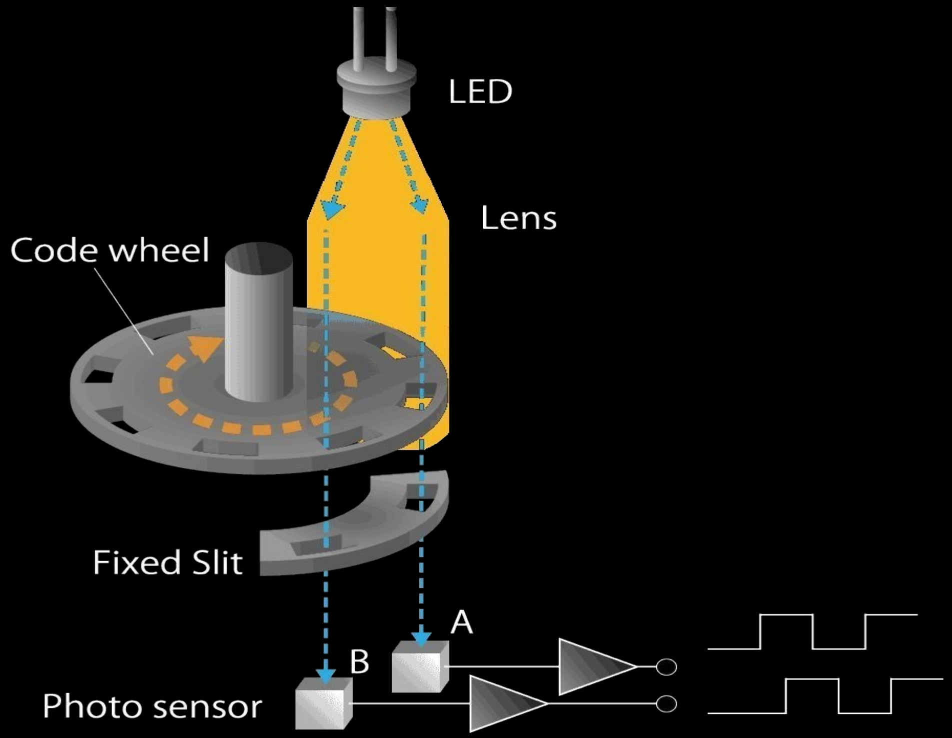


Soft non-linearity: example



Science Notes

Encoder's uncertainty: example



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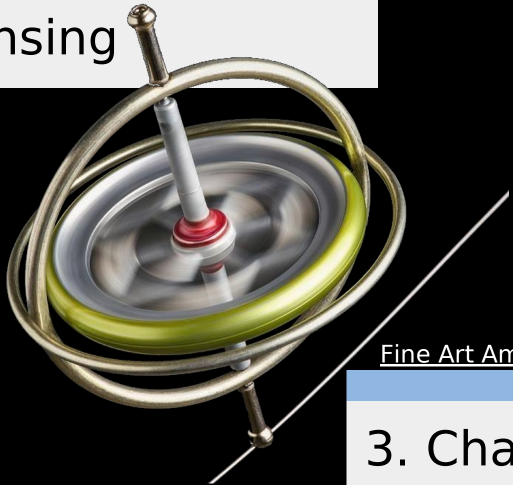
Let's wrap up

1. Sensing



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2. Control

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3. Challenges

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Useful links

https://link.springer.com/book/10.1007/978-3-319-54413-7

https://smartlabai.medium.com/a-brief-overview-of-imitation-learning-8a8a75c44a9c

https://underactuated.csail.mit.edu/index.html

https://www.kalmanfilter.net/default.aspx