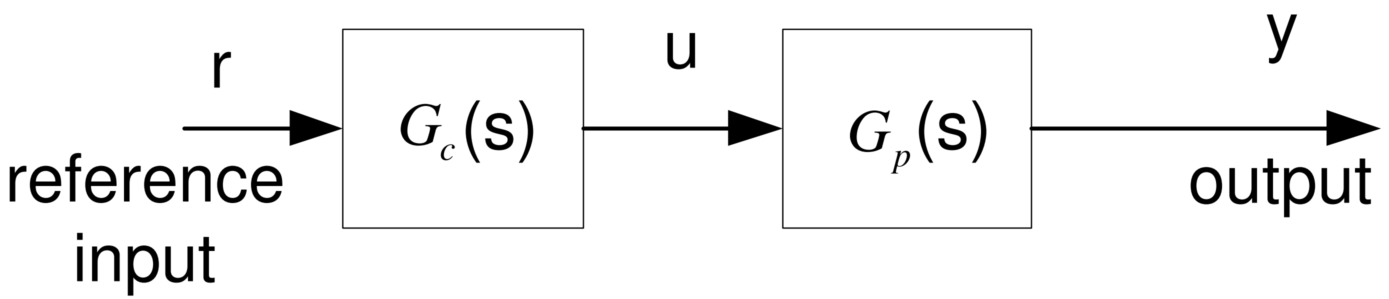
II. Control Design Practice

- Modeling
- System Configurations
- Classical Design Techniques
- Advanced Techniques
- Simulation and Evaluation

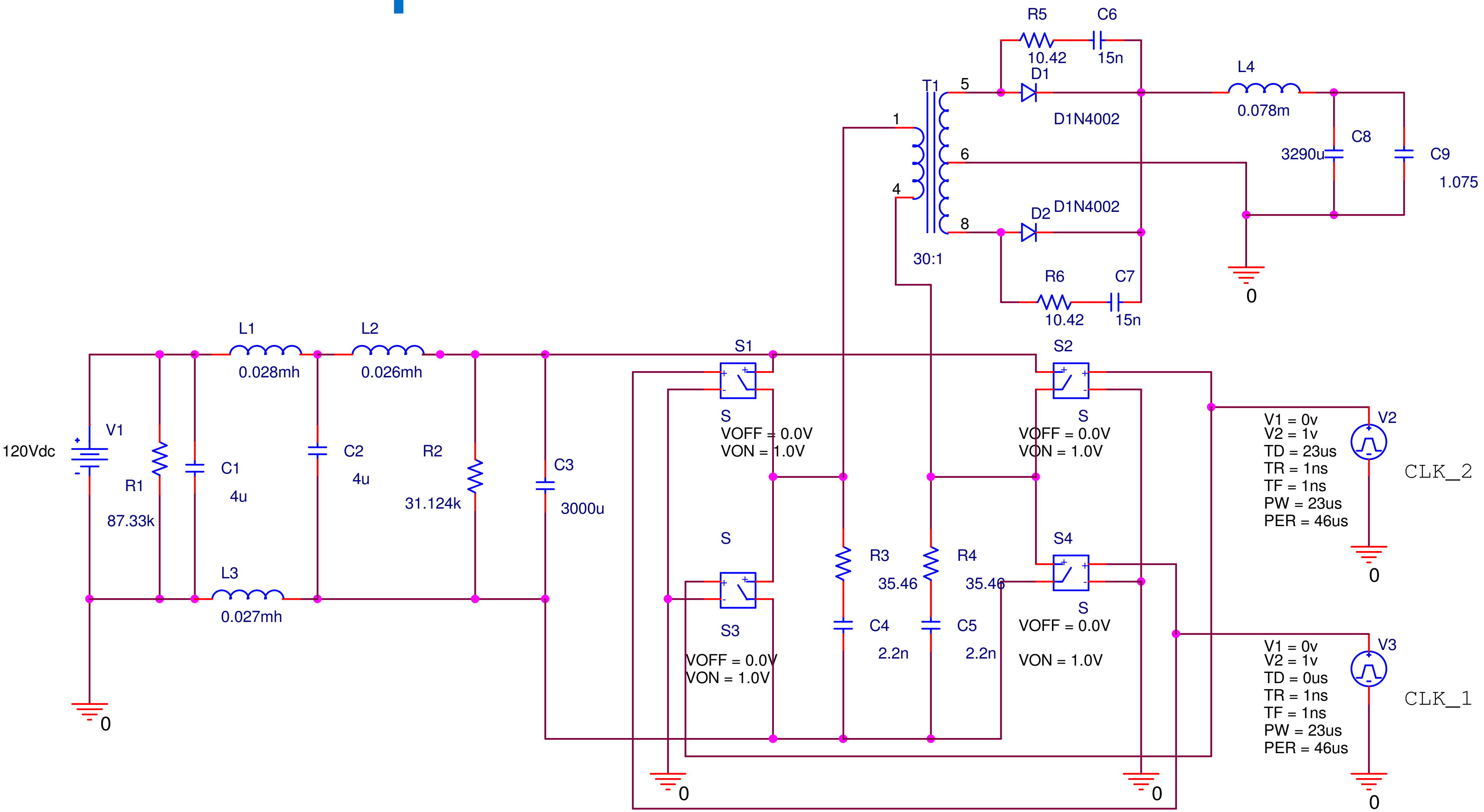
Modeling

- Intuitive Model
  - Understanding of the cause-effect relationship
  - Fly ball governor, first industrial controller, speed regulation of steam engine, 1769
  - Error model: GNC in early years
- Mathematical Model
  - Differential Equation
  - Transfer Function
  - State Space

Open Loop



Example: DC-DC Converter Circuit

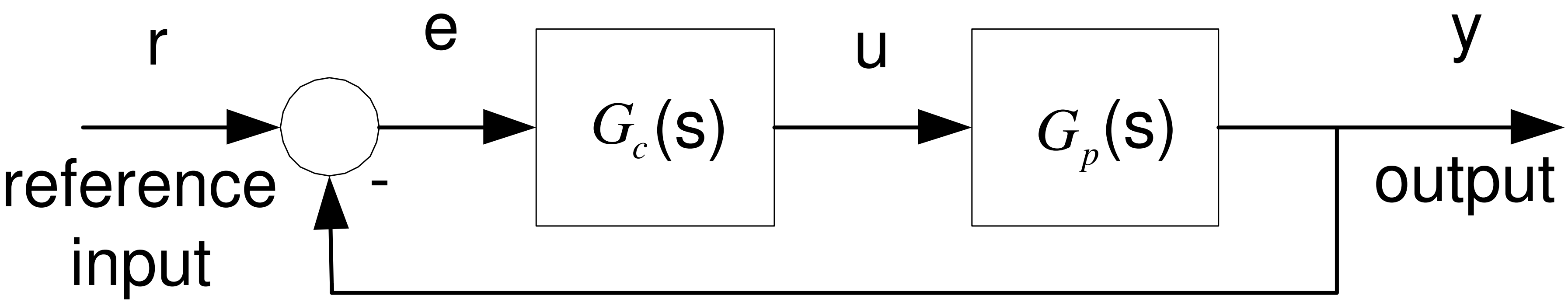


Basis of Open Loop Control

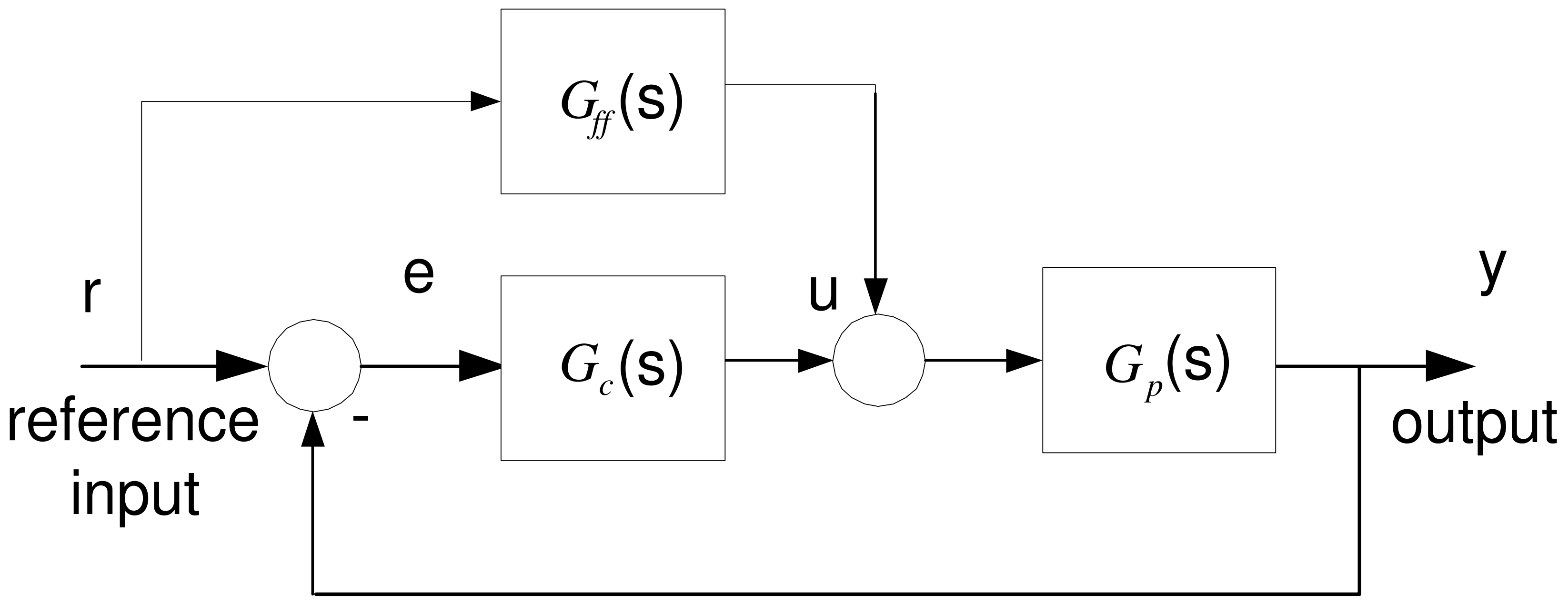
$$V_{out} = \frac{V_{in}}{3 \bullet 255}(Pulse\ Count) - 0.8 - (0.075 \bullet I_{load})$$

- V_{out}: Converter Output Voltage
- 3: Step-down Transformer Turns Ratio
- 255: Max. Pulse Count
- 0.8: Output Rectifier Voltage Drop
- 0.075: Converter Output Impedance

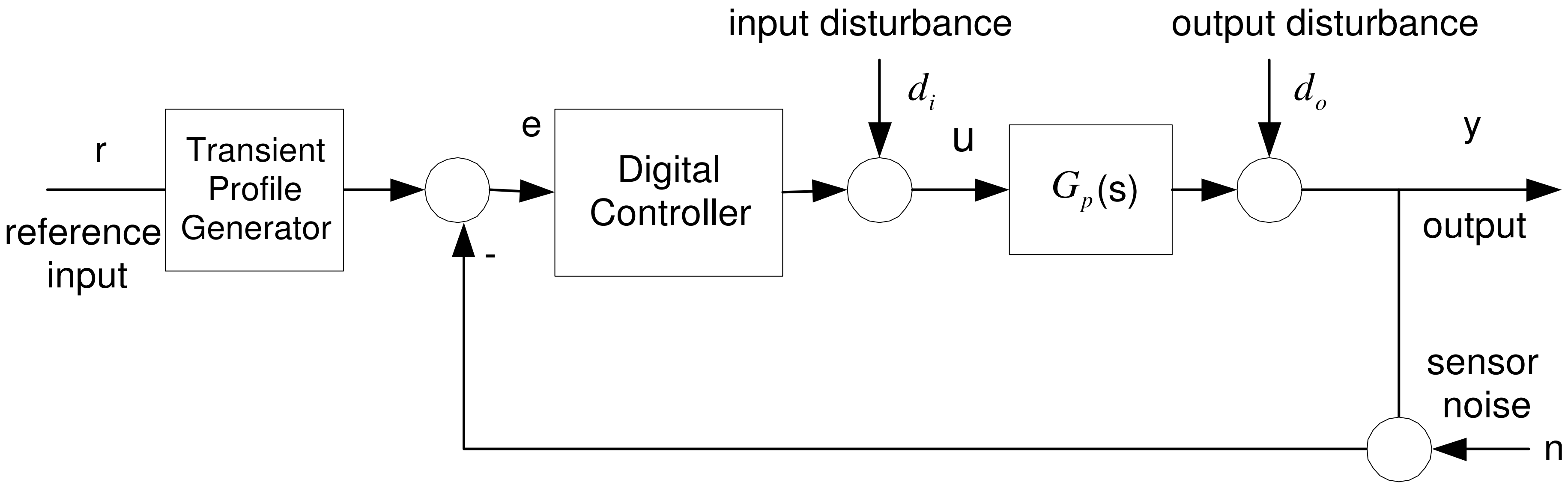
Feedback Control Block Diagram



Feedforward



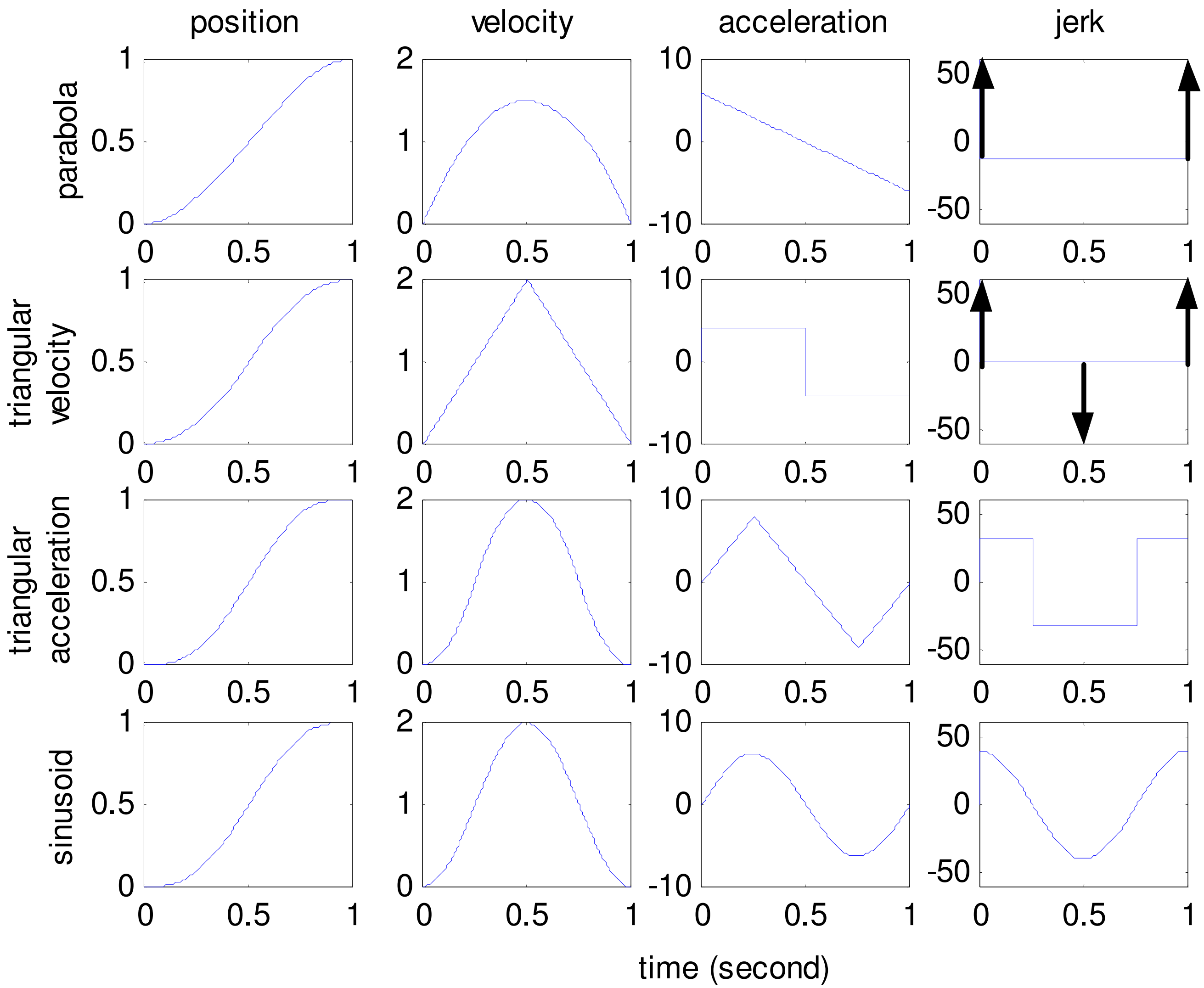
What really happens



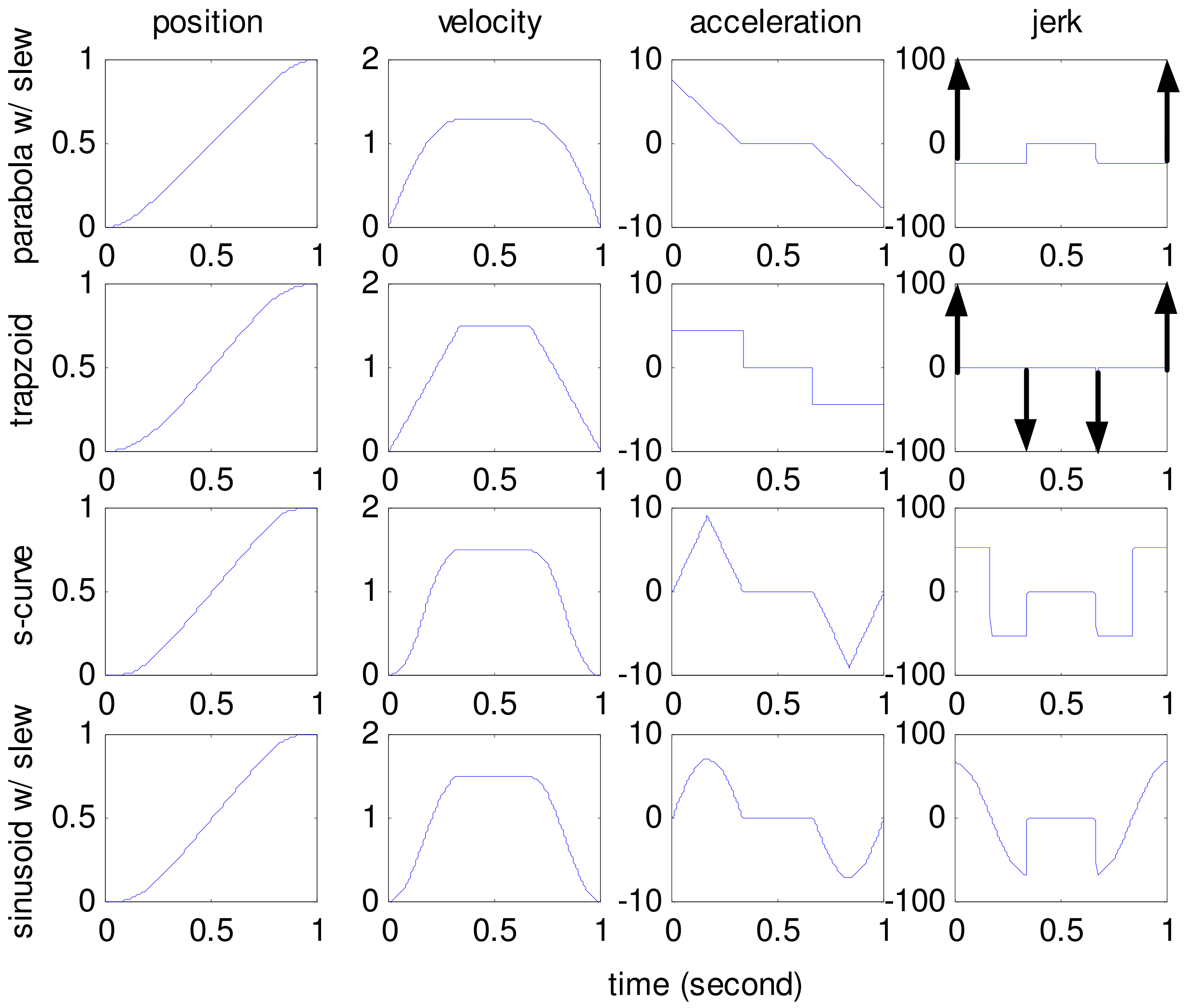
Transient Profile

- Known as Motion Profile in industry
- Provides the desired output trajectory
  - Energy
  - Max speed required
  - Max acceleration (torque) required
  - Smoothness (max Jerk)
    - Reduce mechanical wear and tear
    - Avoid exciting the resonant modes
- Keep the error small and controller aggressive
- Not seen in control textbooks

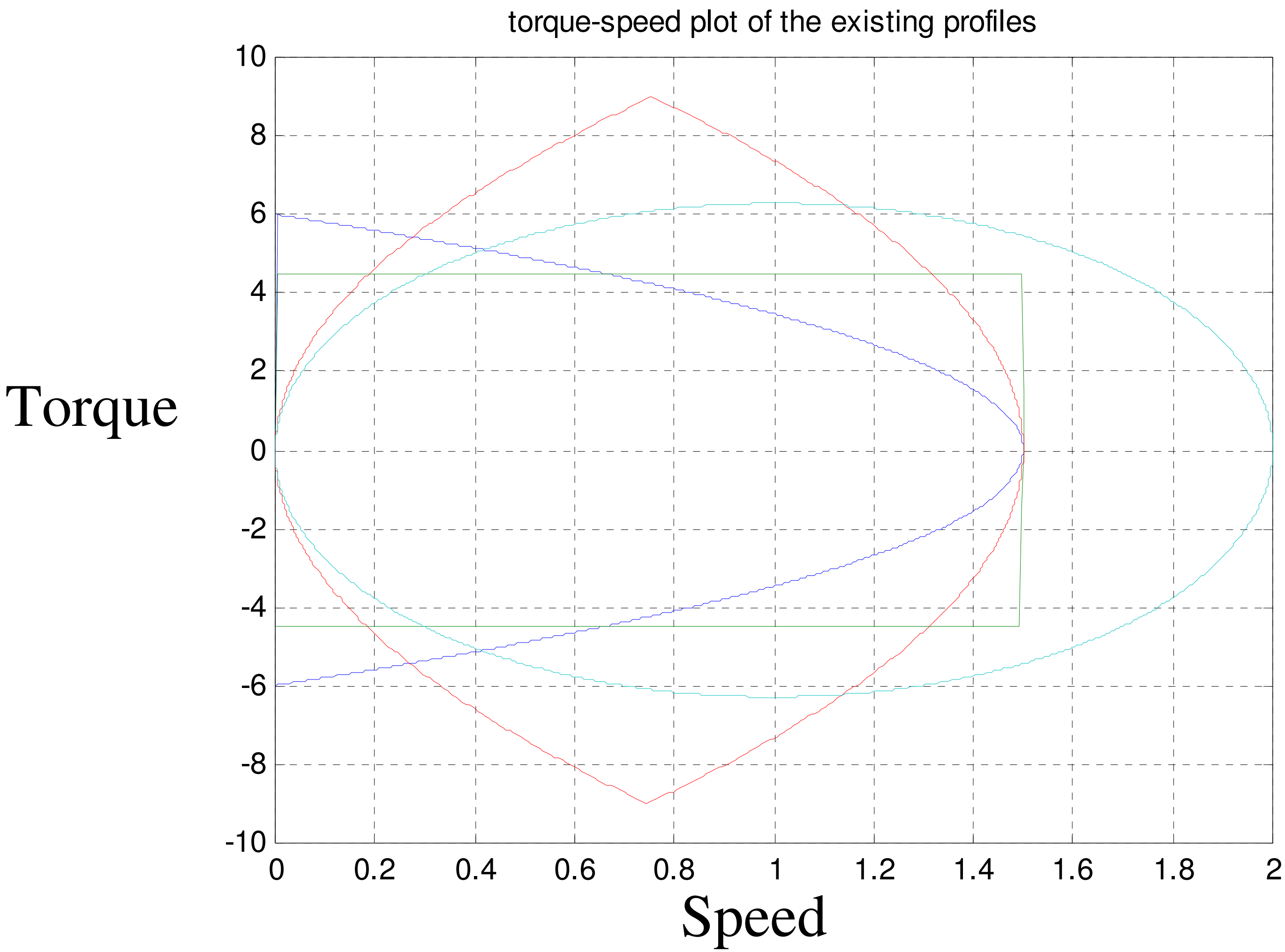
Motion Profile Examples



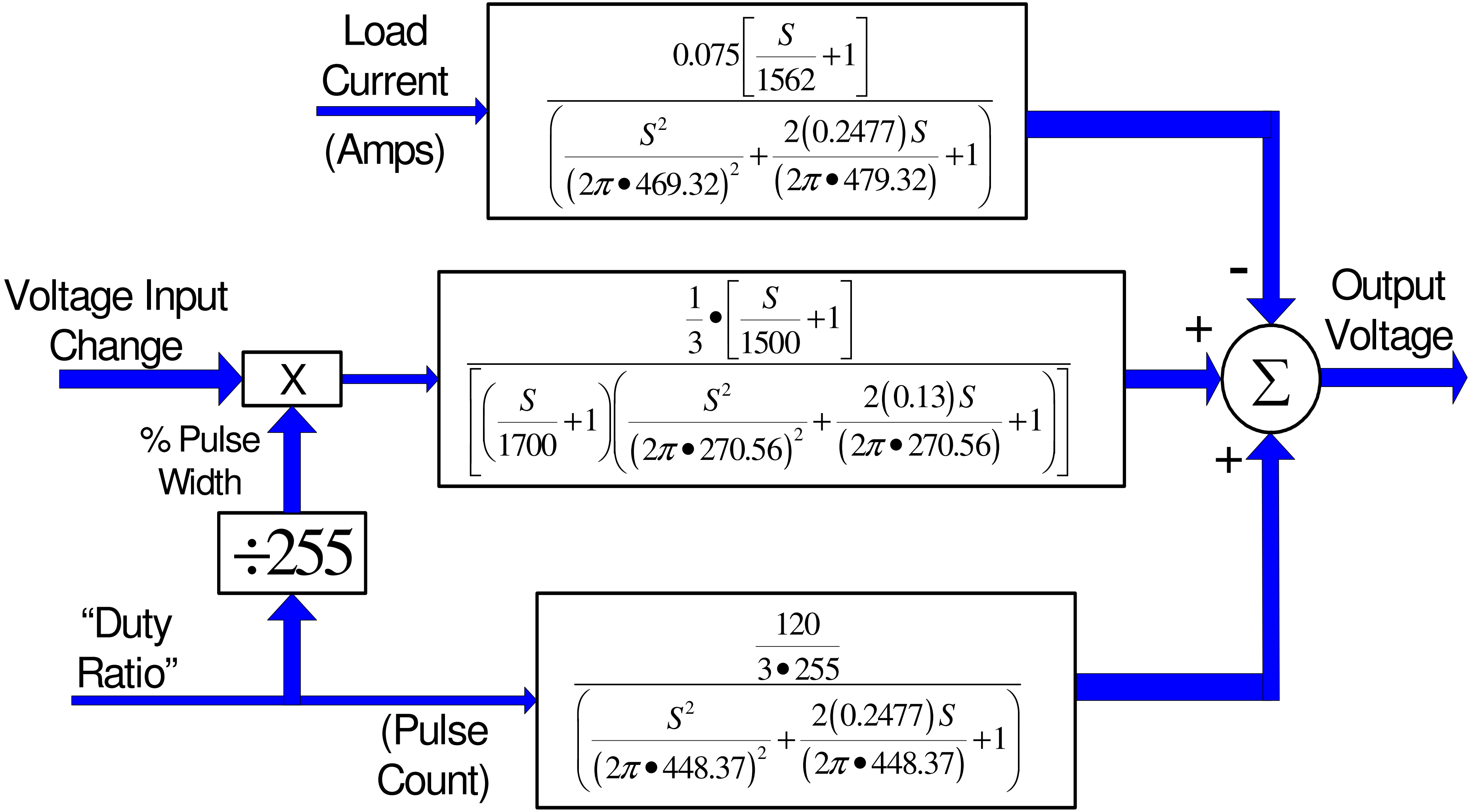
Motion Profile Examples (w/ slew)



Torque-Speed Curves



Disturbances in the conveter

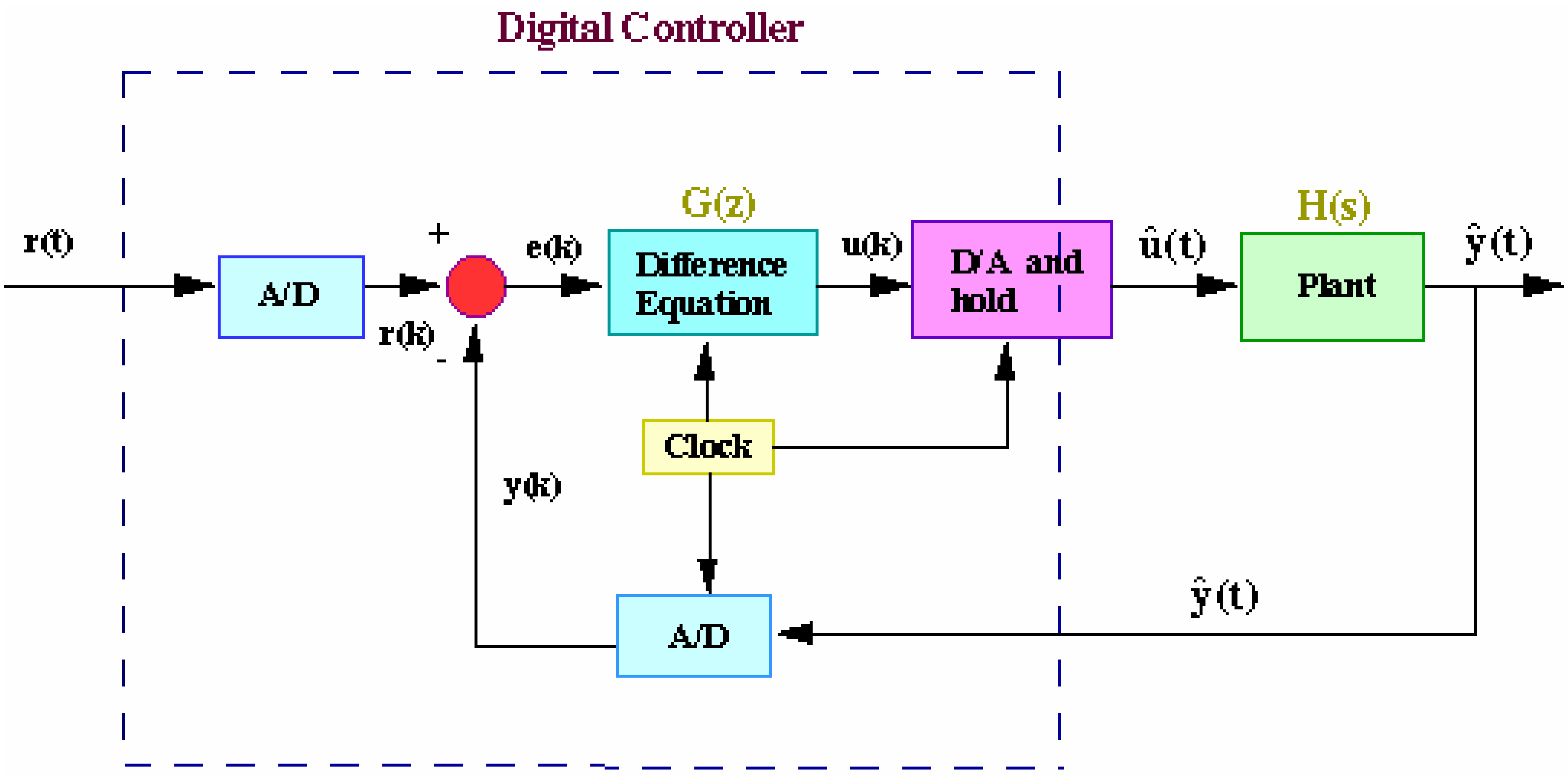


$$\frac{0.075\left[\frac{S}{1562}+1\right]}{\left(\frac{S^2}{(2\pi\bullet 469.32)^2}+\frac{2(0.2477)S}{(2\pi\bullet 479.32)}+1\right)}$$

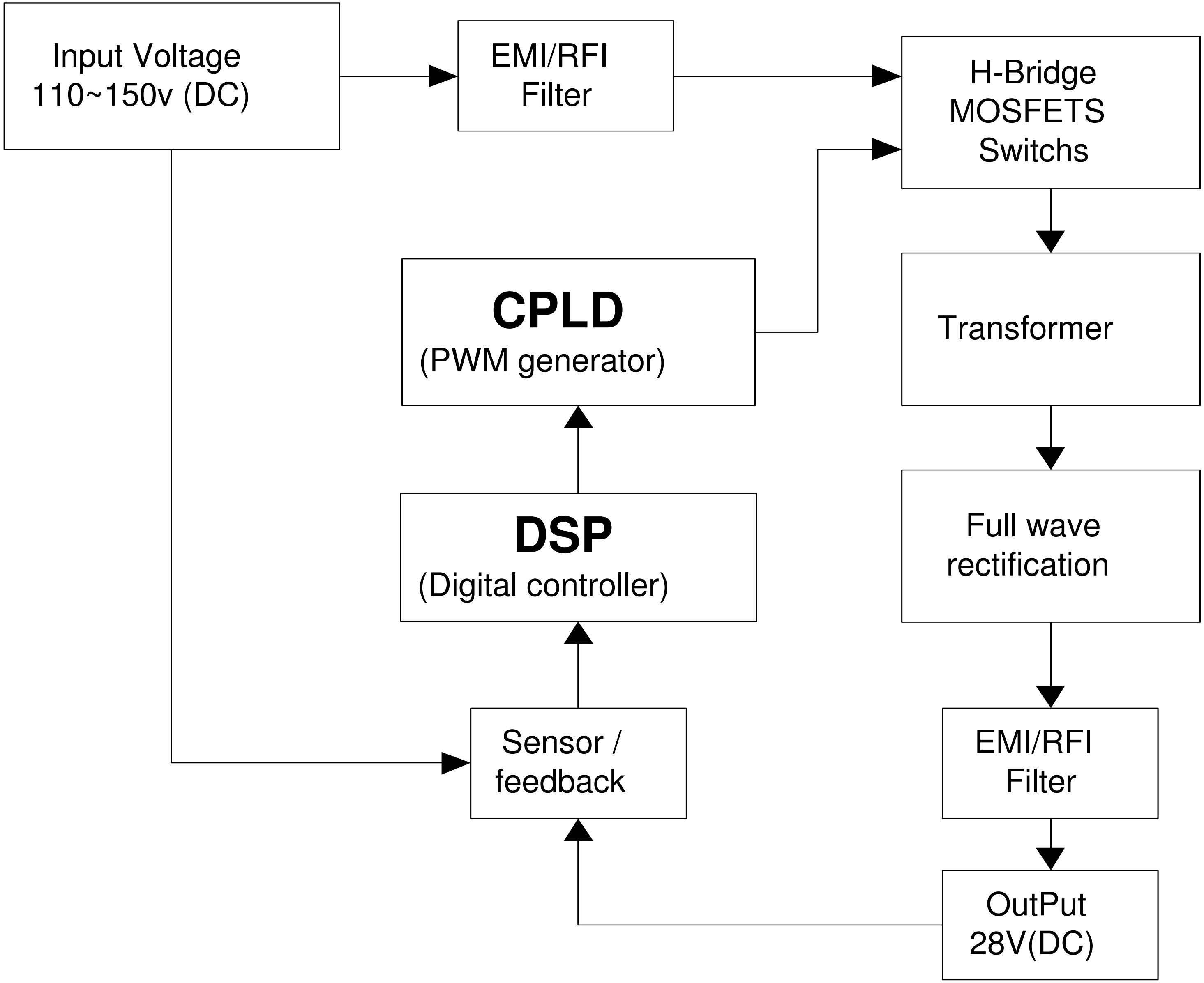
$$\frac{\frac{1}{3}\bullet\left[\frac{S}{1500}+1\right]}{\left[\left(\frac{S}{1700}+1\right)\left(\frac{S^2}{(2\pi\bullet 270.56)^2}+\frac{2(0.13)S}{(2\pi\bullet 270.56)}+1\right)\right]}$$

$$\frac{\frac{120}{3\bullet 255}}{\left(\frac{S^2}{(2\pi\bullet 448.37)^2}+\frac{2(0.2477)S}{(2\pi\bullet 448.37)}+1\right)}$$

Digital Control



Digitally Controlled Power Converter

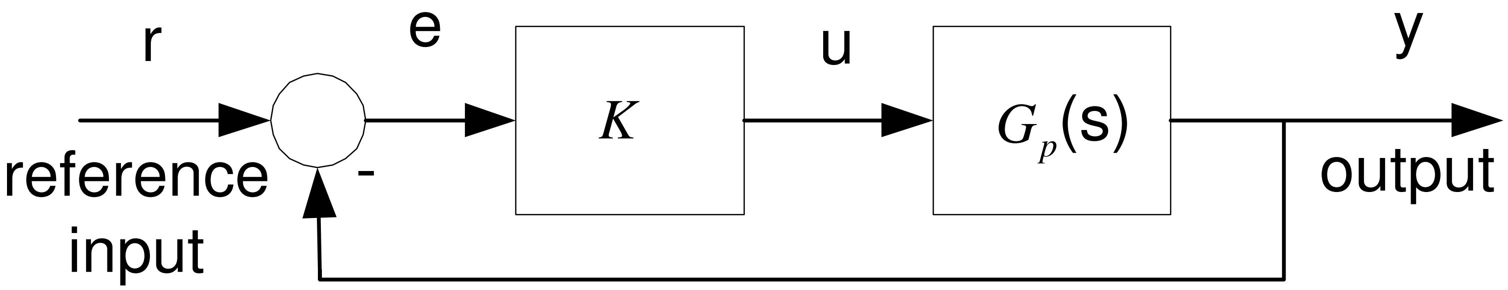


Classical Design Techniques

- Proportional-Integral-Derivative Controller
- Root Locus (Pole/Eigenvalue Assignment)
- Lead-Lag Compensator (Frequency Response, and later, Loop-Shaping)
- State Feedback and Observer Based Design

http://www.engin.umich.edu/group/ctm/

Closing the loop with a Constant Gain



Over a thousand years old

Fly ball governor, etc

Closing the loop with a PID Controller (Proportional-Integral-Derivative)

$$u = k_p e + k_i \int e + k_d \dot{e}$$

$$\frac{U(s)}{E(s)} = k_p + k_i \frac{1}{s} + k_d s$$

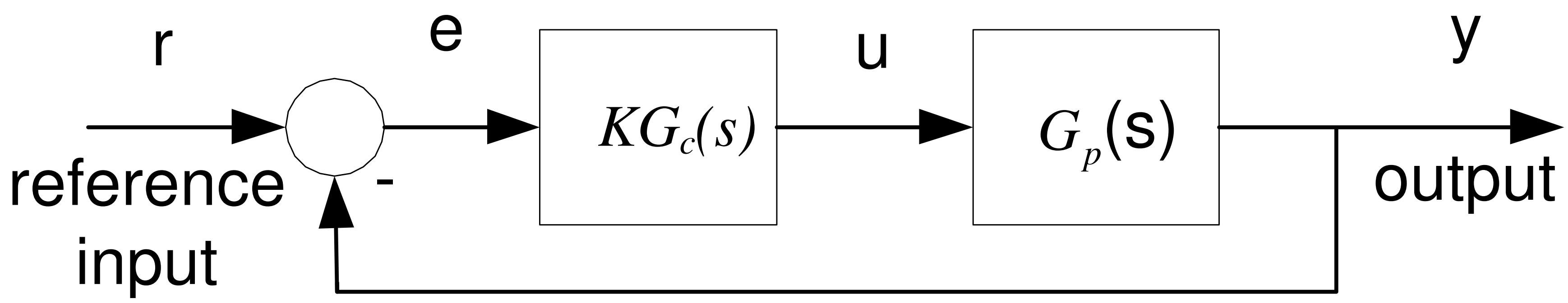
Norm Minorsky, 1922

Used in >90% industrial applications

Dissecting PID

- Proportional Control
  - The essential feedback control means
  - Used over 2000 years ago
  - Effects disappear when error is small
- Integral Control
  - Mainly for reducing steady state
  - Introduces lag
  - May lead to overshoot/instability
- Differential Control
  - Predicative, overcomes lag
  - Noise issue unresolved

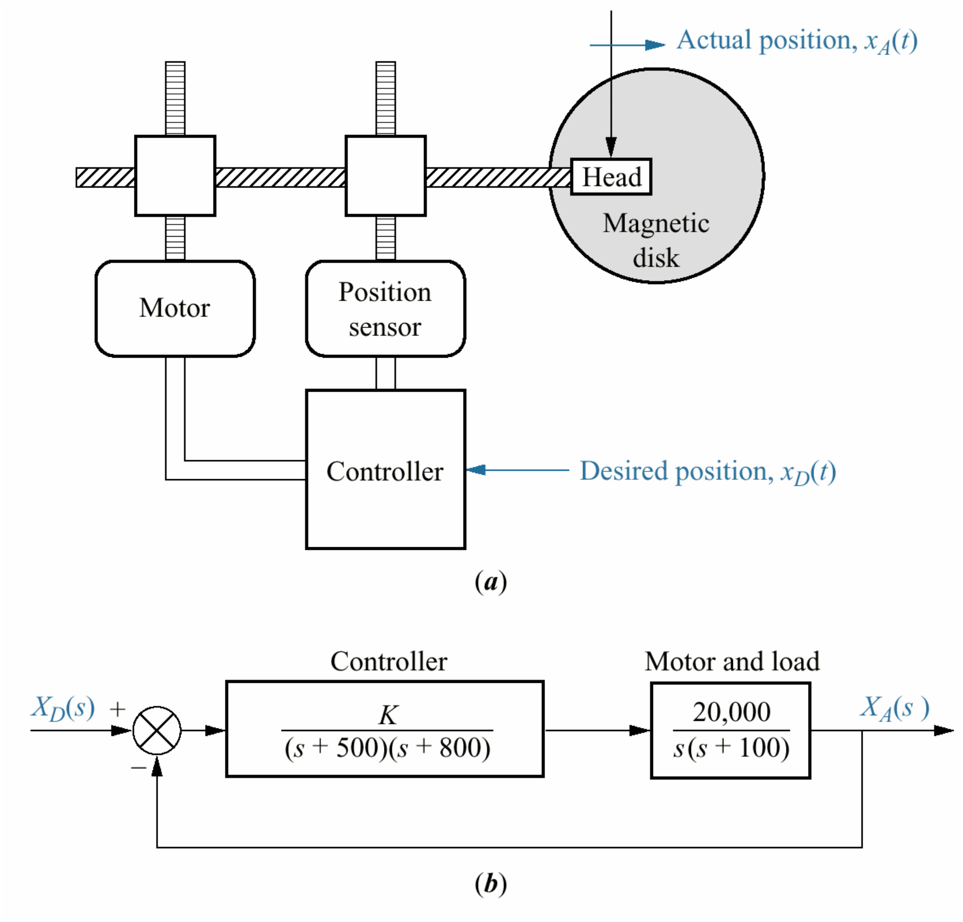
Root Locus



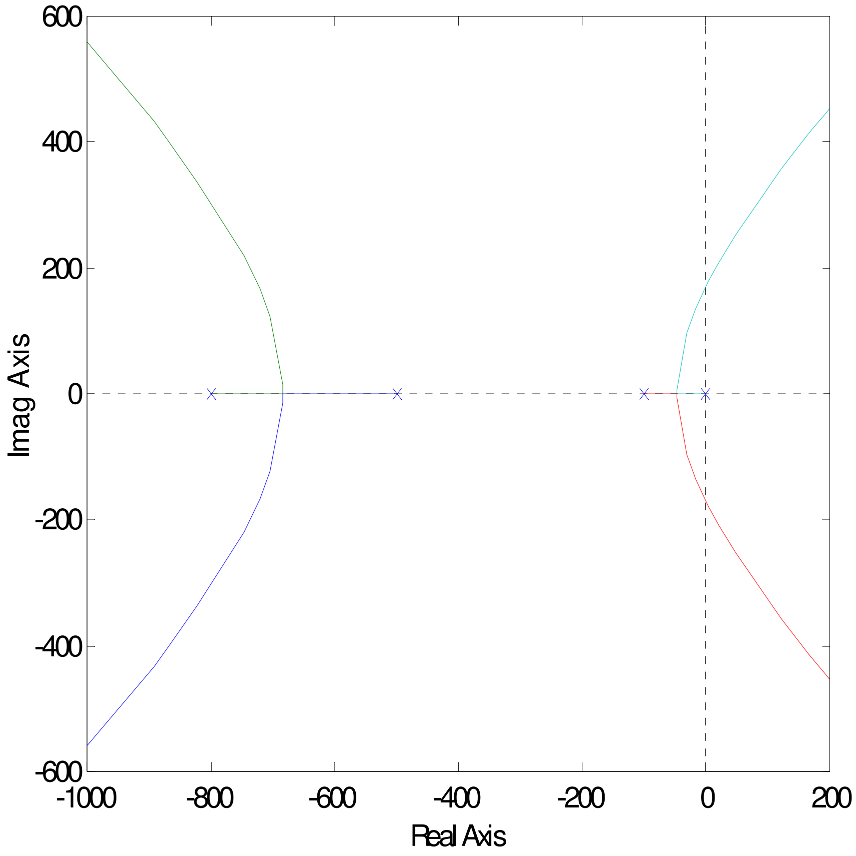
Given $G_c(s)$ and $G_p(s)$,

plot all closed-loop poles (root locus) for K: $0 \rightarrow \infty$

Root Locus



Actual position, $x_A(t)$
Head
Magnetic disk
Motor
Position sensor
Controller
Desired position, $x_D(t)$
(a)
Controller
Motor and load
$X_D(s)$
+
−
$\frac{K}{(s+500)(s+800)}$
$\frac{20{,}000}{s(s+100)}$
$X_A(s)$
(b)



600
400
200
0
-200
-400
-600
Imag Axis
-1000
-800
-600
-400
-200
0
200
Real Axis

State Feedback

- Plant

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

- Control Law

$$u = r - Kx$$

- Closed Loop

$$\dot{x} = (A - BK)x + Br$$

$$y = Cx + Du$$

- Design Criteria

  eig(A-BK) assignment

State Feedback with an Observer

- Plant

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

- Control Law

$$u = r - K\hat{x}$$

- Closed Loop

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y})$$

$$\hat{y} = C\hat{x} + Du$$

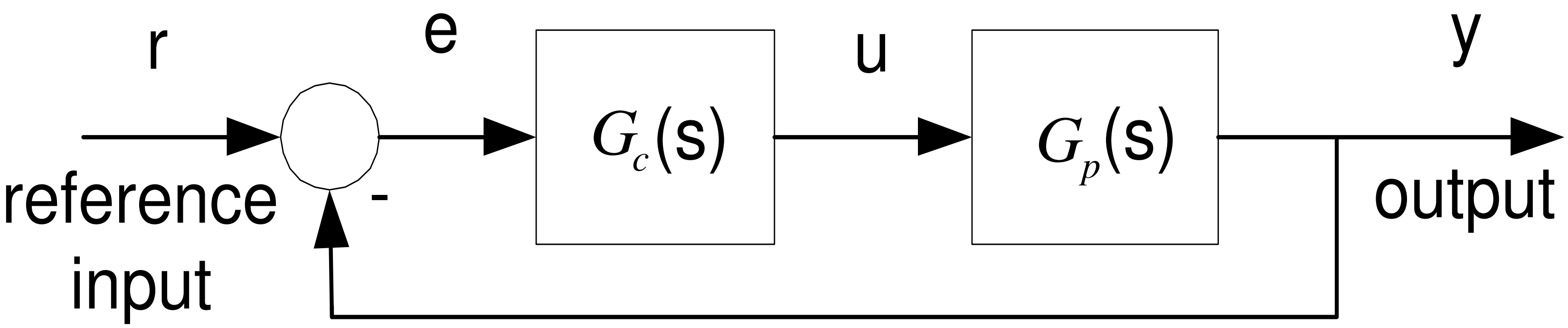
- Separation Principle

  Independence in Control Law and Observer Designs

Practicality

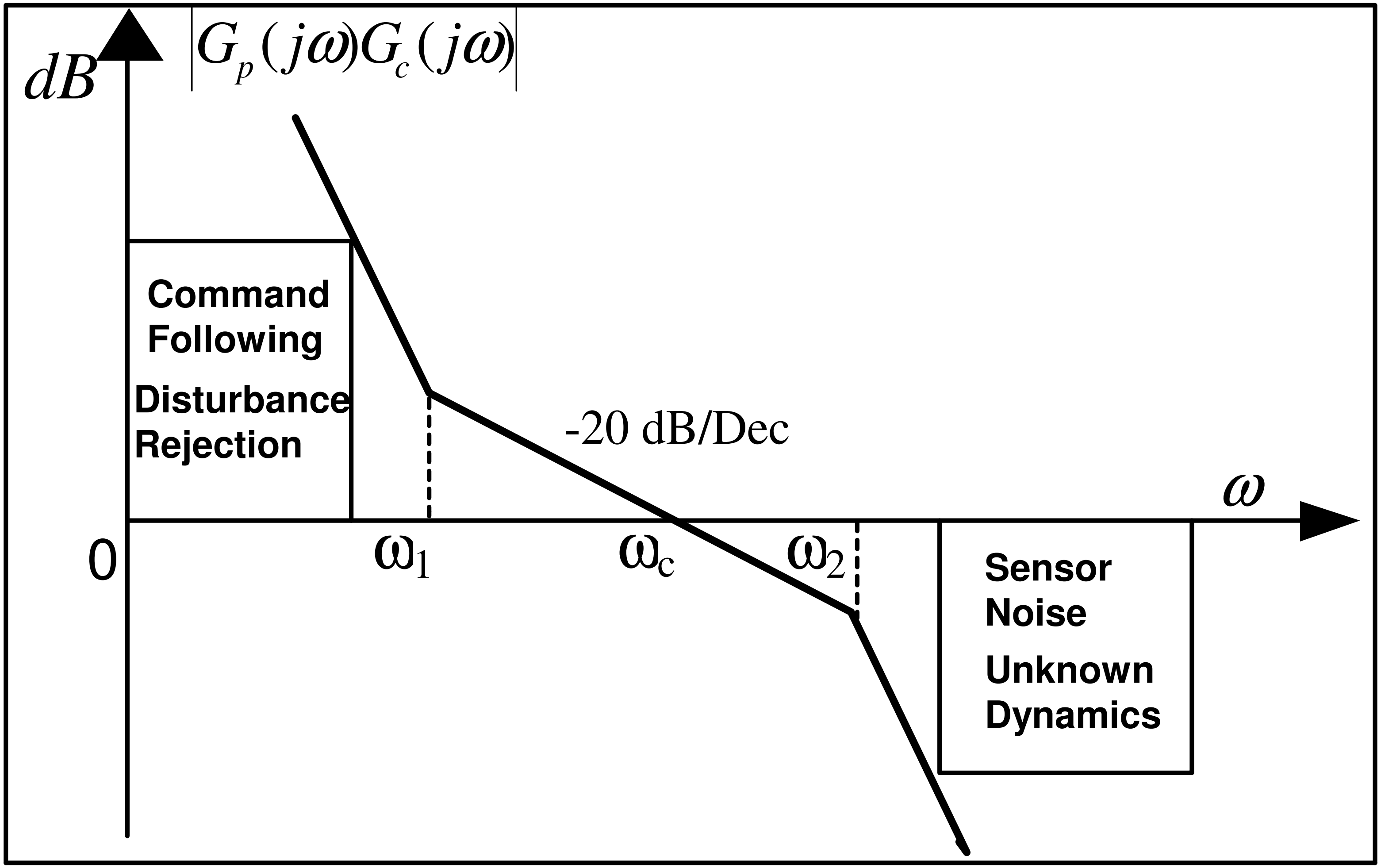
- How to Choose Closed-loop Eigenvalues/poles?
- Observer Eigenvalue Selection?
- Disturbance Rejection?
- Sensor Noise?
- Sensitivity to Plant Changes?

Loop Shaping Design



- Loop Gain Frequency Response: $L(j\omega)=G_c(j\omega)G_p(j\omega)$
- Performance Specs to Loop Gain Constraints
- Loop Gain Shaping by Lead-Lag Compensators

Loop Shaping Design



Advanced Design Techniques

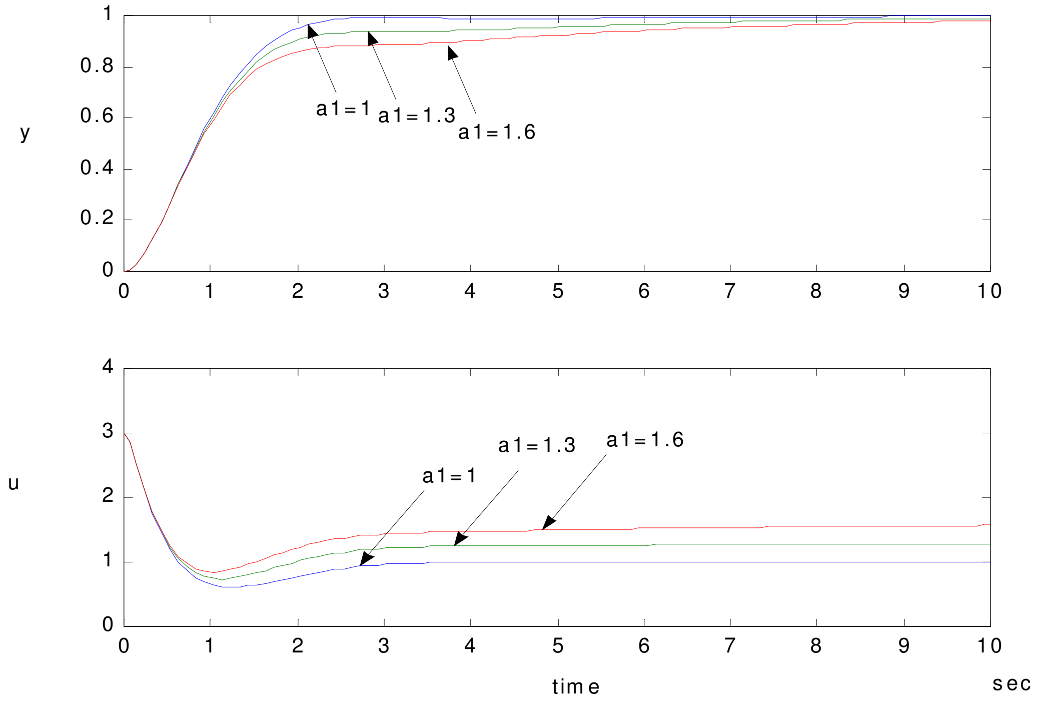
- Nonlinear PID
- Model Independent Methodology
- Parameterization and Practical Optimization
- Wavelet denoising
- Fuzzy Logic
- Neural Networks
- Genetic Algorithms
- …

Misconceptions

- Control Design Is About Pole Placement
- “Optimal” Control
- Step Command
- Must Have a Math Model
- PID is Art / Control Theory is Science

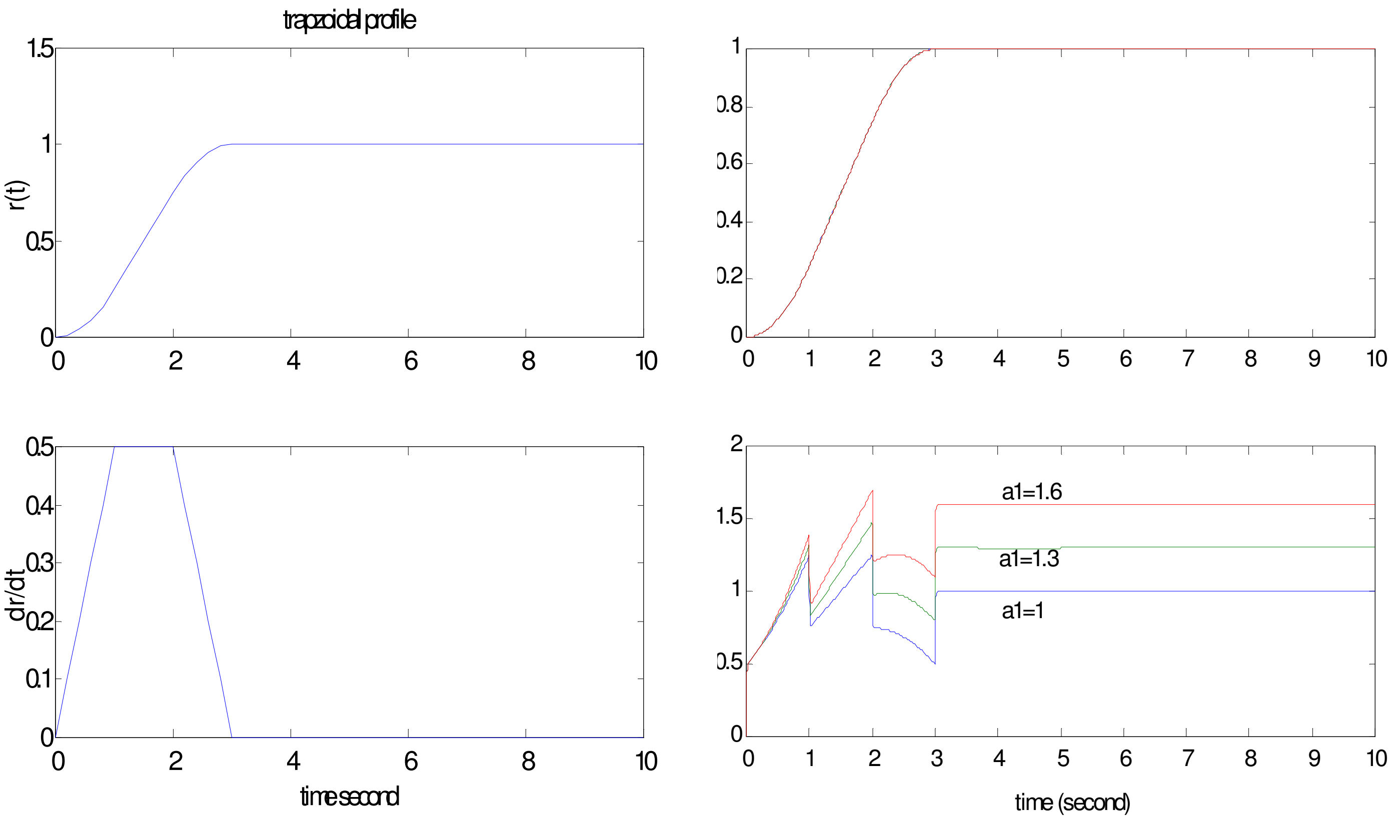
Robustness of PID

- Plant: $\ddot{y} = -a_1 y - a_2 \dot{y} + u \quad a_1 = 1, a_2 = 1$
- Controller: k_p=3, k_i=1, and k_d = 2 (T_{settle} <3 sec)



Transient Profile and Robustness

- Controller: k_p=300, k_i=100, and k_d = 200



Simulating a feedback control system

- Introduction to Matlab/Simulink
  - Matlab Basics
  - Matlab GUI
  - Simulink
- PID Design and Evaluation
  - Simulation Model Setup
  - PID Gain Selection
  - Evaluation of Performance
    - Command Following: how fast and accurate
    - 10% Input Disturbance Test
    - 1% White Noise Test
    - Time Delay Test
    - Smoothness of Control Signal