Introduction to Control
EE160 Fall 2025

Chen, Jiahao
SIST 1D#206

上海科技大学
ShanghaiTech University

Introduction to (Linear) Control (Theory)
EE160 Fall 2025

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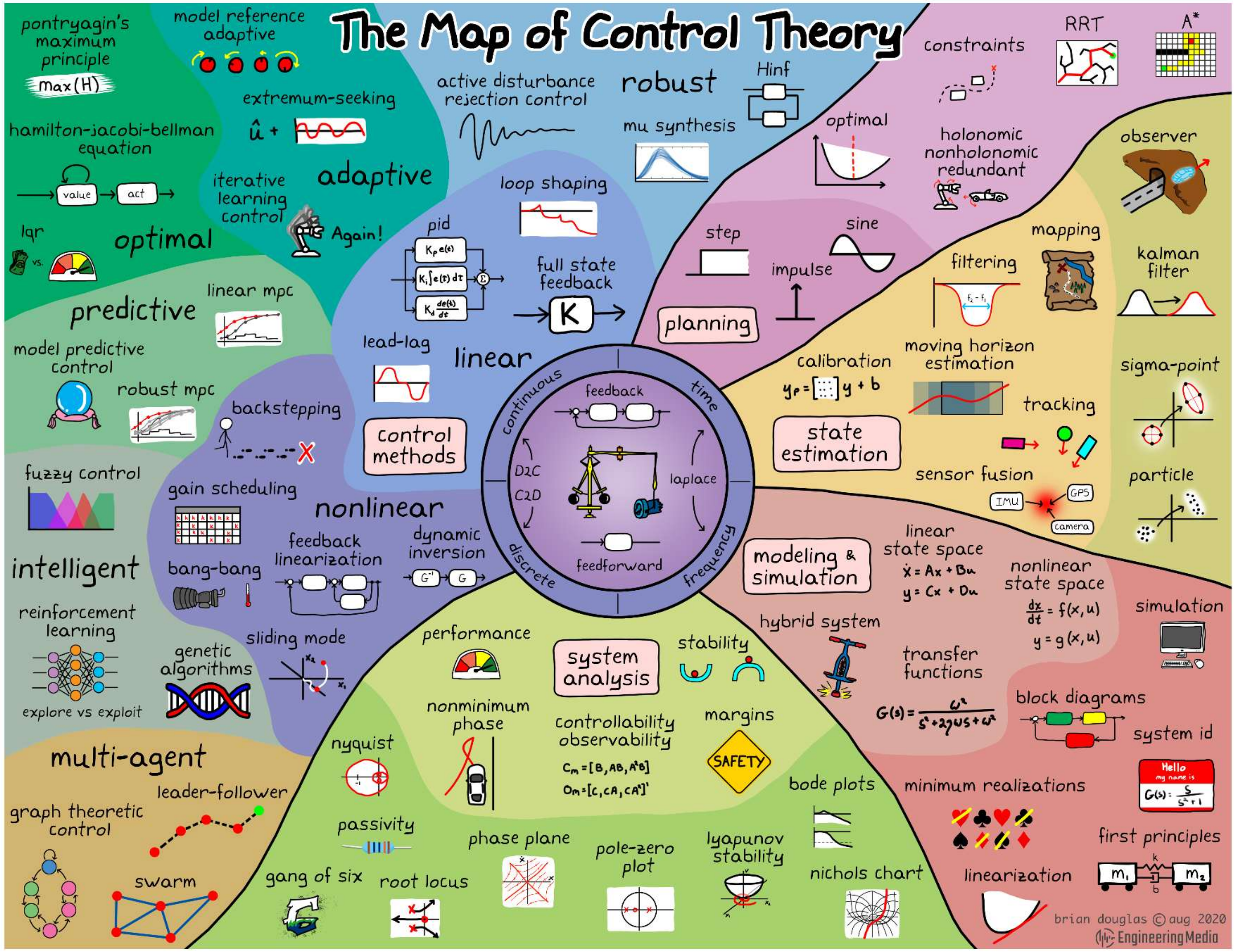
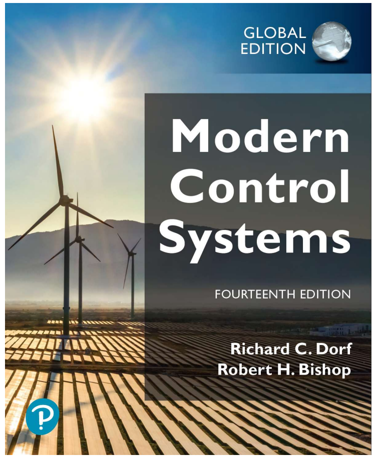
The Map



Bishop



References (1/3)

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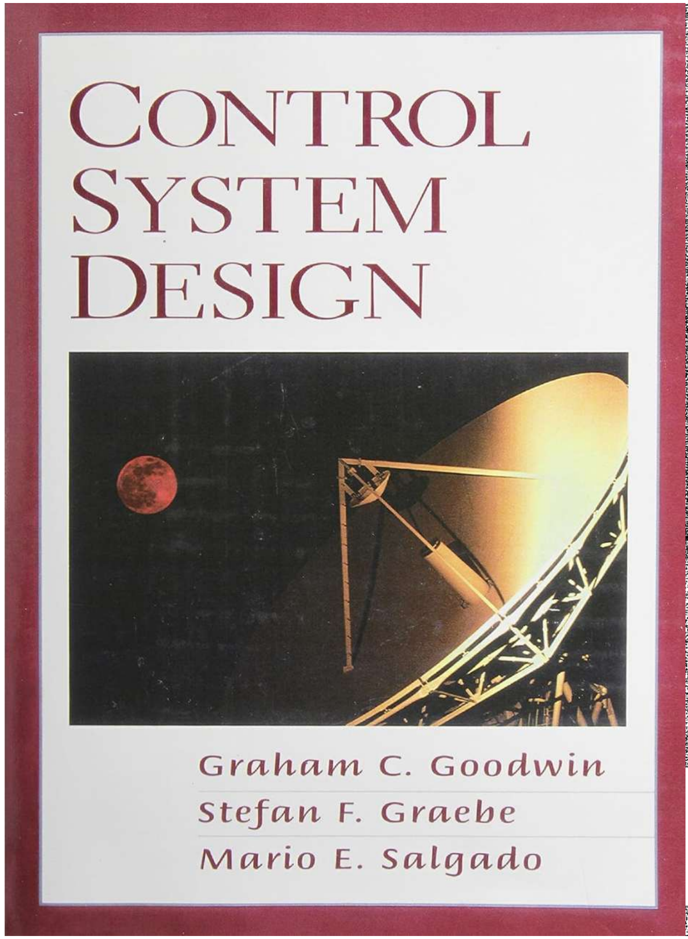
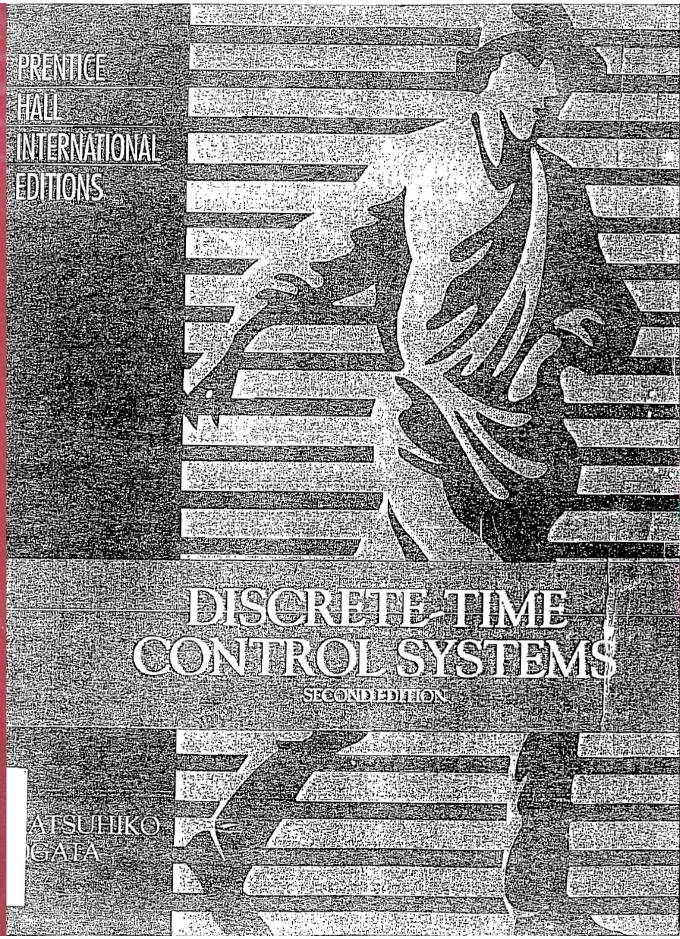
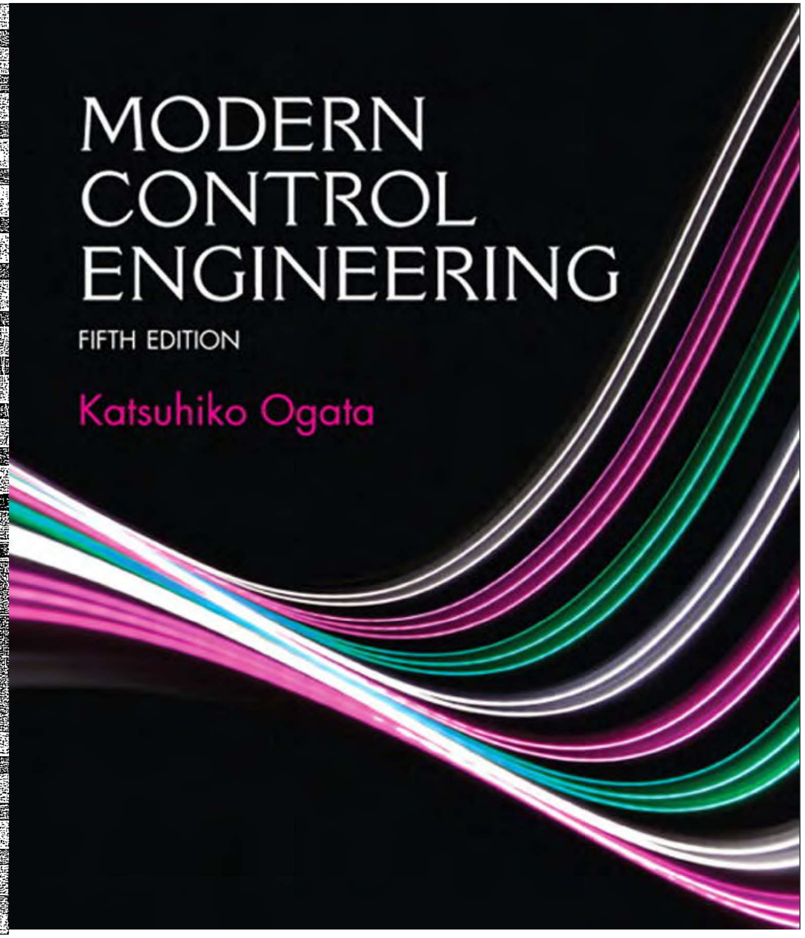
- Linear Systems, Linear Optimal Gaussian, Noises, MPC, Windup, Discrete Time

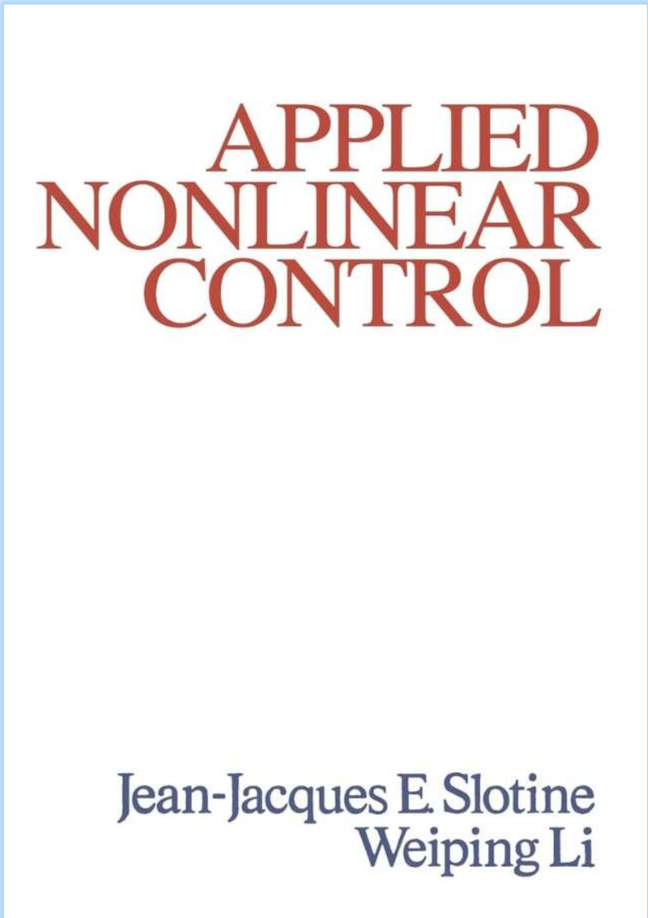


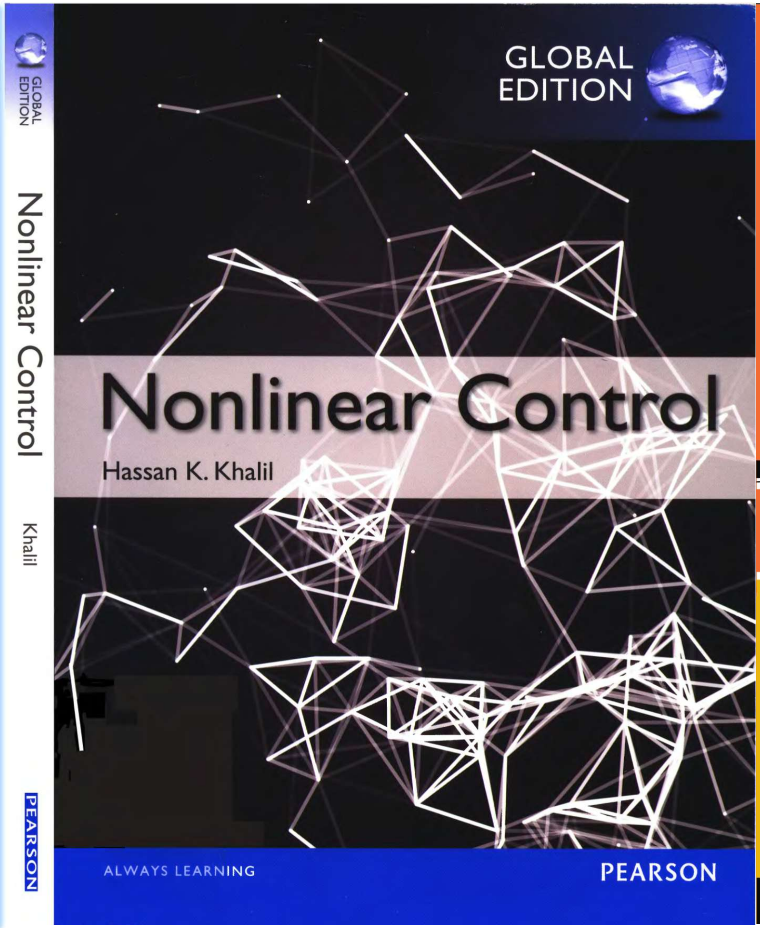


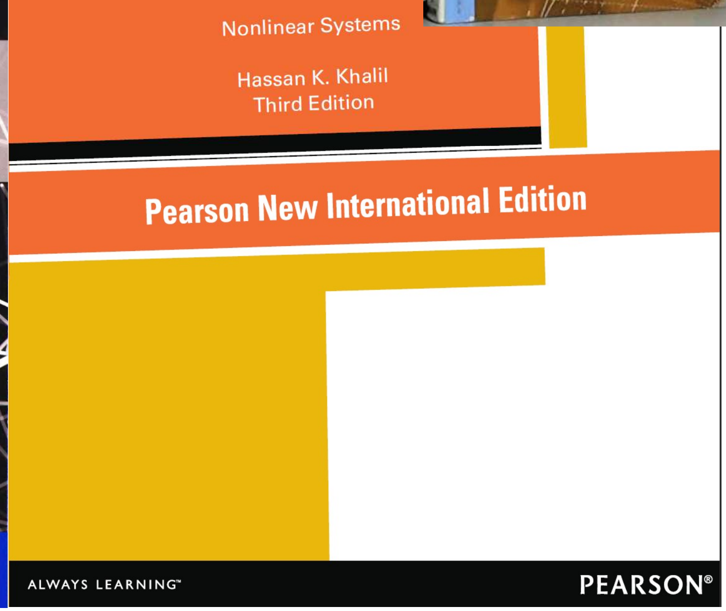


References (2/3)

- Nonlinear Control, e.g., Sliding Mode Control

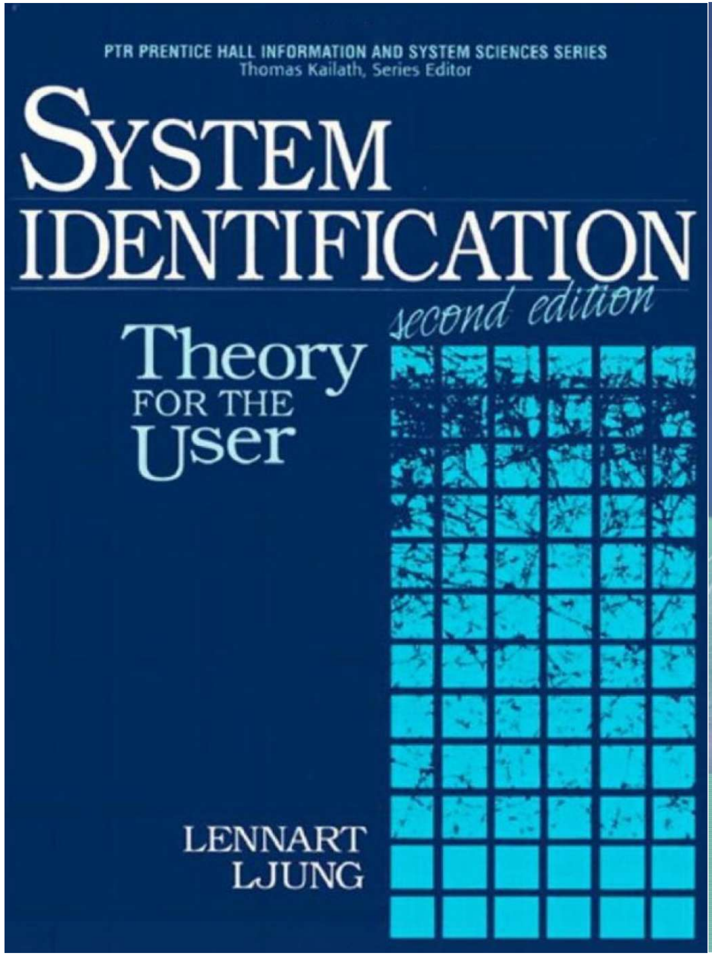


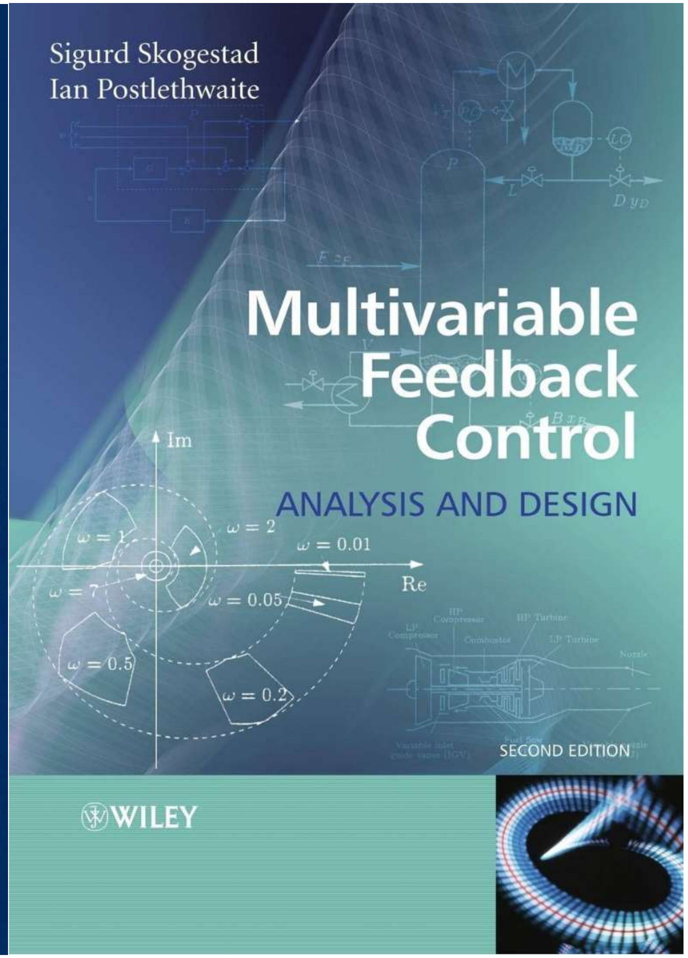


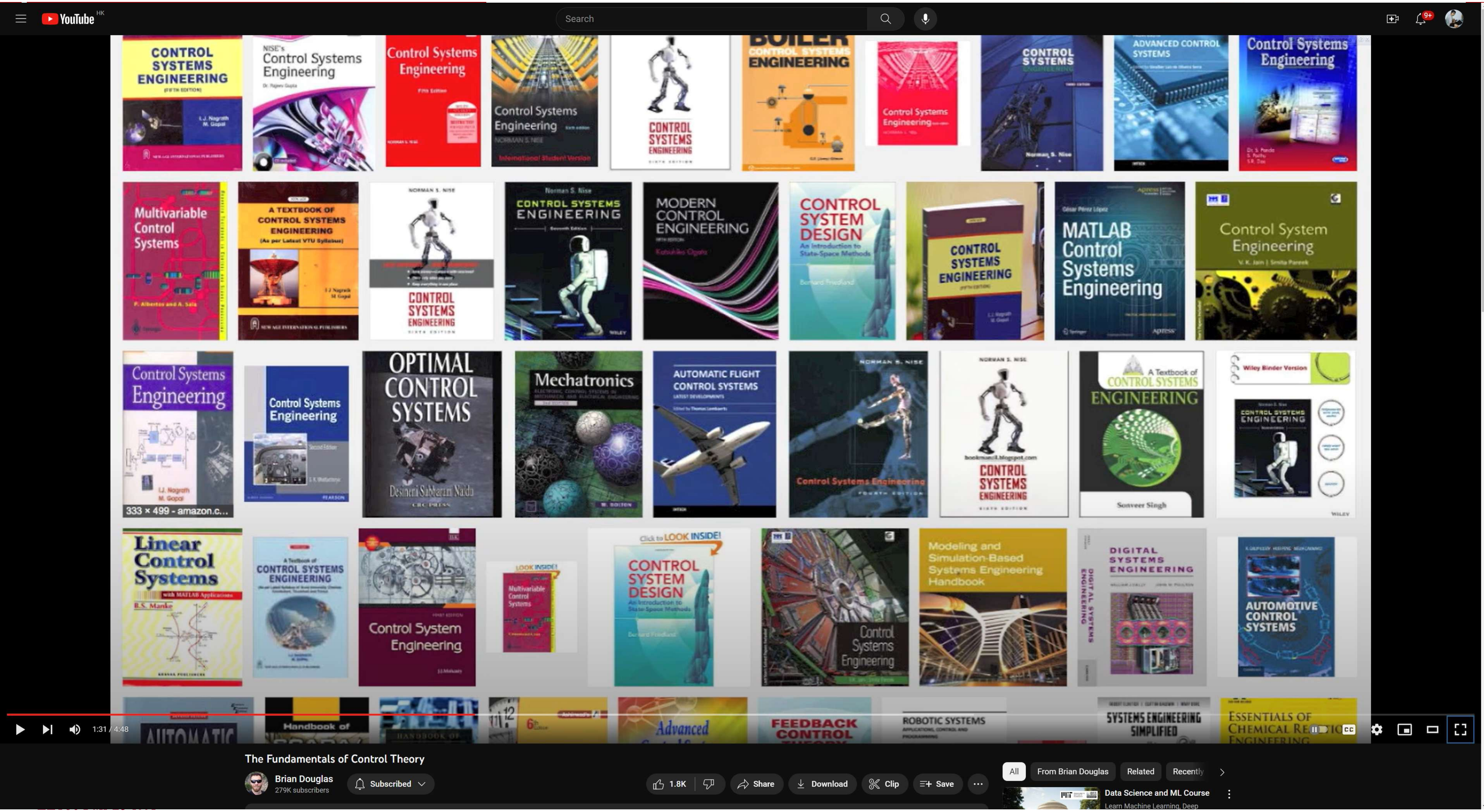


References (3/3)

- Multivariable Control, Robust Control, System Identification



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- Self learning resources:
  - Brian Douglas https://ww2.mathworks.cn/en/videos/series/control-systems-in-practice.html

which is more suited than Bruton's control bootcamp on Youtube

There are more tech talks by MATLAB at:

https://ww2.mathworks.cn/videos/tech-talks/controls.html

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Control Systems in Practice

In this series, you'll learn some of the more practical aspects of being a control systems engineer and designing control systems. The day-to-day role of a control systems engineer is more than just designing a controller and tuning it. Depending on the size and phase of the project, your responsibilities and which groups you work with will probably vary greatly. Designing and testing control systems is still a large portion of the job. This series covers some of the more common control techniques that you'll encounter as a control systems engineer: gain scheduling and feedforward. Often, the best control system is the simplest and, therefore, the most practical in a wide range of control problems. Gain scheduling, a method that adjusts the gains of simple linear controllers to control nonlinear systems, and feedforward, a method that uses setpoint changes and measured disturbances to limit the feedback error, are two popular and simple techniques for developing practical controllers. Finally, this series also covers time delays in dynamic systems—where they come from and why they matter. When time delay becomes a problem for your system, minimizing the delay at the source is almost always preferred over developing a clever way for your controller to handle it. It's easy to assume that a control engineering's job is to spend months developing a state-of-the-art nonlinear controller. However, there are more practical ways of handling these problems.

What Is Feedforward Control?

A control system has two main goals: get the system to track a setpoint, and reject disturbances. Feedback control is pretty powerful for this, but this video shows how feedforward control can supplement feedback to make achieving those goals easier.

What Control Systems Engineers Do

The work of a control systems engineer involves more than just designing a controller and tuning it. This video provides a picture of the types of things you may be exposed to and the groups with which you might interface while working in this field.

Course Information

Logistics

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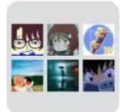
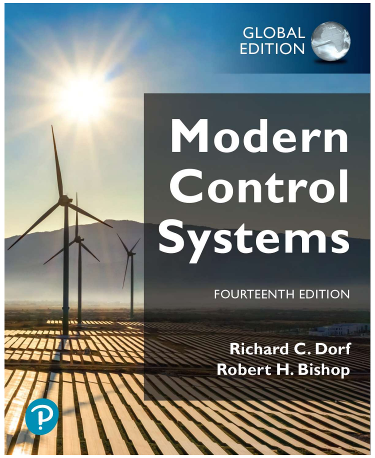
- Course: EE160 Introduction to Control
- Classroom: 教学中心303
- Time: Tuesday and Thursday 10:15–11:55 am
  - Except week 6 and 15
- Instructor: 陈嘉豪; chenjh2@shanghaitech.edu.cn; (021)2068 5662
- TA: 周申韬，黄晟真，吴波，王柯语，陈佳华
- Experiment with LT: 李正浩
- EE160P is optional!
- Grades: 50% homework/experiment + 50% exam
- Textbook: Modern Control Systems 14th Ed by R. Dorf, R. Bishop
  - Lecture notes：https://faculty.sist.shanghaitech.edu.cn/chenjh/docs/courses/EE160/
- Online materials: Blackboard
- Software proficiency: Python and/or Matlab
- Prerequisite: Calculus, Linear Algebra, O.D.E.

节次/周次	星期一	星期二	星期三	星期四
第一节 8:15 - 9:00				
第二节 9:10 - 9:55				
第三节 10:15 - 11:00		控制原理(EE160.01) (陈嘉豪)		控制原理(EE160.01) (陈嘉豪)
第四节 11:10 - 11:55		(1-5 7-14 16,教学中心303)		(1-5 7-14 16,教学中心303)



Group: EE160秋2025班



Valid until 9/16 and will update upon joining group

Review: Two Kernels

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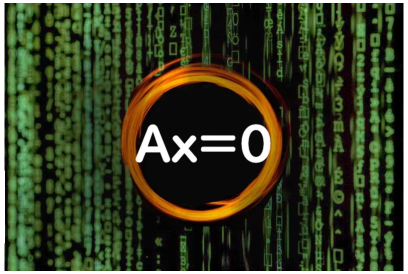
- Integral Transform in Calculus

$$F(\alpha) = \int_a^b f(t)K(\alpha, t)dt.$$

  - Fourier transform has the **Kernel** = $K(\omega, t) = e^{-j\omega t}$, $a = -\infty$, $b = \infty$
  - Laplace transform has the **Kernel** = $K(s, t) = e^{-st}$, $a = 0^-$, $b = \infty$
  - Convolution (see Appendix of lecture notes)



- Eigenvalues in Linear Algebra
  - the **kernel** of A = the null space of A

$$\mathrm{N}(A) = \mathrm{Null}(A) = \ker(A) = \{\mathbf{x} \in K^n \mid A\mathbf{x} = \mathbf{0}\}.$$

  - References:
    - Skogestad's Appendix A (the most powerful)
    - Control Systems: an Introduction by Hassan K. Khalil
    - Appendix E of our textbook by Bishop

- O.D.E.
  - $\frac{\mathrm{d}x}{\mathrm{d}t} = \lambda x$
    - $\Rightarrow \frac{\mathrm{d}x}{x} = \lambda \mathrm{d}t \Rightarrow \ln|x| - \ln|x(0)| = \lambda t \Rightarrow x(t) = x(0)\mathrm{e}^{\lambda t}$

442 APPENDIX B. ELEMENTS OF MATRIX ANALYSIS

Appendix B
Elements of Matrix Analysis

Eigenvalues and eigenvectors:

For an $n \times n$ square matrix A, the n-dimensional vector υ and the scalar λ are the eigenvector and eigenvalue of A, respectively, if

$$A\upsilon = \lambda\upsilon .$$

This equation can be rewritten as

$$(\lambda I - A)\upsilon = 0 ,$$

which shows that the columns of $(\lambda I - A)$ are linearly dependent because a linear combination of them equals zero. Therefore,

$$\det(\lambda I - A) = 0.$$

This is a polynomial equation of degree n, called the ***characteristic equation*** of A. It has n roots, which are the eigenvalues of A. The eigenvalues of a real matrix could be complex, but complex eigenvalues will be in conjugate pairs because the polynomial $\det(\lambda I - A)$ has real coefficients.

In MATLAB, the eigenvalues and eigenvector of a matrix are computed using the command "eig".

$$\frac{\mathrm{d}}{\mathrm{d}t}x = \lambda x, \quad x, \lambda \in \mathbb{R}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}x = Ax, \quad x \in \mathbb{R}^n, \ A \in \mathbb{R}^{n\times n}$$

$$Ax = \lambda x$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathrm{e}^{\lambda x} = \lambda\,\mathrm{e}^{\lambda x}$$

See 如何入门现代控制理论 by J Pan
https://zhuanlan.zhihu.com/p/57051153

Experimental Project

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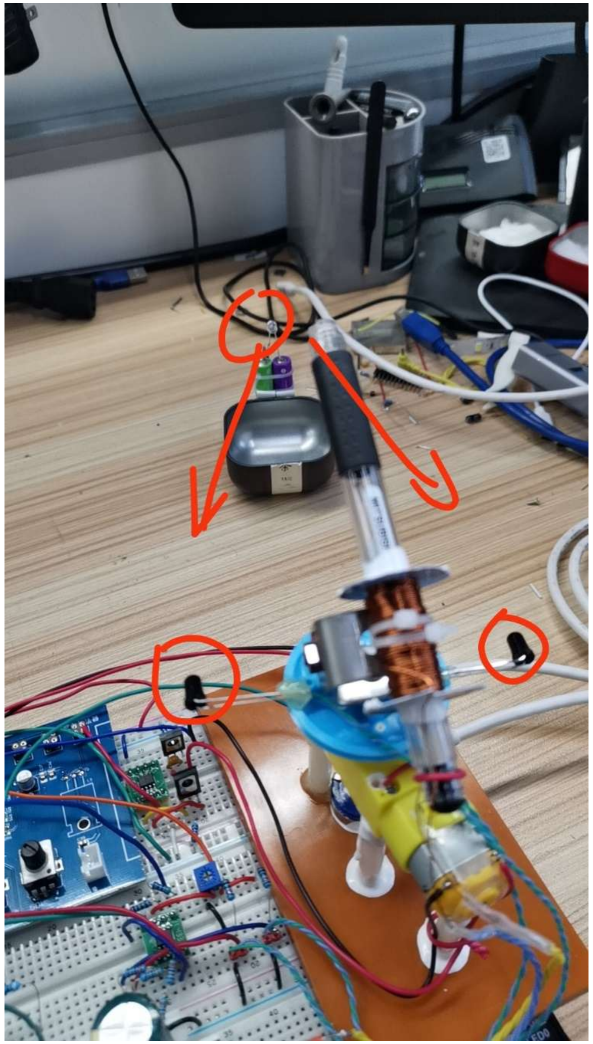
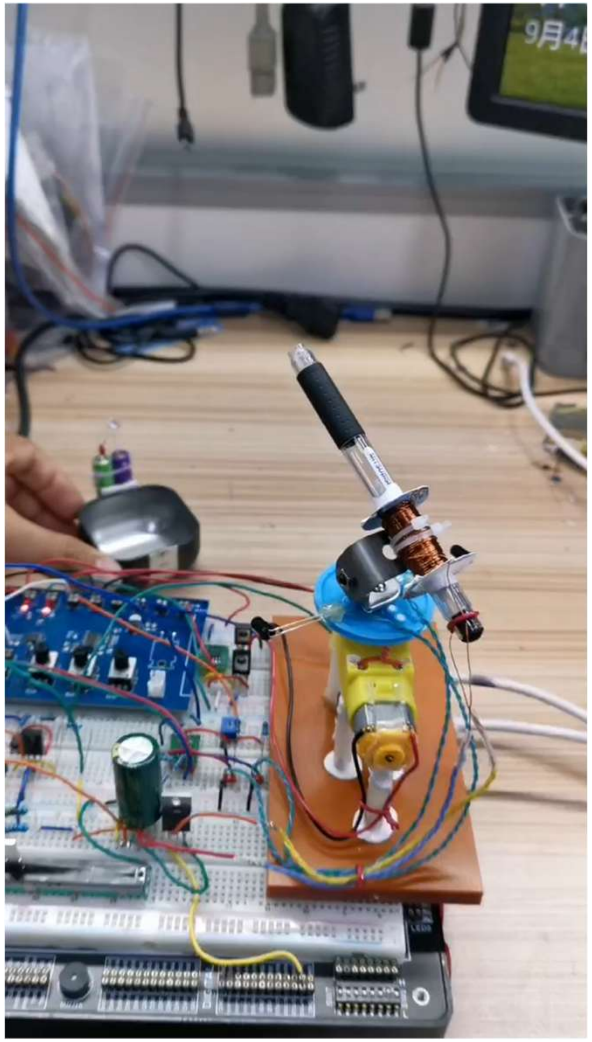
- ~~Electromagnetic Gun Highlights:~~
  - ~~Boost circuit~~
    ~~— with voltage reference~~
  - ~~PID controlled rotating turret~~
  - ~~Ferromagnetic projectile~~

- ~~Skills~~
  - ~~Soldering circuit board~~
  - ~~Hot melt glue~~

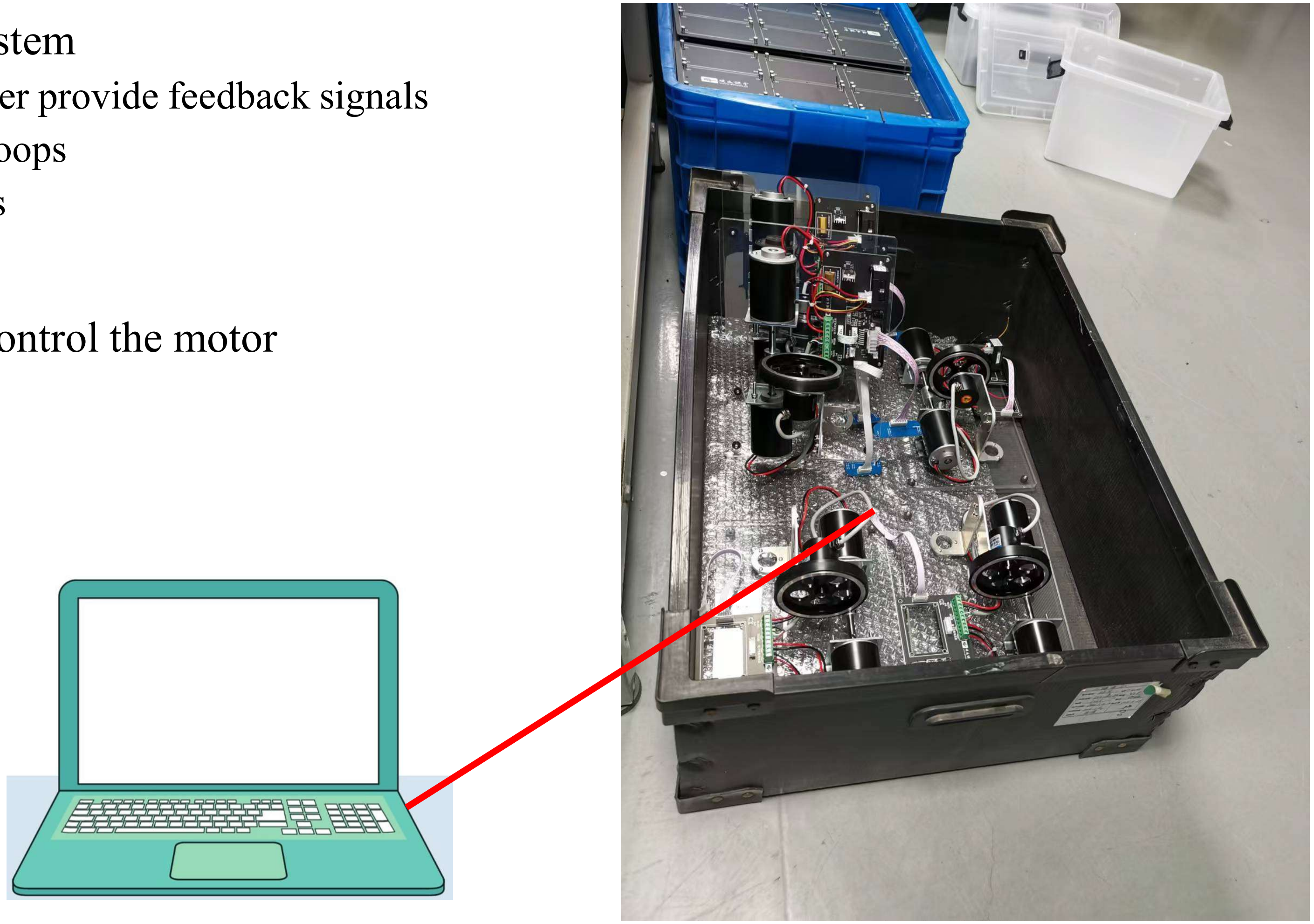




Experimental Project

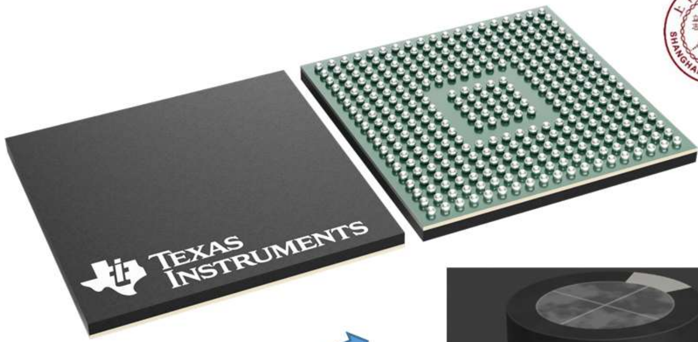
- A simple motor control system
  - Current sensor and encoder provide feedback signals
  - PI control and cascaded loops
  - Sweep frequency analysis

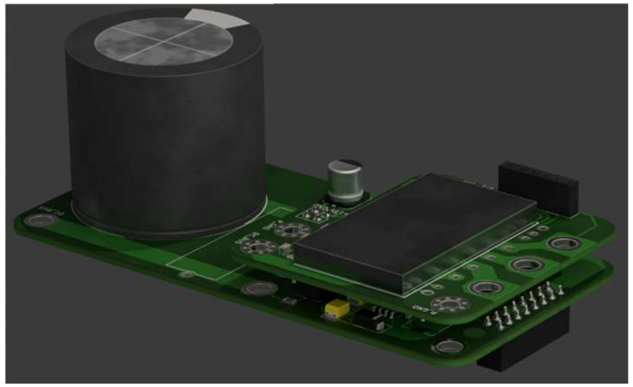
- Simulink will be used to control the motor



Experimental Project

- DSP based ac motor control system
  - TMS320F28388D in 337-pin (ZWT) package
  - Current sensor and encoder provide feedback signals
  - PI control and cascaded loops
  - Sweep frequency analysis





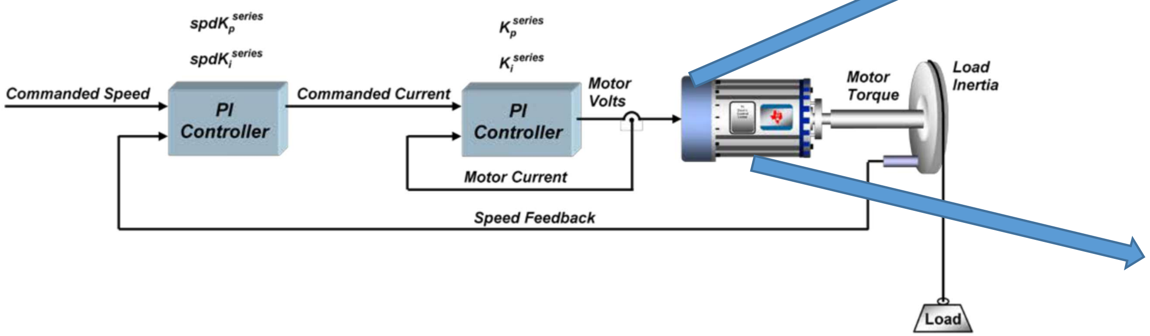


Figure 11-6. Cascaded Speed Control Loop

https://www.ti.com/product/TMS320F28388D

Control Theory

Relation to Cybernetics

- **Cybernetics** is concerned with "control and communication in the animal and the machine"

  -Wiener

- **Cyber** is short for cybernetics, used as an adjective defined as: of, relating to, or characteristic of the *culture of computers, information technology, virtual reality or even internet*.
- **Control theory** is mainly concerned with the control of dynamical systems, or more specifically, single-input single-output (SISO) dynamical systems (typically, second-order).

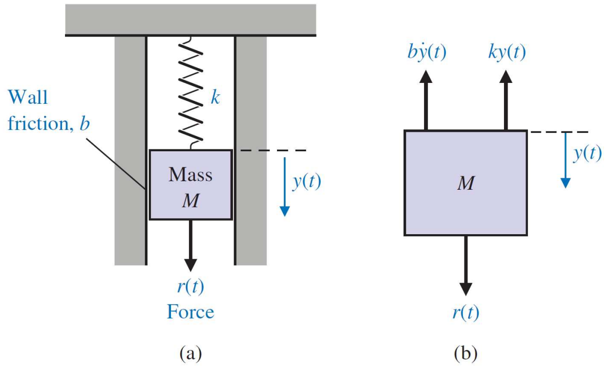


FIGURE 2.2 (a) Spring-mass-damper system. (b) Free-body diagram.

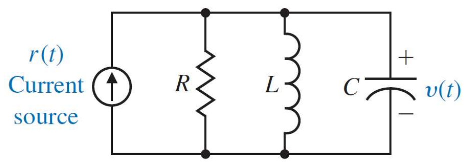


FIGURE 2.3 RLC circuit.

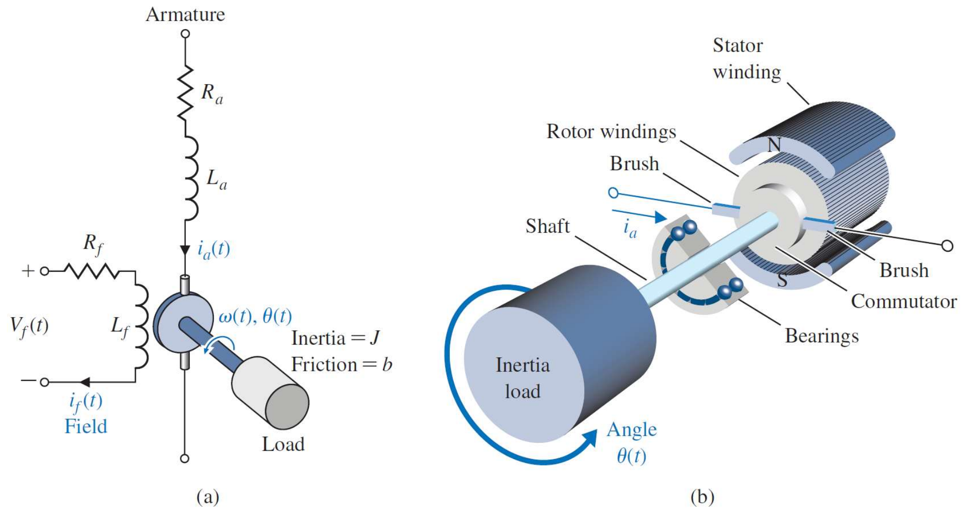


FIGURE 2.18 A DC motor (a) electrical diagram and (b) sketch.

J. Rosenberg, in Rugged Embedded Systems, 2017

What is Control Theory?

- What is control theory about?
  - Control theory deals with the control of dynamical systems in engineered processes and machines. The objective is to develop a model or algorithm governing the application of system inputs to drive the system to a **desired state**, while **minimizing any delay, overshoot, or steady-state error** and ensuring a level of **control stability**; often with the aim to achieve **a degree of optimality**.

    Quoted: Wikipedia

  - The purpose of a control system is to control a supply of energy to make the actual output of the system (the controlled variable) agree as closely as possible with the desired value (the reference input), regardless of the manner in which the **reference input varies** and regardless of how or where **external disturbances**, such as loads and variations in the level of energy supply, act on the system.

    Quoted: *PDF Control by Richard M. Phelan*

  - Control theory is concerned with **modifying the behavior of dynamical systems** so as to achieve **desired goals**. These goals include maintaining relevant outputs of a system around desired constant values, assuring that the outputs follow specified trajectories, or more generally ensuring that the overall system optimizes a specified performance criterion.

    Quoted: *The Maturing of Adaptive Control by K.S. Narendra*

C.T. studies Three Problems

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System Identification Problem

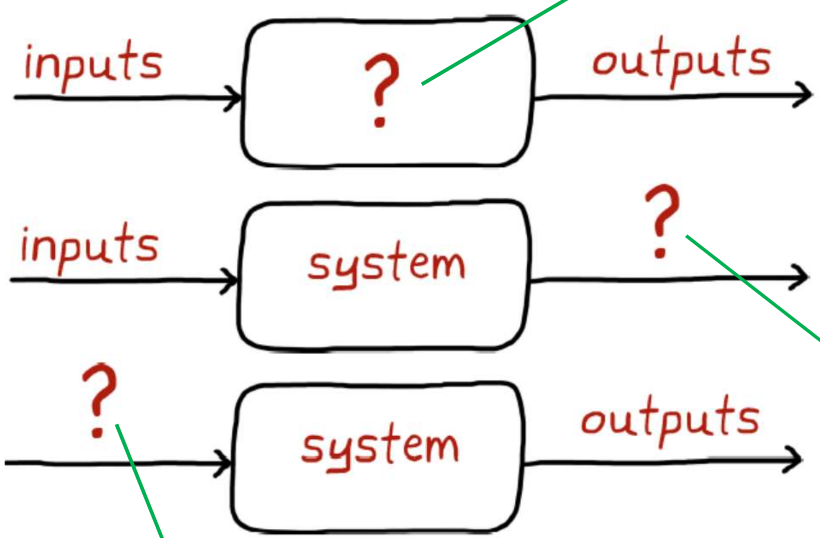
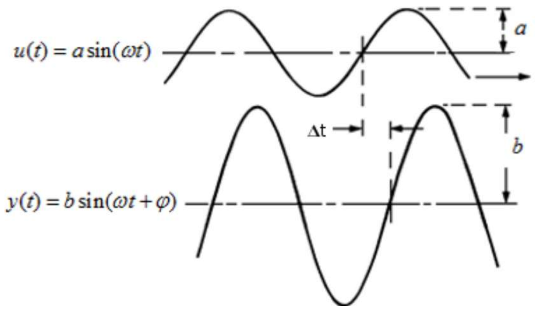


Fig. Three different problems arise in control systems



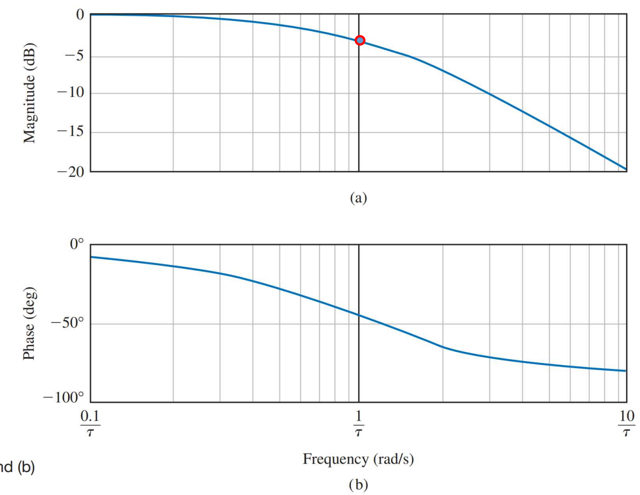


FIGURE 8.6
Bode plot for $G(j\omega) = 1/(j\omega\tau + 1)$: (a) magnitude plot and (b) phase plot.

Simulation Problem

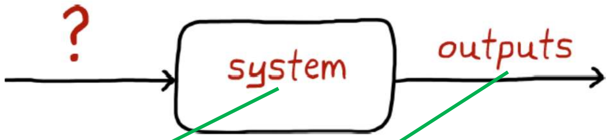
```
fx = DYNAMICS_MACHINE(t, ACM.x, ACM) # @t
for i in range(NS):
    k1[i] = fx[i] * hs
    xk[i] = ACM.x[i] + k1[i]*0.5

fx = DYNAMICS_MACHINE(t, xk, ACM)  # @t+hs/2
for i in range(NS):
    k2[i] = fx[i] * hs
    xk[i] = ACM.x[i] + k2[i]*0.5

fx = DYNAMICS_MACHINE(t, xk, ACM)  # @t+hs/2
for i in range(NS):
    k3[i] = fx[i] * hs
    xk[i] = ACM.x[i] + k3[i]

fx = DYNAMICS_MACHINE(t, xk, ACM)  # @t+hs
for i in range(NS):
    k4[i] = fx[i] * hs
    # ACM.x_dot[i] = (k1[i] + 2*(k2[i] + k3[i]) + k4[i])/6.0 / hs # derivatives
    ACM.x[i] = ACM.x[i] + (k1[i] + 2*(k2[i] + k3[i]) + k4[i])/6.0
```

Runge-Kutta Method (ode4)

Control Problem (see next page)

https://github.com/horychen/ee275/blob/master/python_tutorial_cjh.ipynb

What is Control?



- What is control?
  - There are DYNAMICS, e.g.,

$$\frac{\mathrm{d}}{\mathrm{d}t}x = 1; \quad \frac{\mathrm{d}}{\mathrm{d}t}x = -1; \quad \frac{\mathrm{d}}{\mathrm{d}t}x = x; \quad \frac{\mathrm{d}}{\mathrm{d}t}x = -x; \quad \frac{\mathrm{d}}{\mathrm{d}t}x = x^2; \quad \frac{\mathrm{d}}{\mathrm{d}t}x = -x^2$$

  - There is a GOAL, e.g., make x to be 0, as $t \to \infty$
  - There is an INPUT, e.g., $\frac{\mathrm{d}}{\mathrm{d}t}x = x^2 + u$
    - The input is a function of the state: $u(x)$

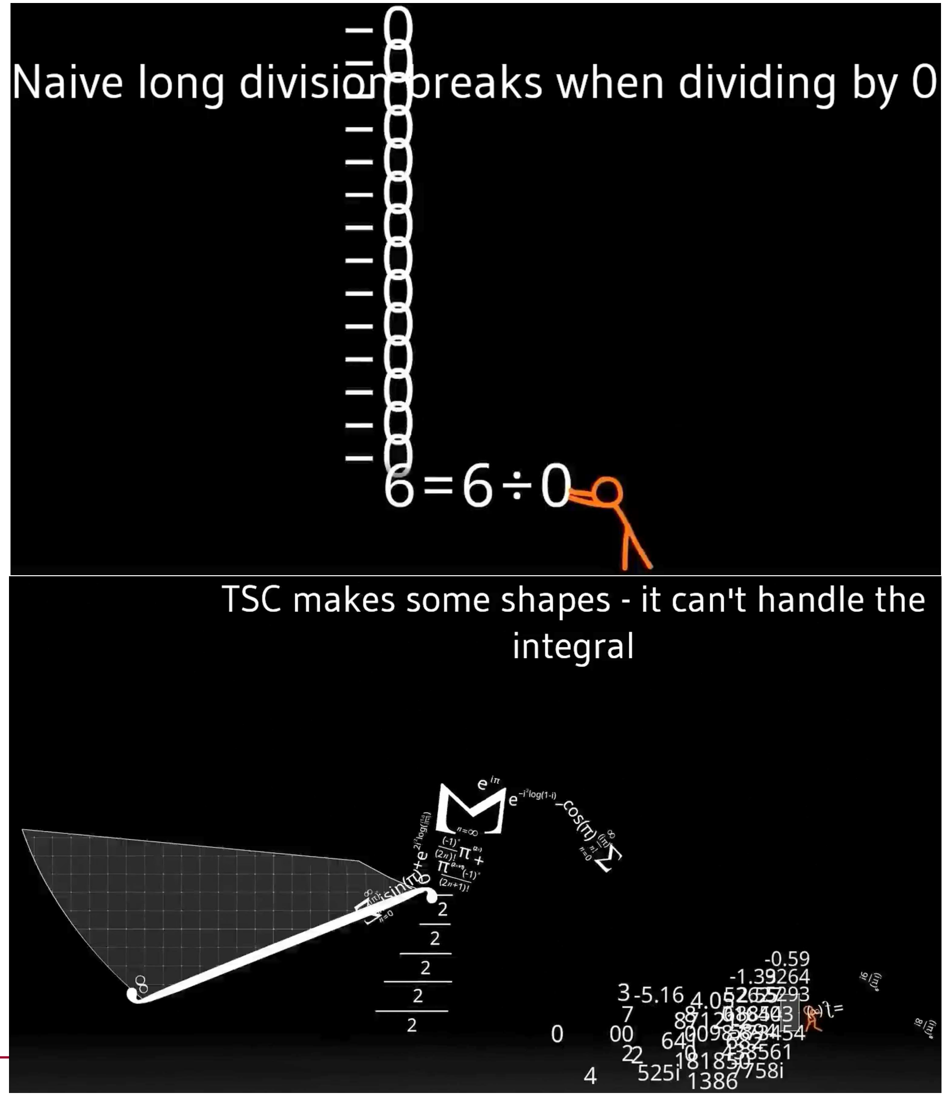


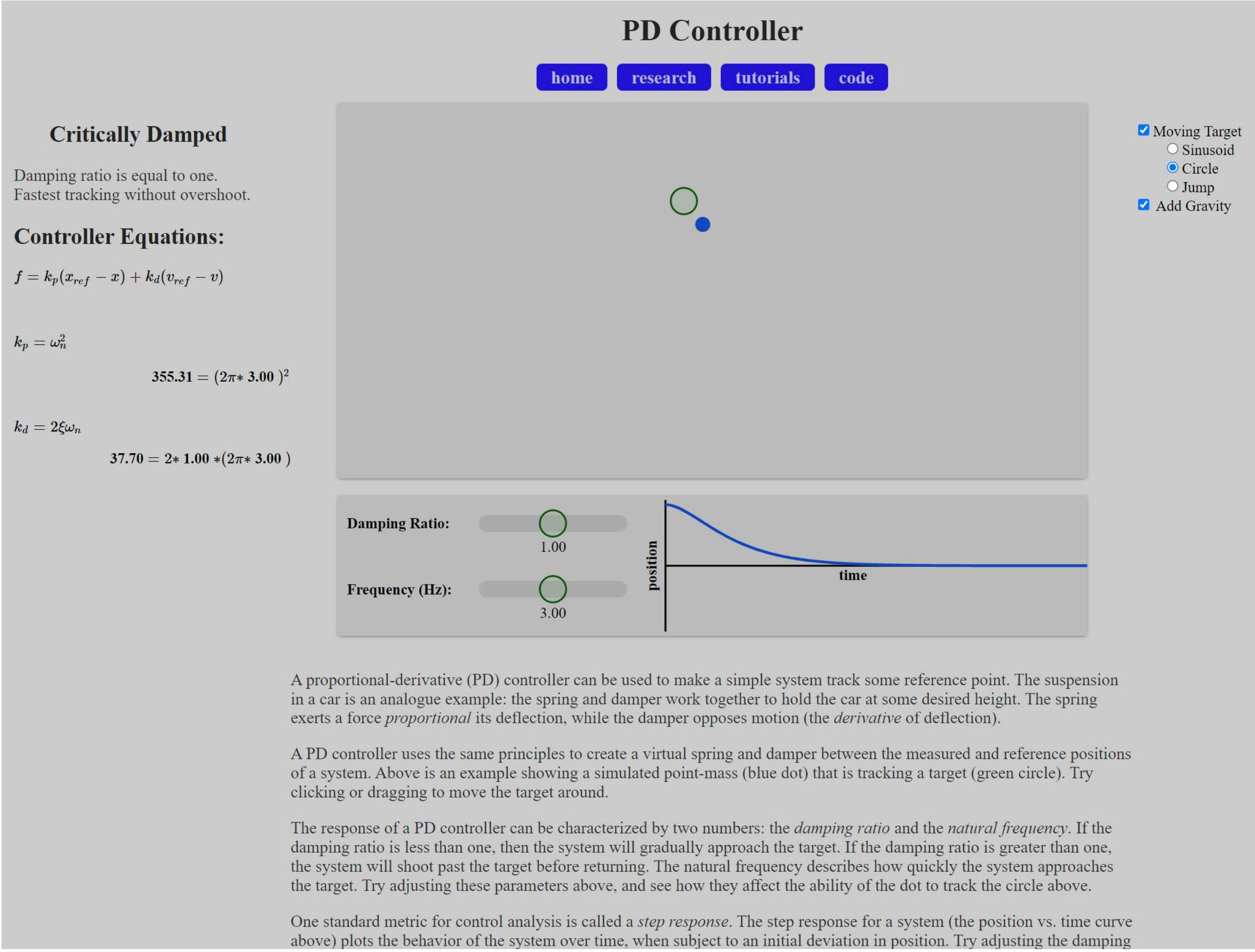
Figure. Screenshots in Animation versus math by Alan Becker.

Control of a Second Order System

- How about 2nd order dynamics?

$$\frac{d^2}{dt^2}x + a\frac{d}{dt}x + bx + f(x,y) = u$$

$$\frac{d^2}{dt^2}y + c\frac{d}{dt}y + dy + g(x,y) = v$$



https://www.matthewpeterkelly.com/tutorials/pdControl/index.html

Feedback Control

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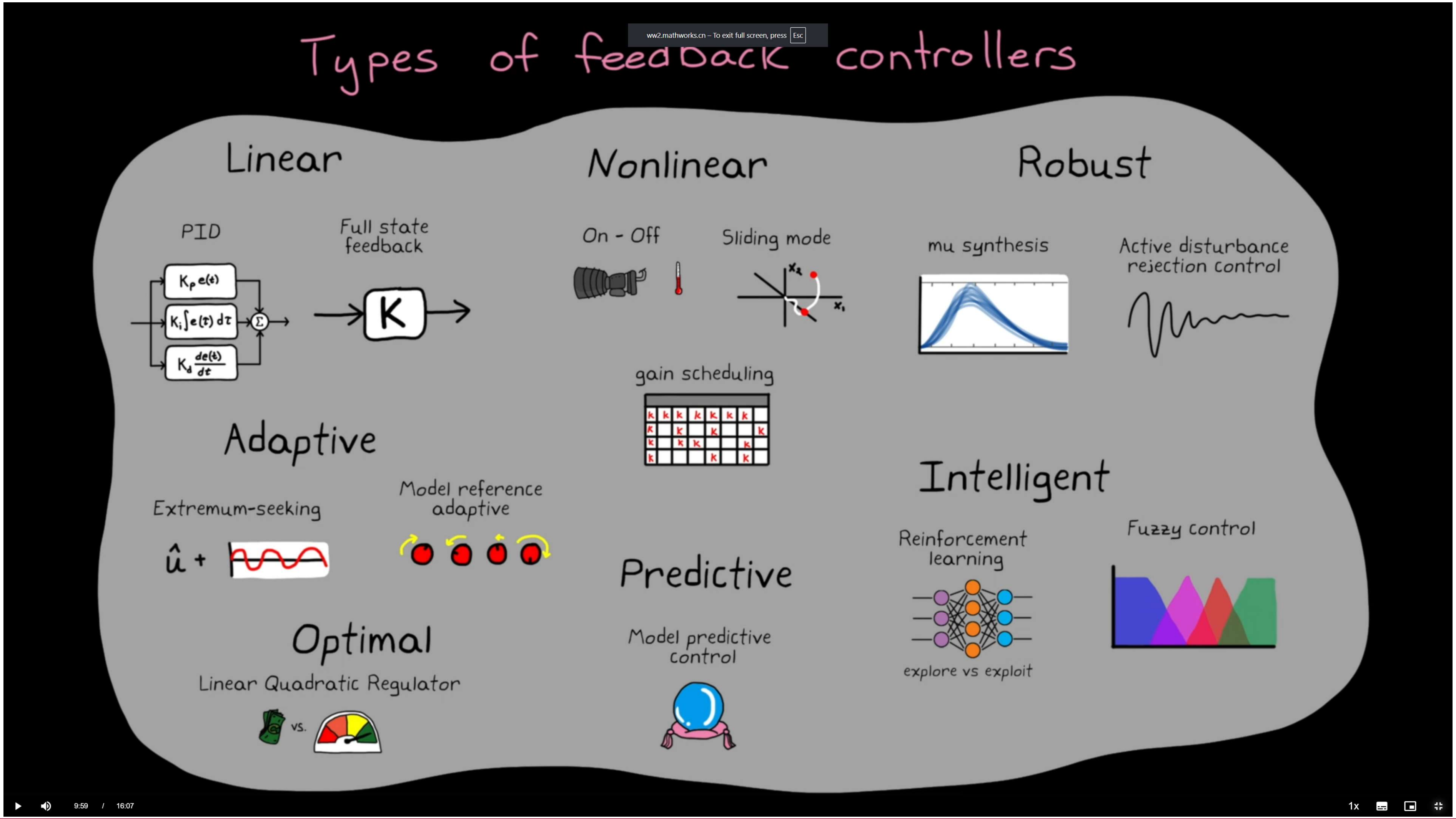

https://ww2.mathworks.cn/en/videos/closed-loop-control-an-overview-of-feedback-controllers-1737524680430.html

Negative Feedback explained with Block Diagram

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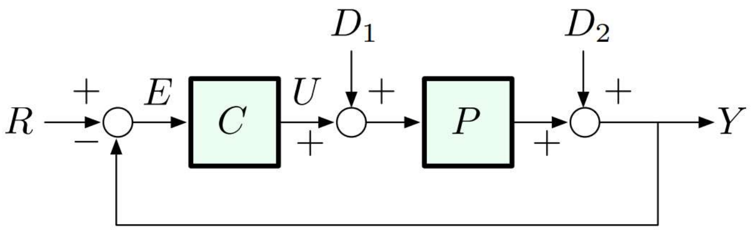
Feedback Control in Five Minutes



Systems:

C – controller

(or compensator)

P – plant

Variables:

R – reference

E – error

D_1, D_2 – disturbances

U – control (or input)

Y – output

Key relations:

$$Y = D_2 + P(U + D_1) \quad U = CE \quad E = R - Y$$

https://courses.grainger.illinois.edu/ece486/fa2025/documentation/lectures/slides_2014/lec01.pdf

Negative Feedback explained with Block Diagram

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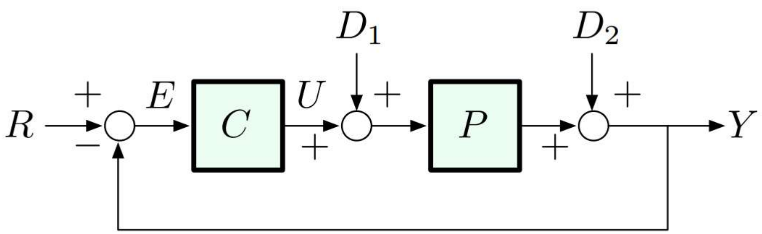
Feedback Control in Five Minutes



$$Y = D_2 + P(U + D_1) \quad U = CE \quad E = R - Y$$

Let's express Y in terms of R, D_1, D_2:

$$\begin{aligned} Y &= D_2 + P(CE + D_1) \\ &= D_2 + P\big(C(R - Y) + D_1\big) \qquad \text{negative feedback!!} \\ &= D_2 + PCR - PCY + PD_1 \end{aligned}$$

$$Y = \frac{PC}{1 + PC} R + \frac{P}{1 + PC} D_1 + \frac{1}{1 + PC} D_2$$

Negative Feedback explained with Block Diagram

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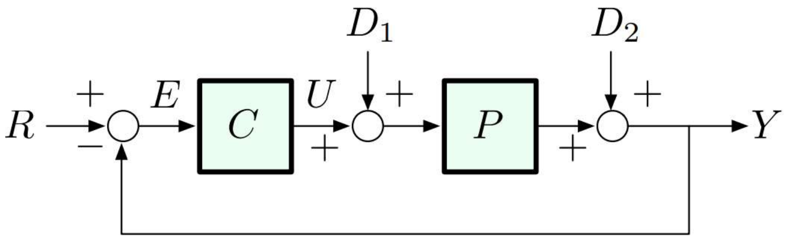
Feedback Control in Five Minutes



$$Y = \frac{PC}{1+PC}R + \frac{P}{1+PC}D_1 + \frac{1}{1+PC}D_2$$

Suppose C is a large positive *gain*. What happens as $C \to \infty$?

$$\frac{PC}{1+PC}R \xrightarrow{C\to\infty} R \qquad \text{reference tracking}$$

$$\frac{P}{1+PC}D_1 + \frac{1}{1+PC}D_2 \xrightarrow{C\to\infty} 0 \qquad \text{disturbance rejection}$$

Bottom line: in the limit $C \to \infty$, $Y = R$

(this "Big Picture" is too good to be true — we will fill in all the details!!)

More Block Diagrams

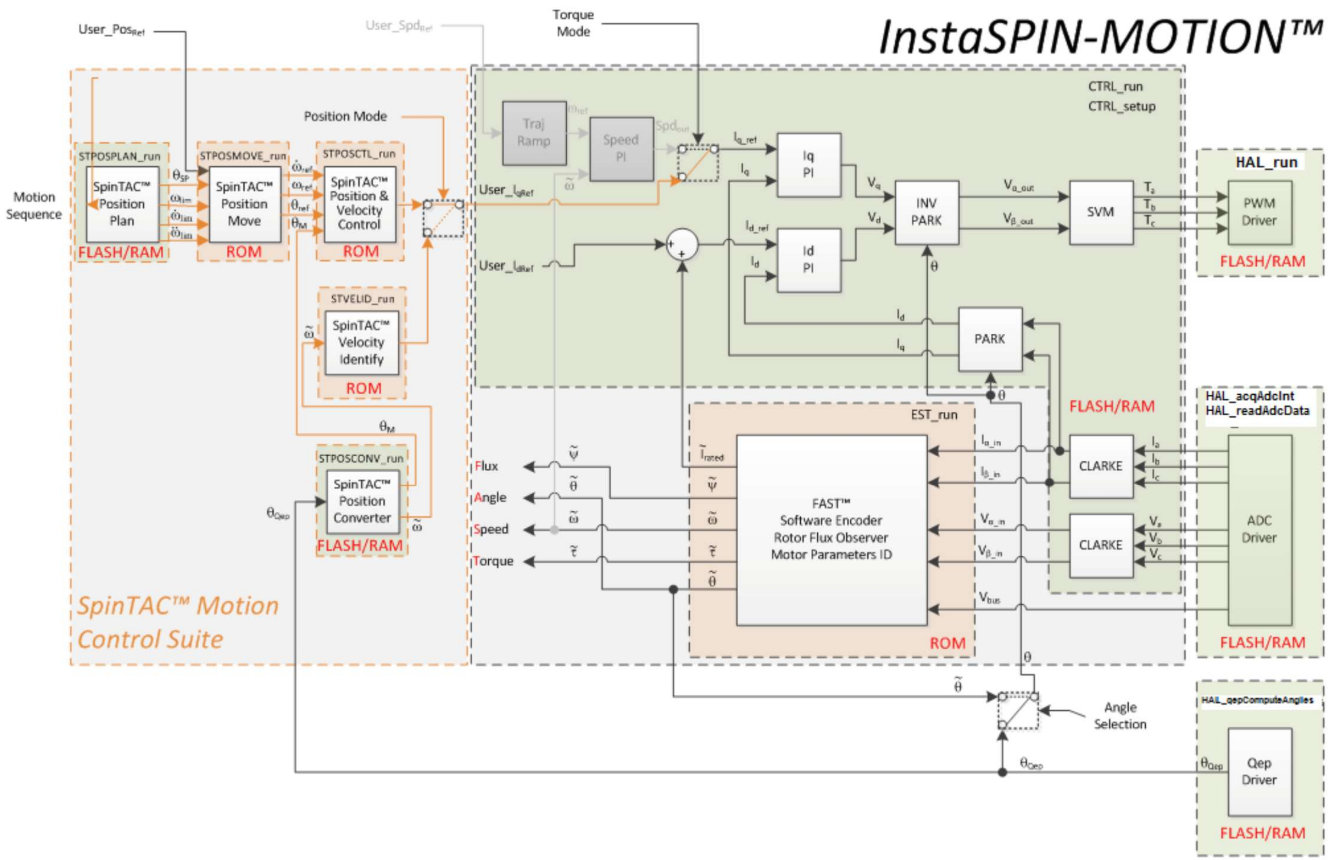


Figure 1-14. InstaSPIN-MOTION Position Control with Mechanical Sensor and Redundant FAST Software Sensor

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EE160P Requirements

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- One goal: The EE160 Project is about the **modeling, simulation, and control** of a nonlinear system of your choice.
- Two options:
  - 1. Pick at least one of the application examples we recommended
  - 2. Propose a control problem of your own choice.
- Three tasks:
  - 1. Proposal report (with references):
    - form your team (<=3) and roughly break down the task modeling and define control objective, linearize your system and do open-loop simulation
  - 2. Project report (5-10 pages)
    - design your control law and brief analysis;
    - verify effectiveness of your control law;
    - check the robustness of your algorithm
  - 3. Presentation (with live simulation demonstrate)
    - problem formulation and its solution
    - live simulation demonstration(play with tuning parameters)
- There is only “Pass” or “Not Pass” for the project