# Robot Control: Overview

CS 6341 Robotics
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# Robot Control

- Convert task specifications to forces and torques at the actuators


- Moving an object from one place to another
- Tracing a trajectory for a spray paint gun
- Applying a polishing wheel to a workpiece
- Writing on a chalkboard

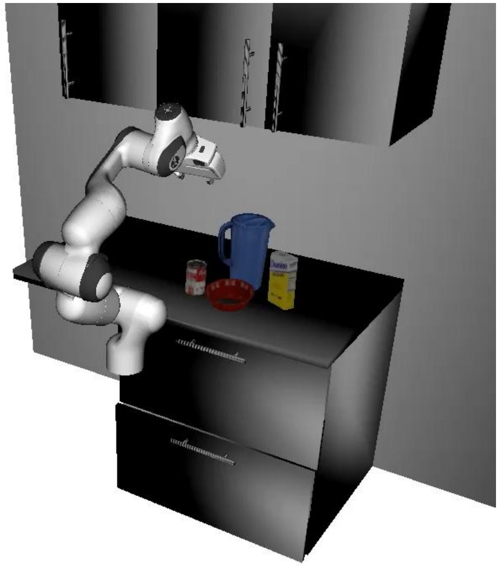
# Motion Control

- Goal: follow a given robot trajectory
  - Trajectory of desired end-effector configuration $X_d(t)$
  - Trajectory of desired joint positions $\theta_d(t)$

Can include

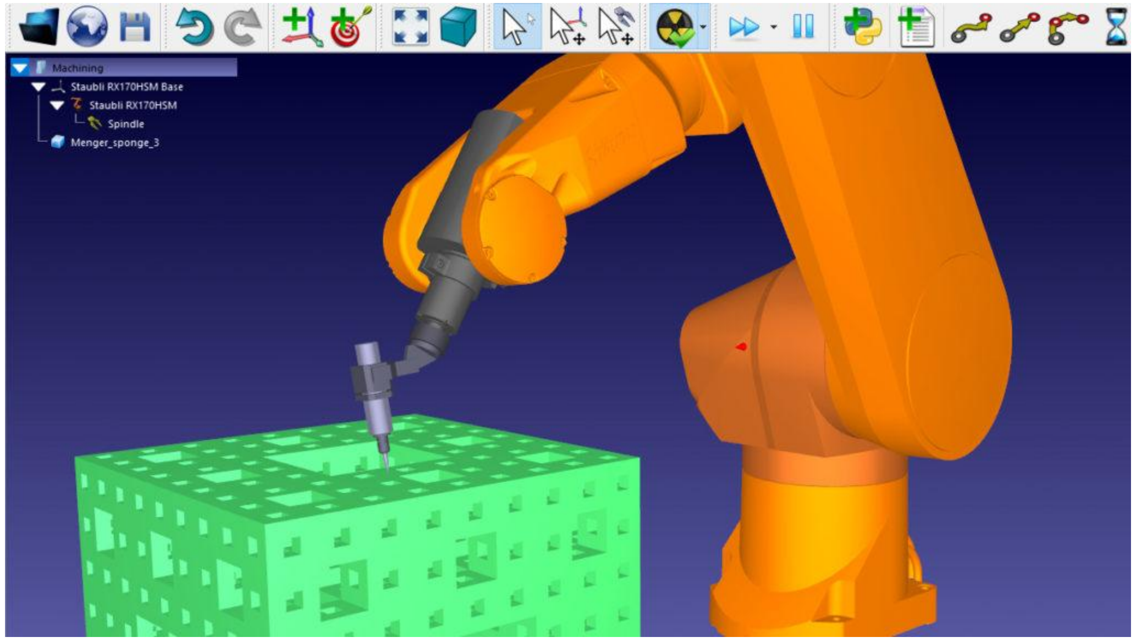
$\dot{\theta}_d(t)$

$\ddot{\theta}_d(t)$



# Force Control

- Goal: apply forces and torques to the environments




https://robodk.com/blog/force-control-robot-machining/

# Hybrid Motion-Force Control

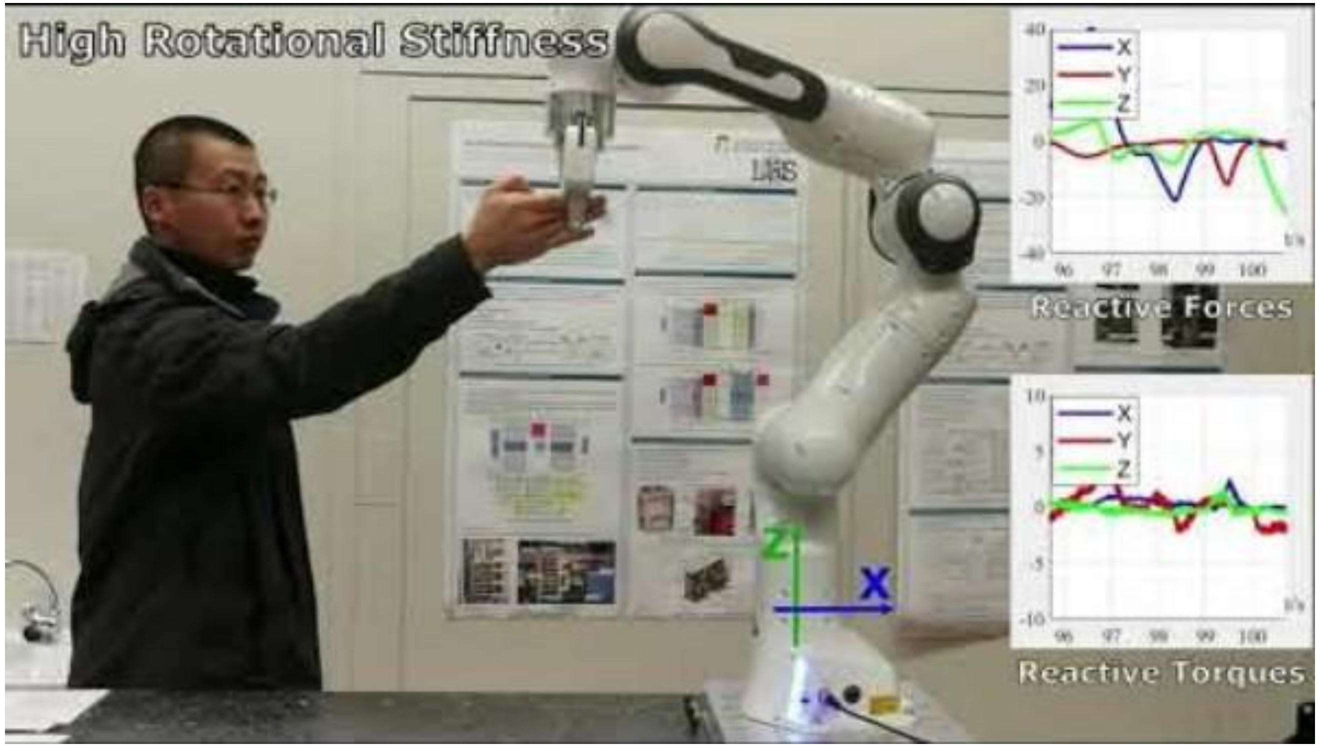
- Goal: generate both force and motion

https://youtu.be/9NbwE4PMeyQ

# Impedance Control

- Goal: robot end-effector is asked to render particular mass, spring, and damper properties.

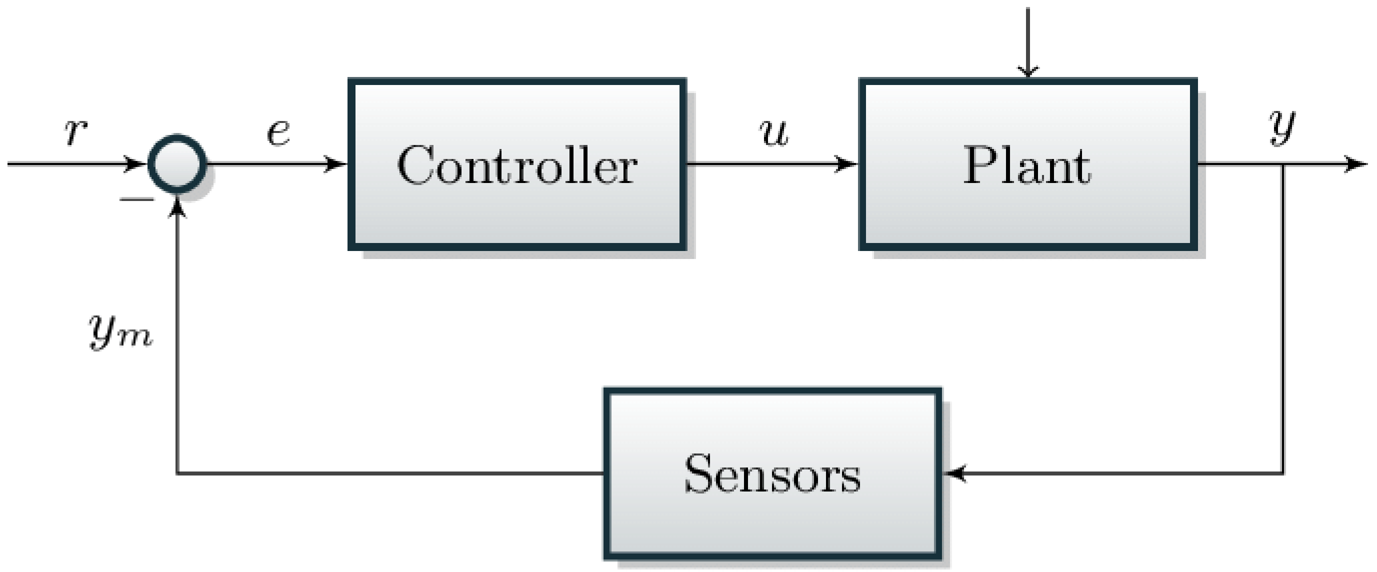

https://www.youtube.com/watch?v=FJBPNJR2QJU




https://youtu.be/XwiX2vv14Qs

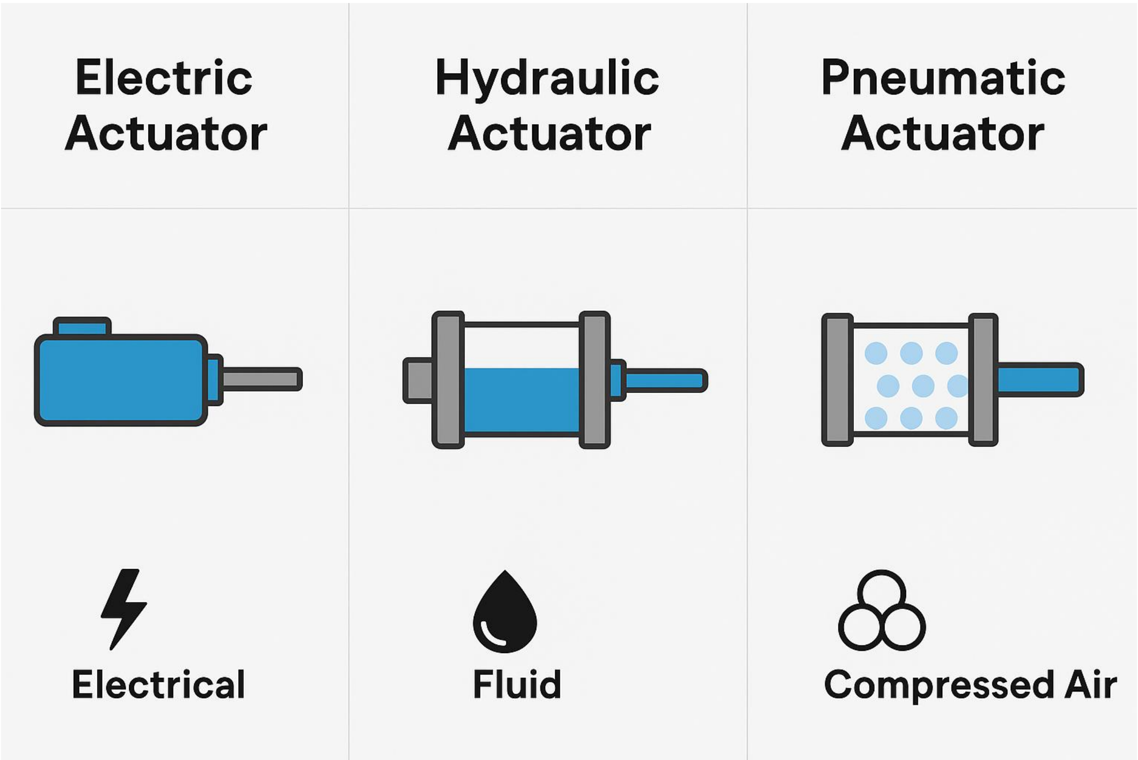
# Using Feedback in Control

- Feedback control
  - Use sensors for position, velocity and force
  - Compare with the desired behavior to compute the control signals



# Actuators

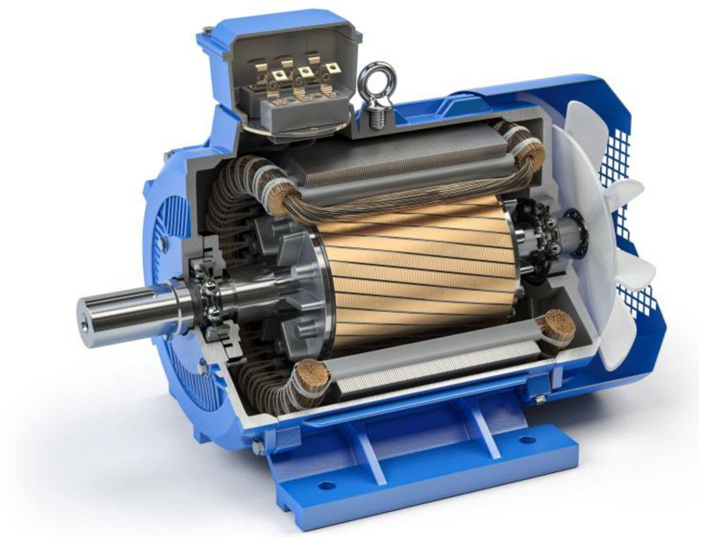
- An **actuator** converts **energy** (usually electrical, hydraulic, or pneumatic) into **mechanical motion** (force or torque)




Hydraulic and Pneumatic Actuators:
Electricity → Mechanical rotation (motor) → Fluid/Air pressure (pump) → Motion (actuator)

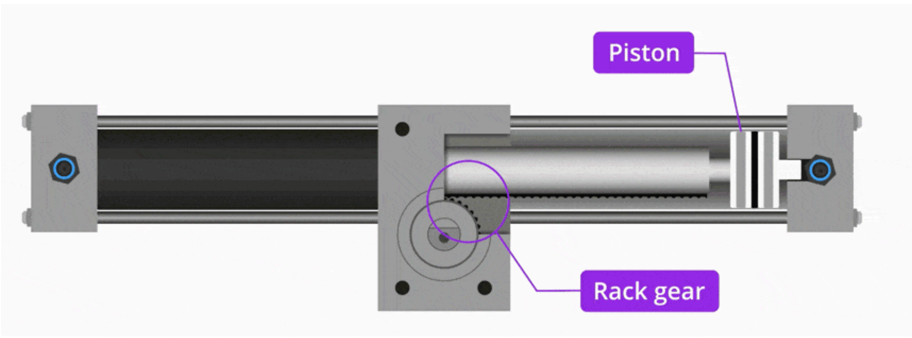
# Actuators

- Electric actuators → Best for precision and control (industrial & collaborative robots).
- Hydraulic actuators → Best for power and stiffness (heavy-duty or dynamic humanoids).
- Pneumatic actuators → Best for speed, simplicity, and soft interaction (grippers, lightweight robots)



Electric actuator

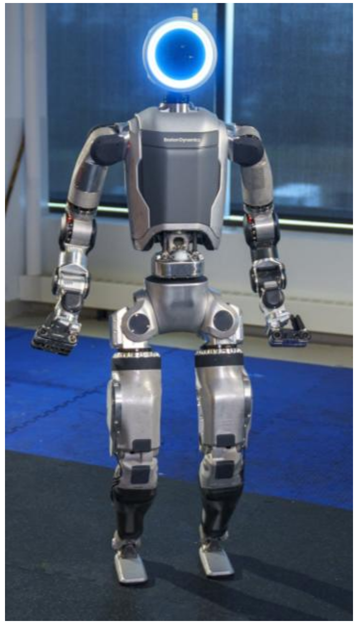
Hydraulic actuator




Pneumatic actuator

# Boston Dynamics Atlas

Hydraulic Version

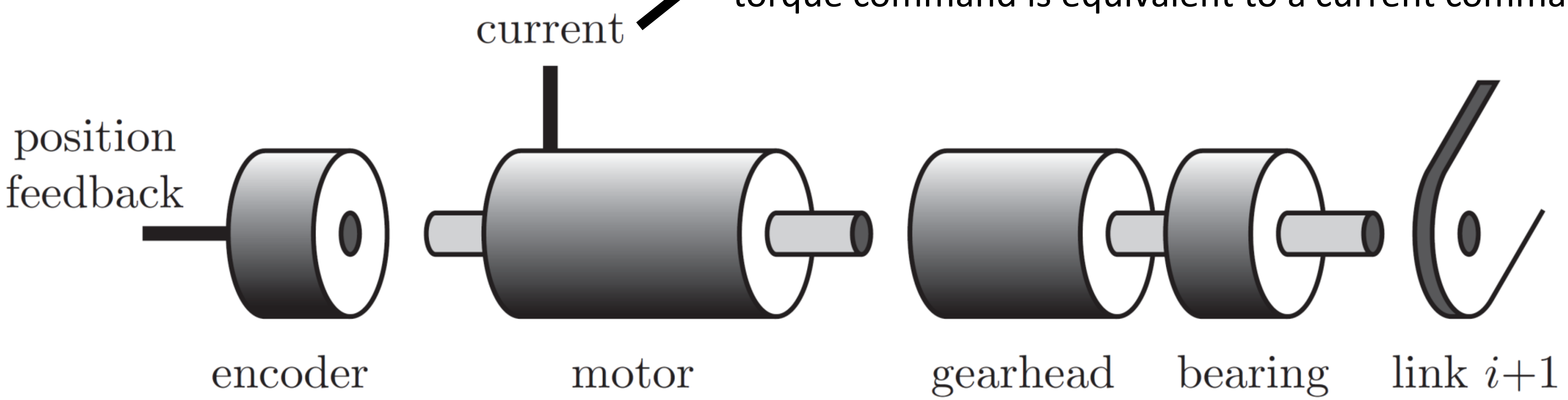


Electric Version

| Version | Height | Weight |
| --- | --- | --- |
| Atlas (2013, hydraulic) | 188 cm (6′2″) | ~150 kg (330 lb) |
| Atlas HD (2016, hydraulic, "next-gen"/battery) | 150 cm (4′11″) | 80 kg (176 lb) |

# Actuation with DC Electric Motors

a torque proportional to the current through the motor, this torque command is equivalent to a current command

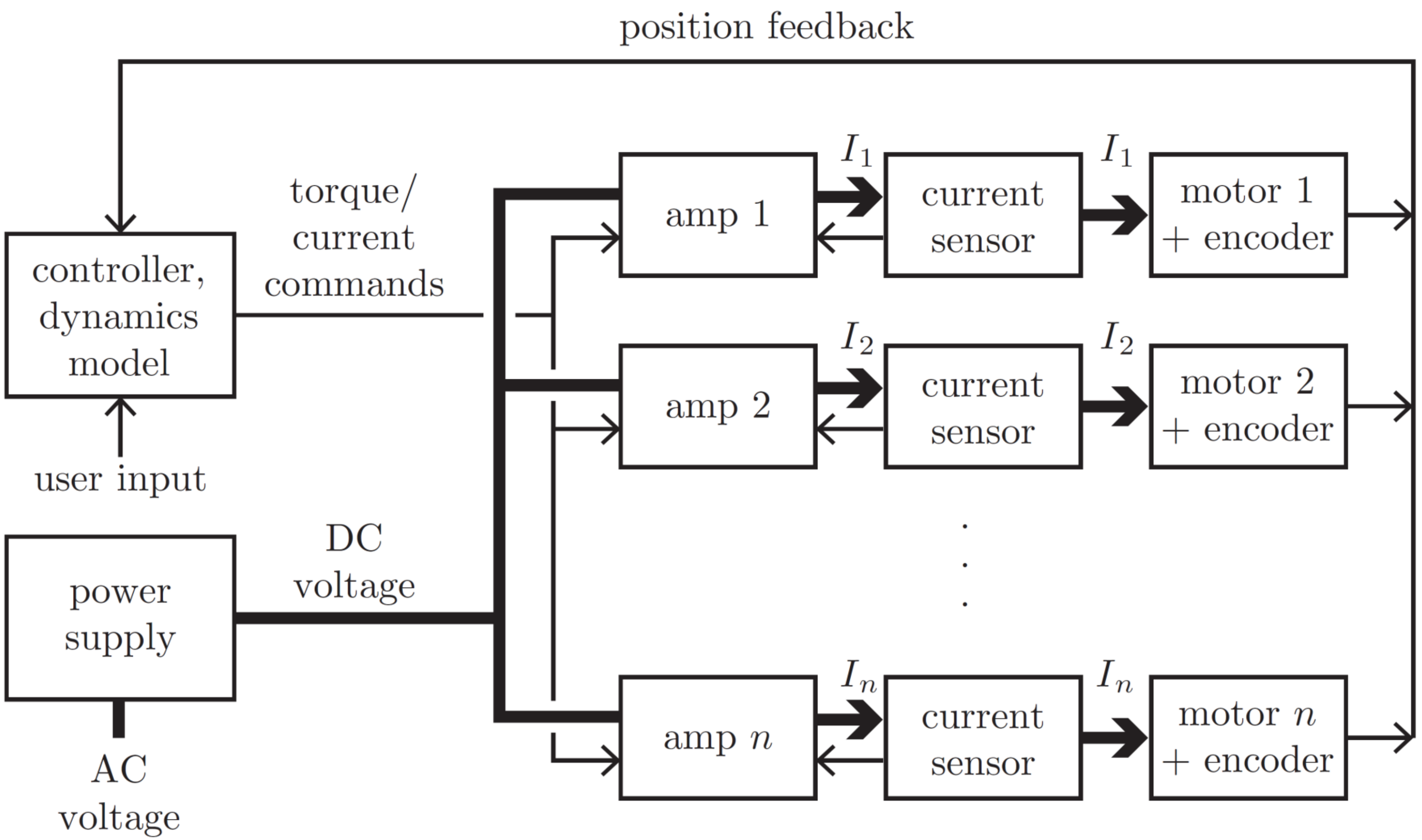



measures the position of the joint

Increase torque
Reduce speed

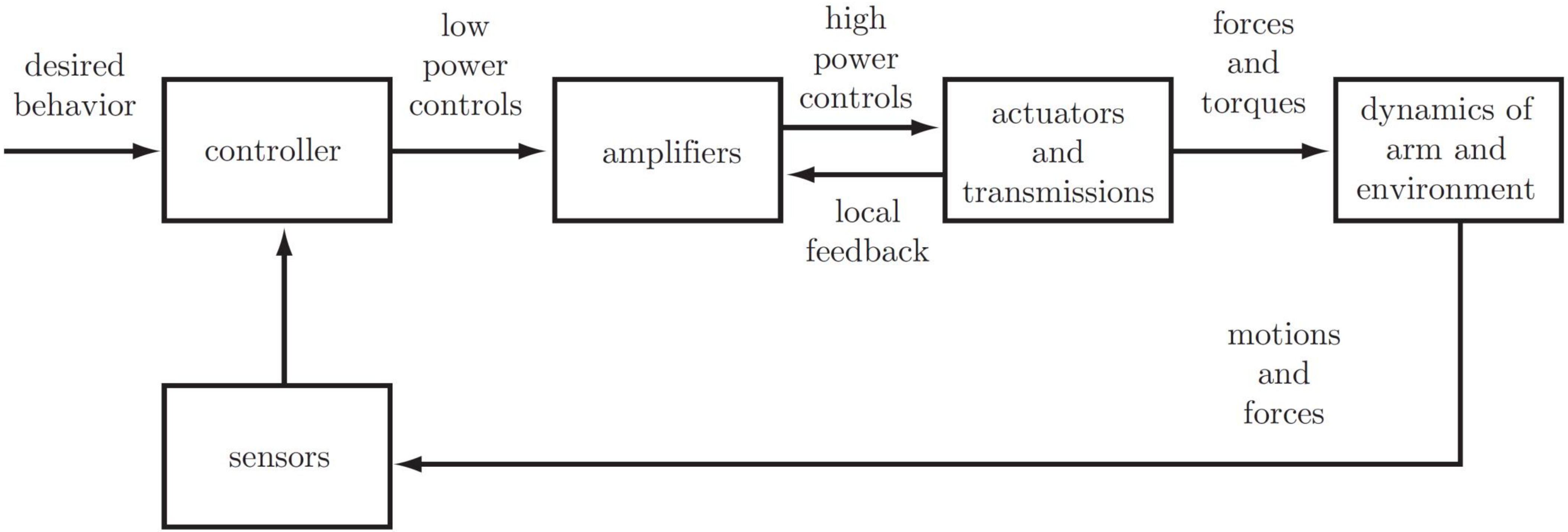
isolating the gearhead (and motor) from wrench components due to link i + 1

# Actuation with DC Electric Motors




amplifier adjust the voltage sense the joint position

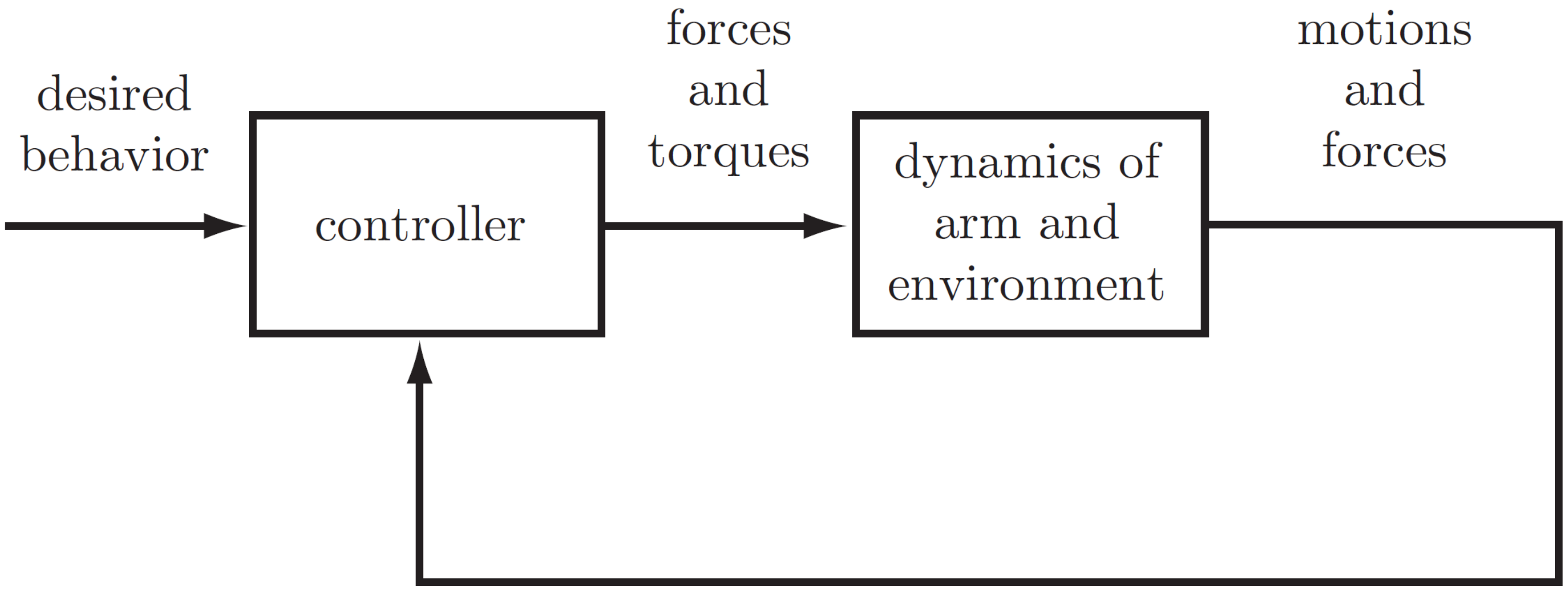
# Control System Overview




- Potentiometers, encoders, or resolvers for joint position and angle sensing
- Tachometers for joint velocity sensing
- Joint force-torque sensors
- Multi-axis force-torque sensors at the “wrist" between the end of the arm and the end-effector

# Control System Overview

- A simplified system



# Robot Dynamics

commanded joint torques

geometric Jacobian

$$M(\theta)\ddot{\theta} + c(\theta, \dot{\theta})\dot{\theta} + g(\theta) = \tau + J(\theta)^T F_{\text{tip}}$$

inertia matrix

Coriolis/centrifugal terms

gravity torques

Wrench acting on the robot by the environment

**environment-on-robot**

# Robot Dynamics

- For example, Lynch & Park 8.4

The robot applies an external wrench at the end-effector

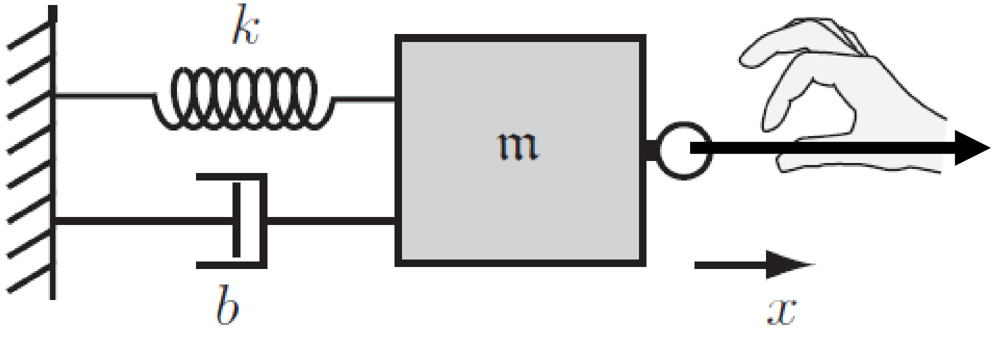
$$\tau = M(\theta)\ddot{\theta} + c(\theta, \dot{\theta}) + g(\theta) + J^{\mathrm{T}}(\theta)\mathcal{F}_{\mathrm{tip}}$$

$$\begin{aligned} M(\theta) &= \mathcal{A}^T \mathcal{L}^{\mathrm{T}}(\theta)\mathcal{G}\mathcal{L}(\theta)\mathcal{A}, \\ c(\theta, \dot{\theta}) &= -\mathcal{A}^T \mathcal{L}^T(\theta)\left(\mathcal{G}\mathcal{L}(\theta)\left[\mathrm{ad}_{\mathcal{A}\dot{\theta}}\right]\mathcal{W}(\theta) + [\mathrm{ad}_{\mathcal{V}}]^{\mathrm{T}}\mathcal{G}\right)\mathcal{L}(\theta)\mathcal{A}\dot{\theta} \\ g(\theta) &= \mathcal{A}^T \mathcal{L}^T(\theta)\mathcal{G}\mathcal{L}(\theta)\dot{\mathcal{V}}_{\mathrm{base}}. \end{aligned}$$

# Mass-Spring-Damper Dynamics

Spring force $-kx$

$k$= **spring constant**, or **stiffness**




External force $f$

Damping force $-b\dot{x}$

Newton's second law

$$f - kx - b\dot{x} = m\ddot{x}$$

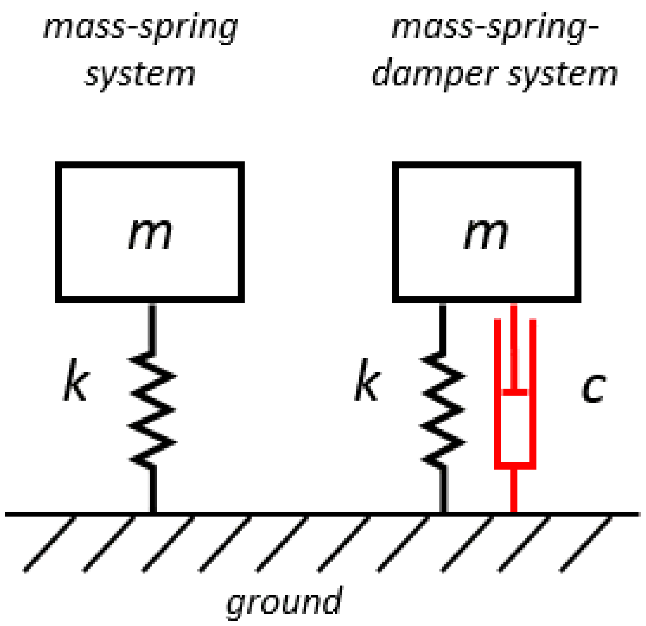
$$m\ddot{x} + b\dot{x} + kx = f$$

Robot dynamics

$$M(\theta)\ddot{\theta} + c(\theta, \dot{\theta})\dot{\theta} + g(\theta) = \tau + J(\theta)^T F_{\text{tip}}$$

# Mass-Spring-Damper Dynamics

- Damper: **resists motion** and **dissipates energy** — like friction or air resistance (slowing it down over time)

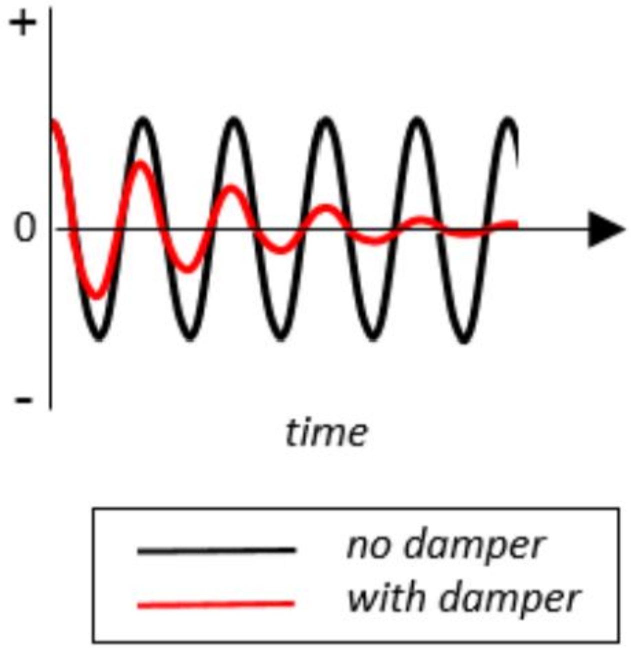


# Mass-Spring-Damper Dynamics

$$m\ddot{x} + b\dot{x} + kx = f$$

- Frequency = how many complete cycles (back-and-forth motions) happen per second
  - Unit: Hertz (Hz), cycles per second
- Natural frequency: frequency the system would oscillate at if there were no damping

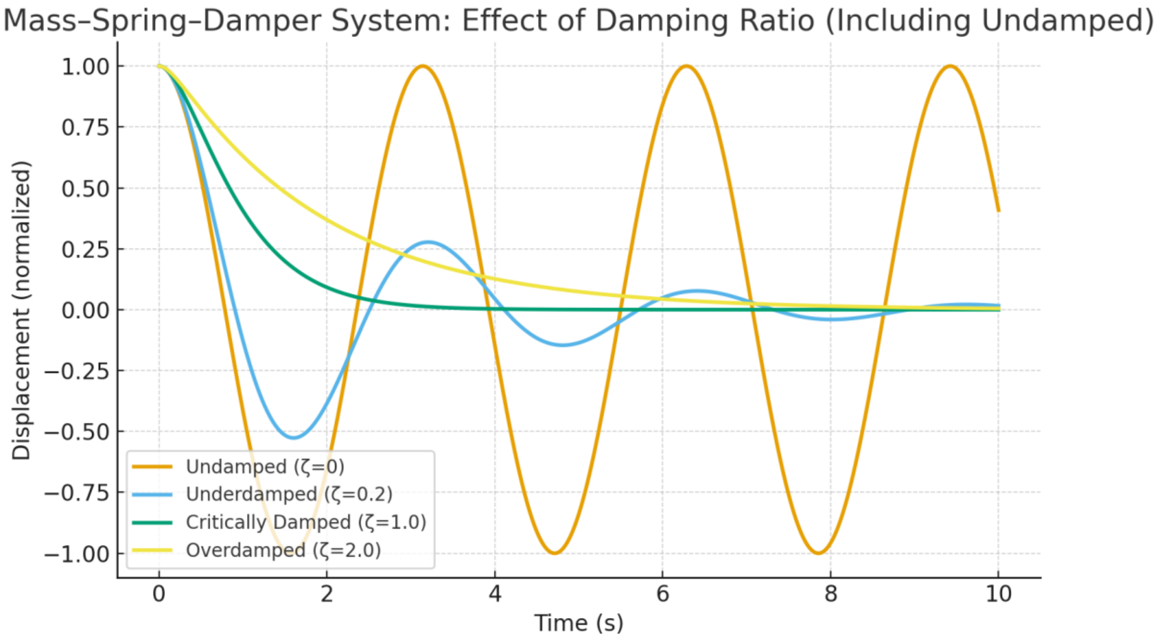
radians per second $\omega_n = \sqrt{\frac{k}{m}}$ Hertz $f_n = \frac{\omega_n}{2\pi}$




- Damped Natural Frequency $\omega_d$

$\omega_d = \omega_n \sqrt{1 - \zeta^2}$ Damping ratio $\zeta = \frac{b}{2\sqrt{km}}$

# Mass-Spring-Damper Dynamics $m\ddot{x} + b\dot{x} + kx = f$




$$\zeta = \frac{b}{2\sqrt{km}}$$

| Damping Ratio (ζ) | Behavior | Motion | Damped Frequency |
|---|---|---|---|
| **$\zeta = 0$** | Undamped | Pure oscillation | $\omega_n$ |
| **$0 < \zeta < 1$** | Underdamped | Oscillates and decays | $\omega_n\sqrt{(1-\zeta^2)}$ |
| **$\zeta = 1$** | Critically damped | No oscillation, fastest return | 0 |
| **$\zeta > 1$** | Overdamped | No oscillation, slow return | *Imaginary* (no real $\omega_n$) |

# Controlled Dynamics of a Single Joint

- Desired joint position $\theta_d(t)$
- The current joint position $\theta(t)$
- Joint error $\theta_e(t) = \theta_d(t) - \theta(t)$

- Error dynamics: the differential equation governing the evolution of the joint error

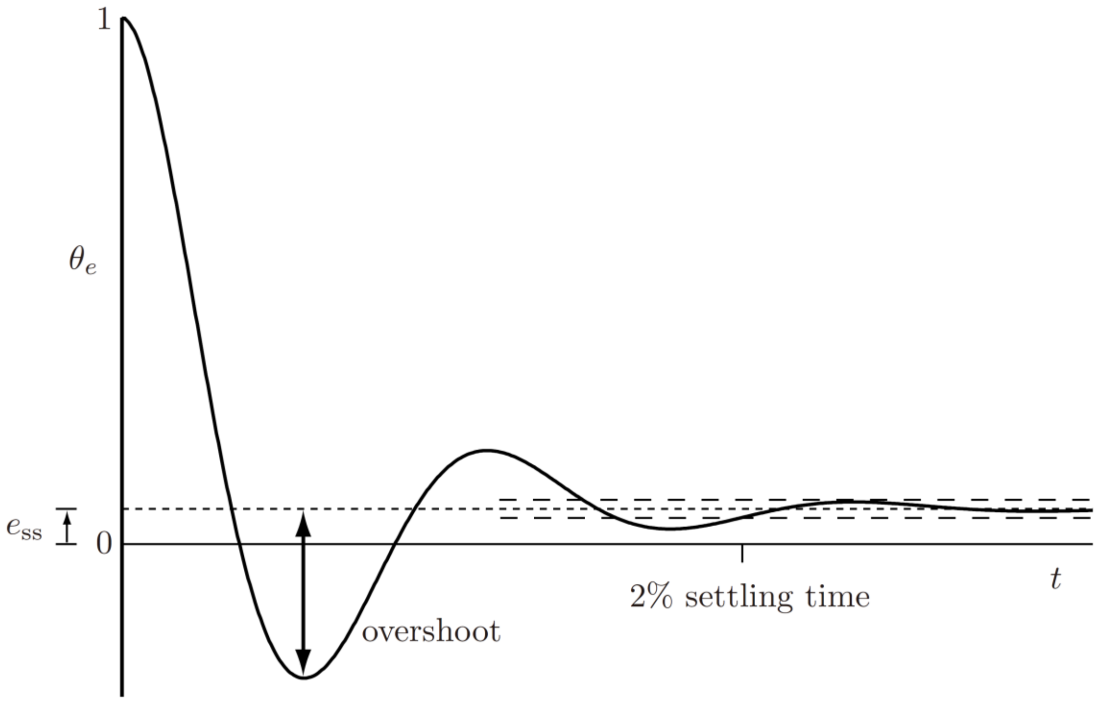
- Feedback controller: create an error dynamics to make $\theta_e(t)$ become zero or a small value when t increases

# Error Response

- How well a controller works?
  - Specify a nonzero initial error $\theta_e(0)$ and see how the controller reduces the error

- Error response $\theta_e(t), t > 0$
  - Initial conditions $\theta_e(0) = 1$
    $\dot{\theta}_e(0) = \ddot{\theta}_e(0) = \cdots = 0$

  - Steady-state error $\theta_e(t)$ as $t \to \infty$

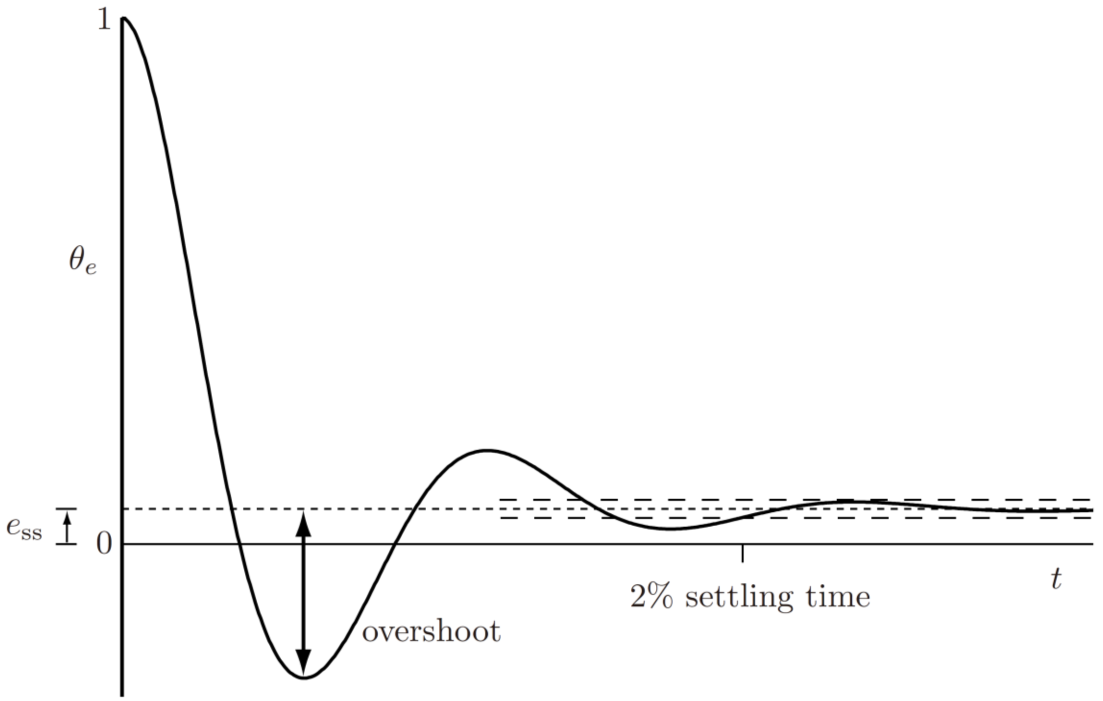


# Error Response

- (2%) Settling time: first time T such that $|\theta_e(t) - e_{\mathrm{ss}}| \leq 0.02(\theta_e(0) - e_{\mathrm{ss}})$ for all $t \geq T$

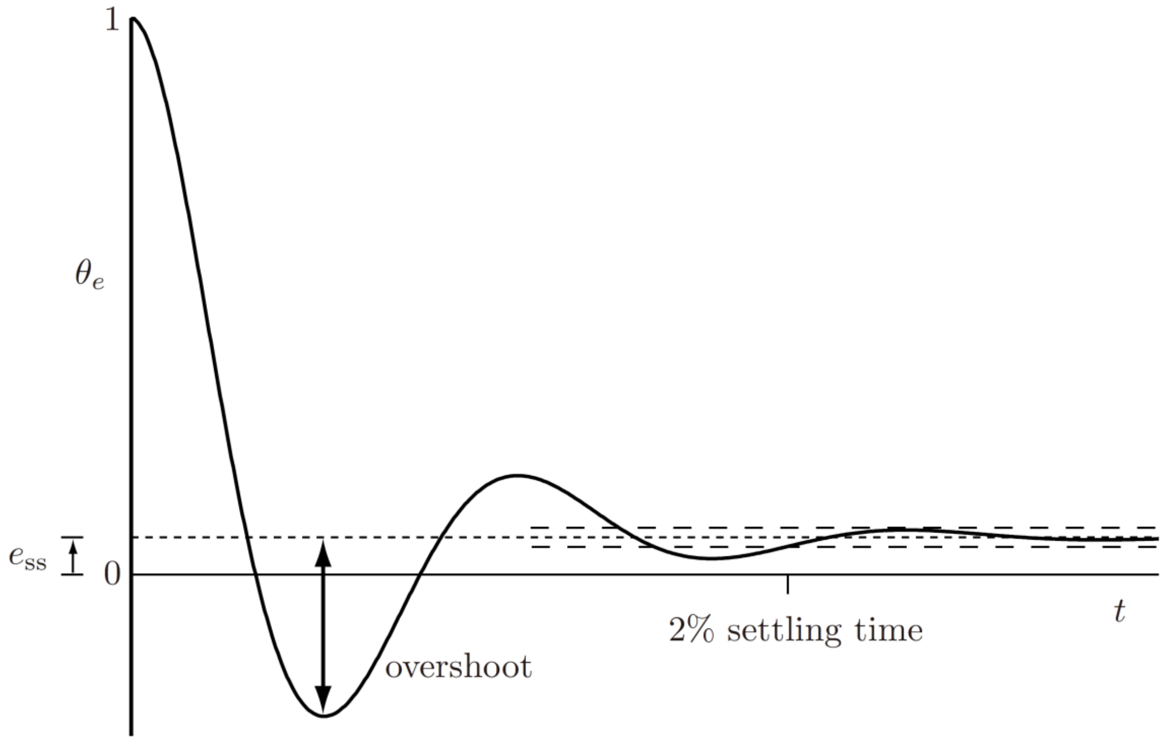
- Overshoot

$$\text{overshoot} = \left| \frac{\theta_{e,\min} - e_{\mathrm{ss}}}{\theta_e(0) - e_{\mathrm{ss}}} \right| \times 100\%$$



# Error Response

- A good error response
  - steady-state error    Little or no
  - overshoot    Little or no
  - 2% settling time    A short



# Summary

- Robot control
- Actuators
- Mass-Spring-Damper Dynamics
- Error dynamics

# Further Reading

- Chapter 11 in Kevin M. Lynch and Frank C. Park. Modern Robotics: Mechanics, Planning, and Control. 1st Edition, 2017.