# Intelligent Command Generation for Flexible Systems

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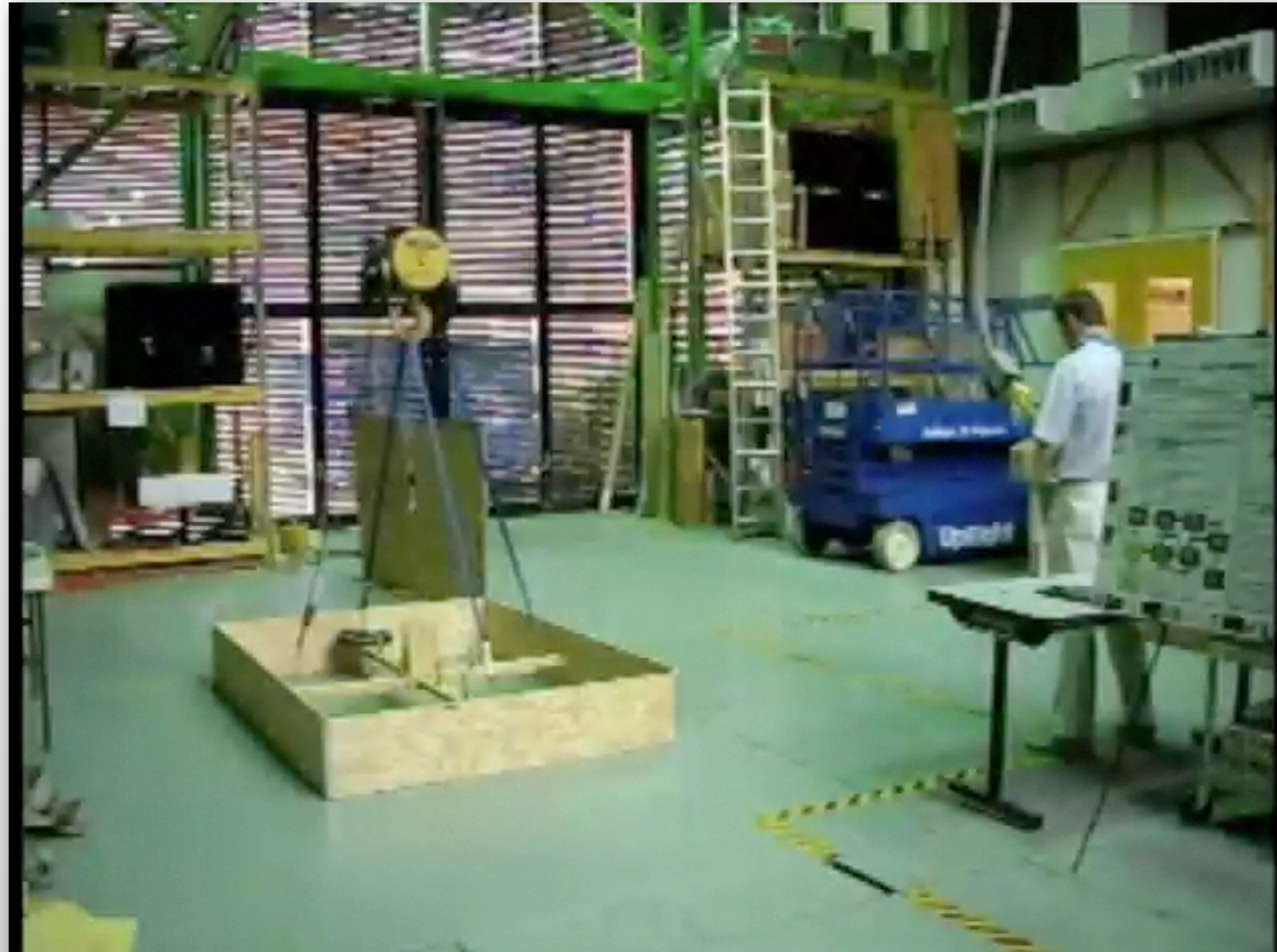
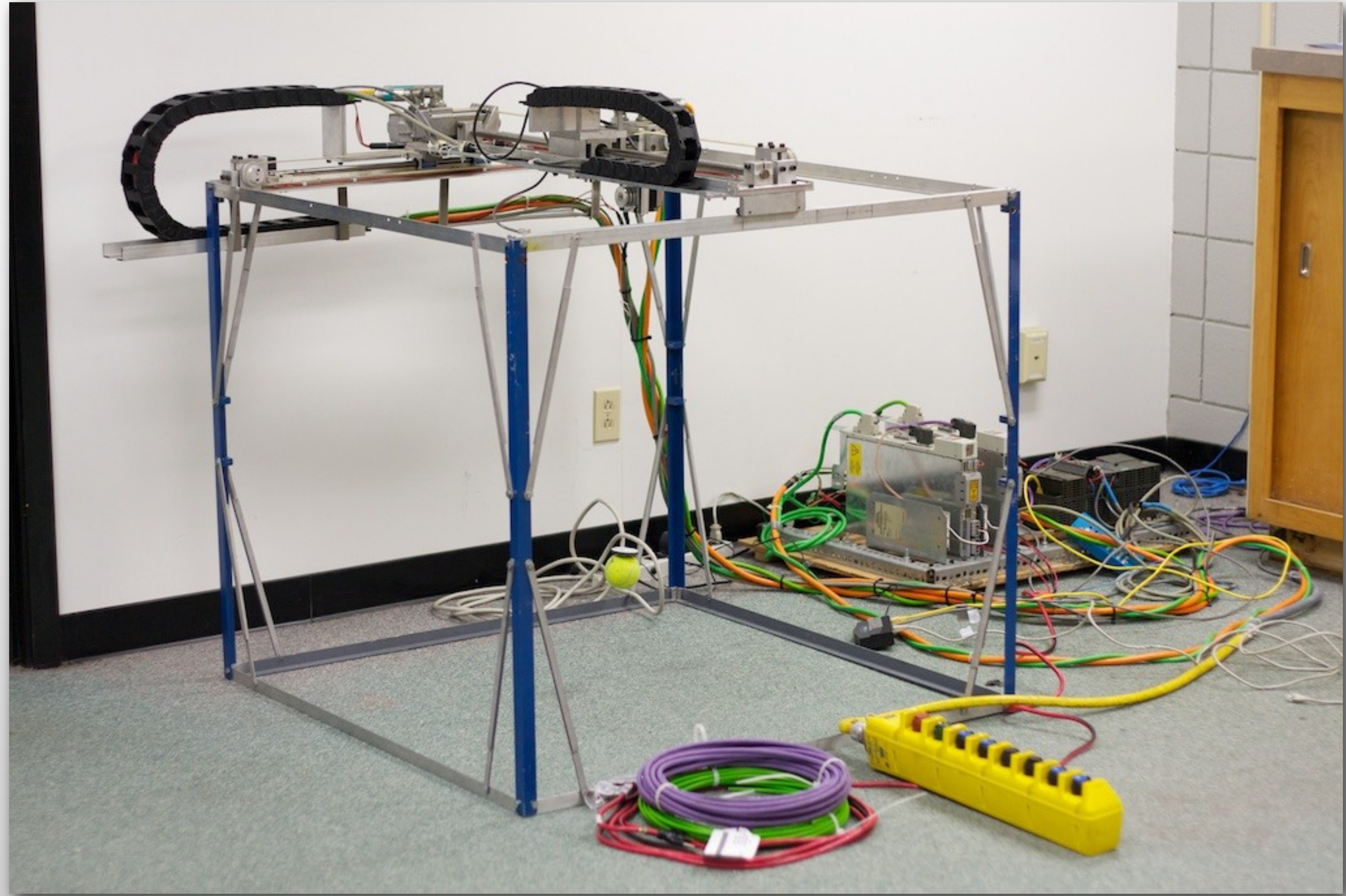
# 10-ton Bridge Crane

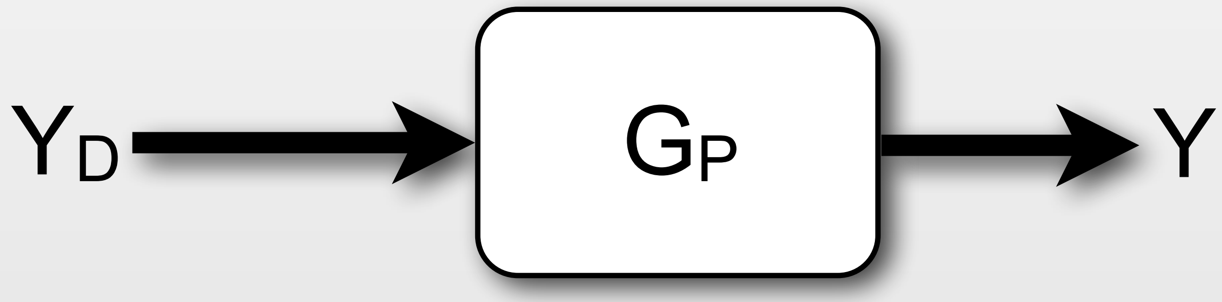


# A Smaller Crane



# A Smaller Crane

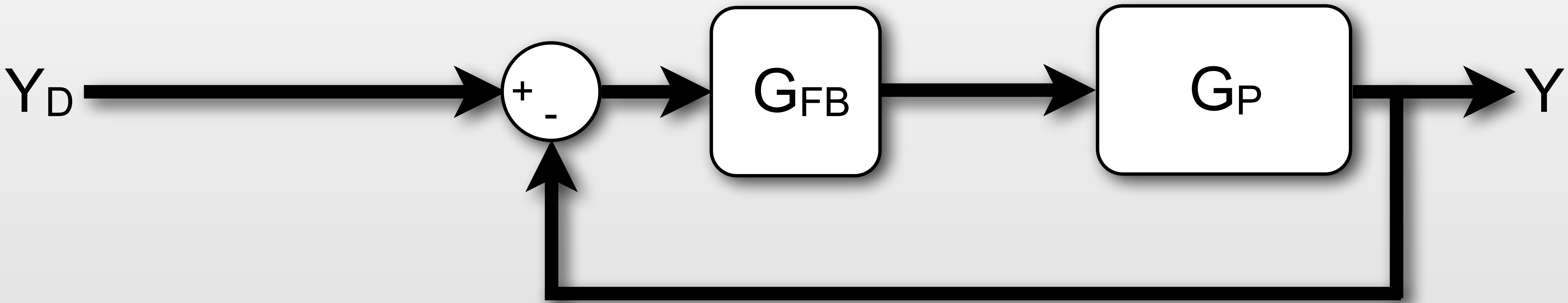
# Motion Control




**Goal: $Y = Y_D$**

- $G_P$ - Plant, the system to control

# Motion Control




**Goal: $Y = Y_D$**

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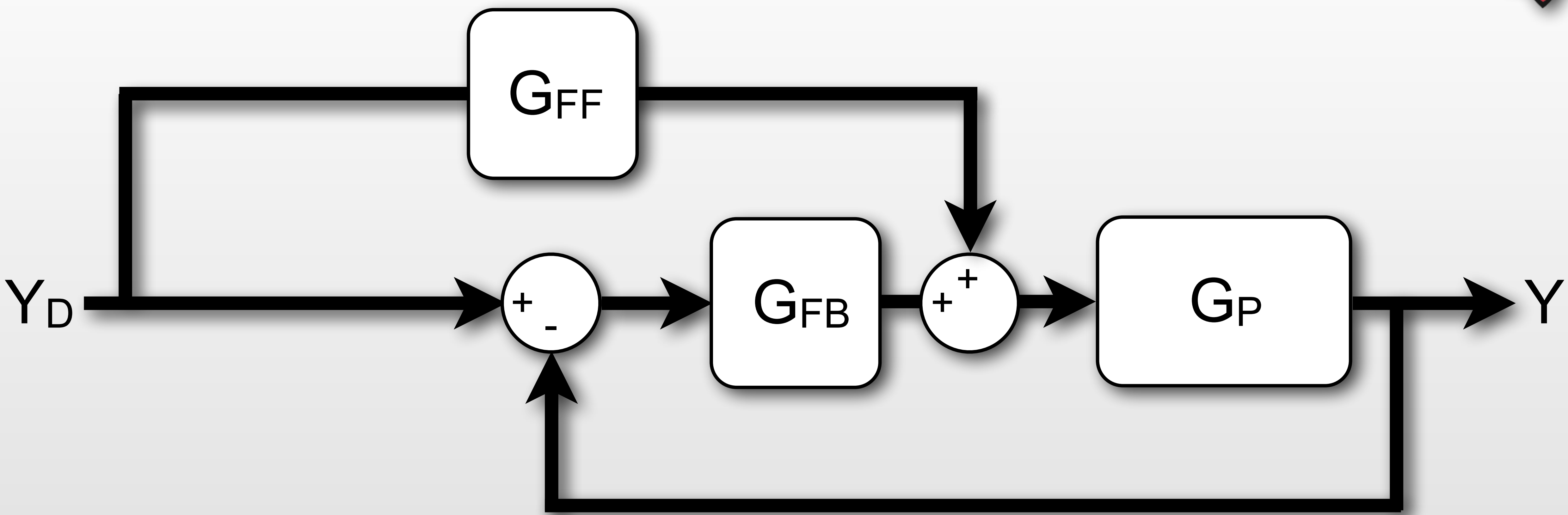
- $G_{FB}$ - Feedback controller

# Motion Control




**Goal: $Y = Y_D$**

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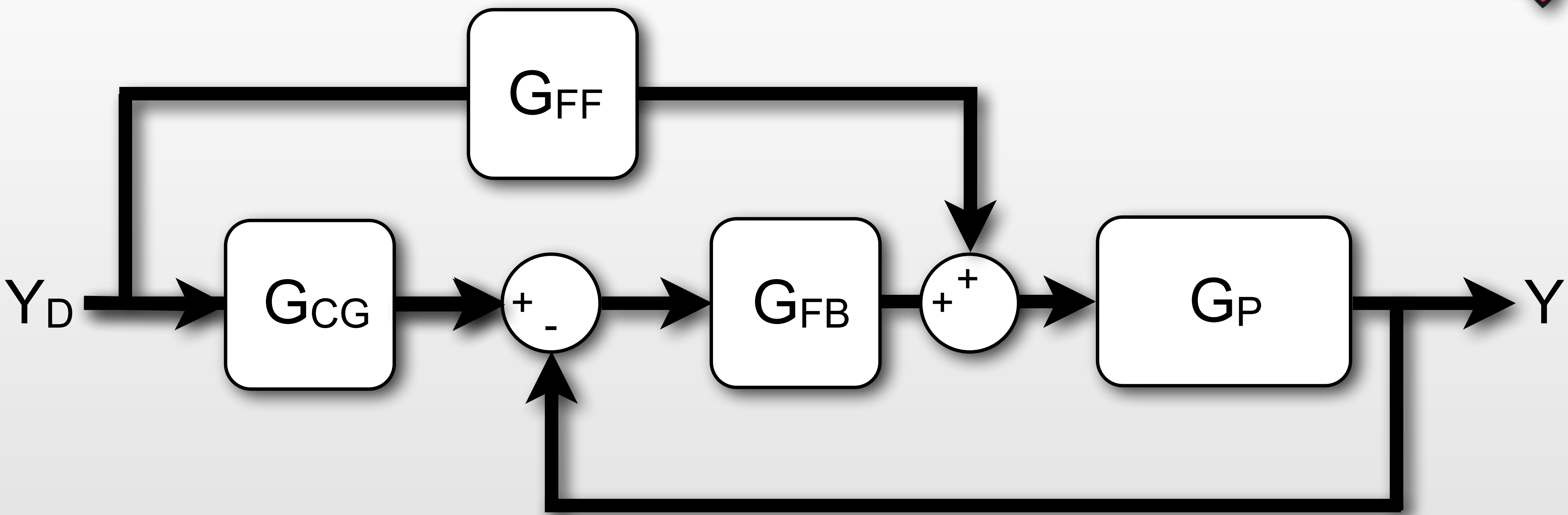
- $G_{FF}$ - Feedforward controller

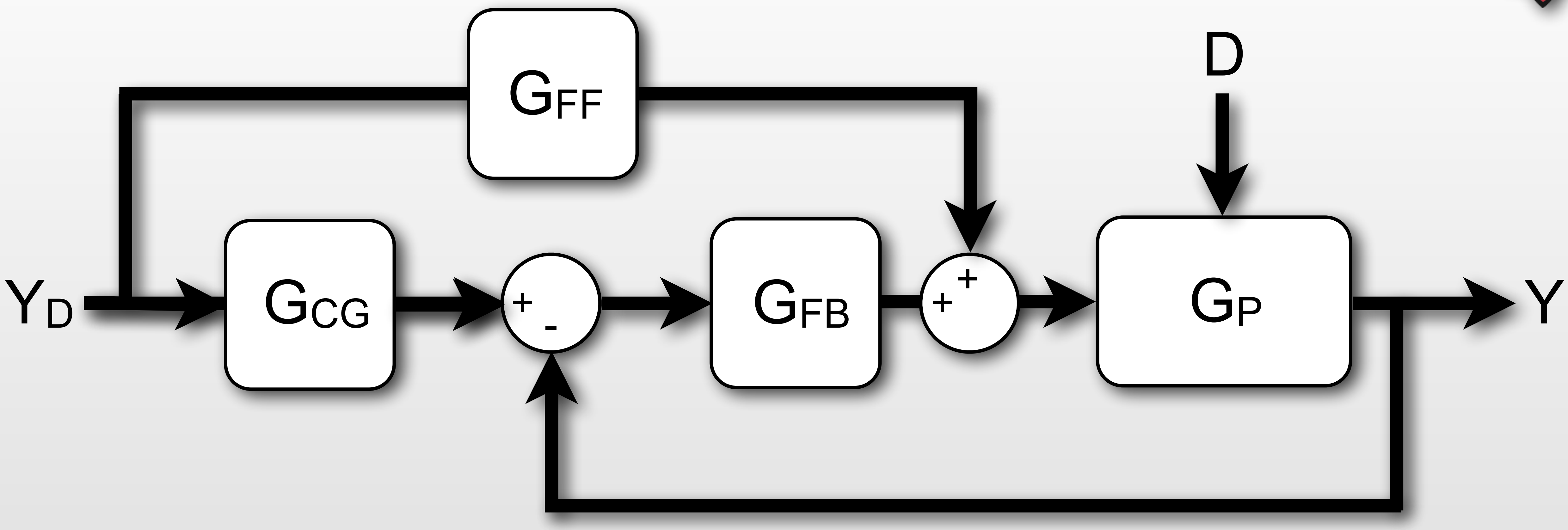
# Motion Control




**Goal: $Y = Y_D$**

- $G_P$ - Plant, the system to control
- $G_{FB}$ - Feedback controller
- $G_{FF}$ - Feedforward controller
- $G_{CG}$ - Command generator

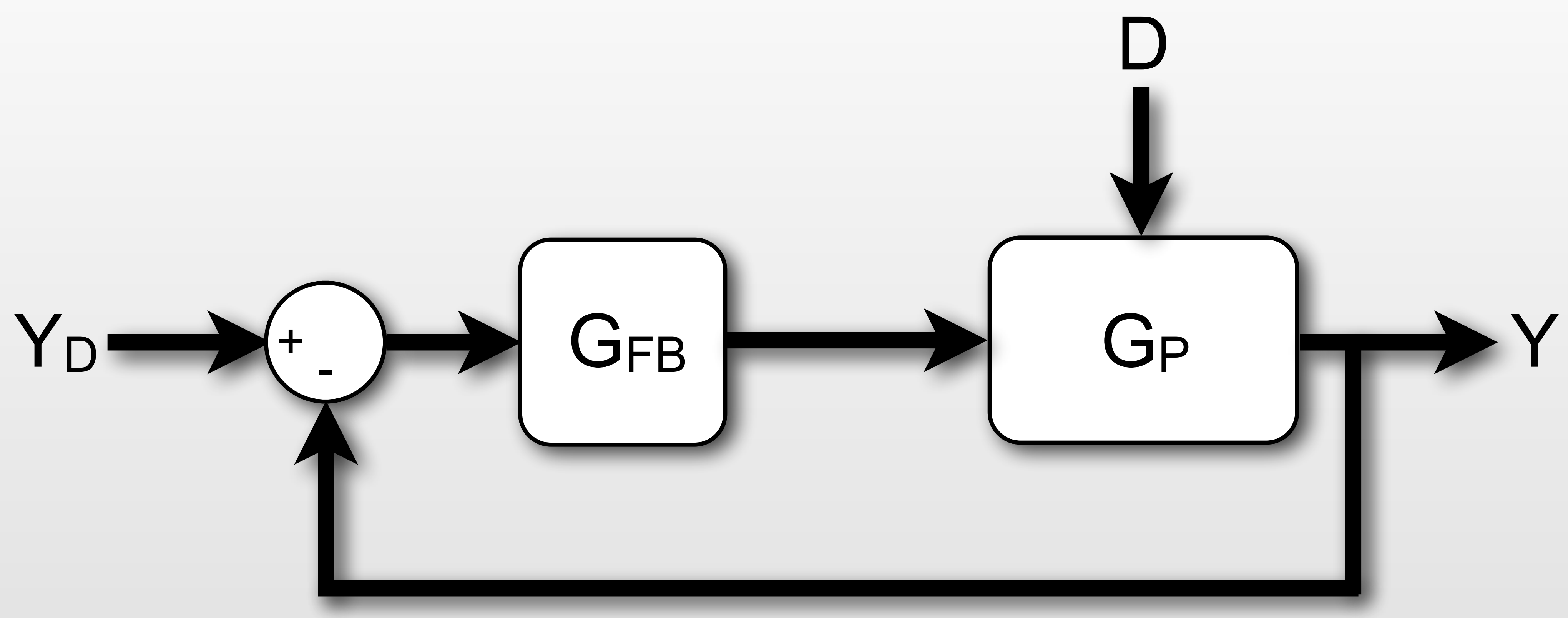
# Motion Control




**Goal: $Y = Y_D$**

- $G_P$ - Plant, the system to control
- $G_{FB}$ - Feedback controller
- $G_{FF}$ - Feedforward controller
- $G_{CG}$ - Command generator

# Feedback Control



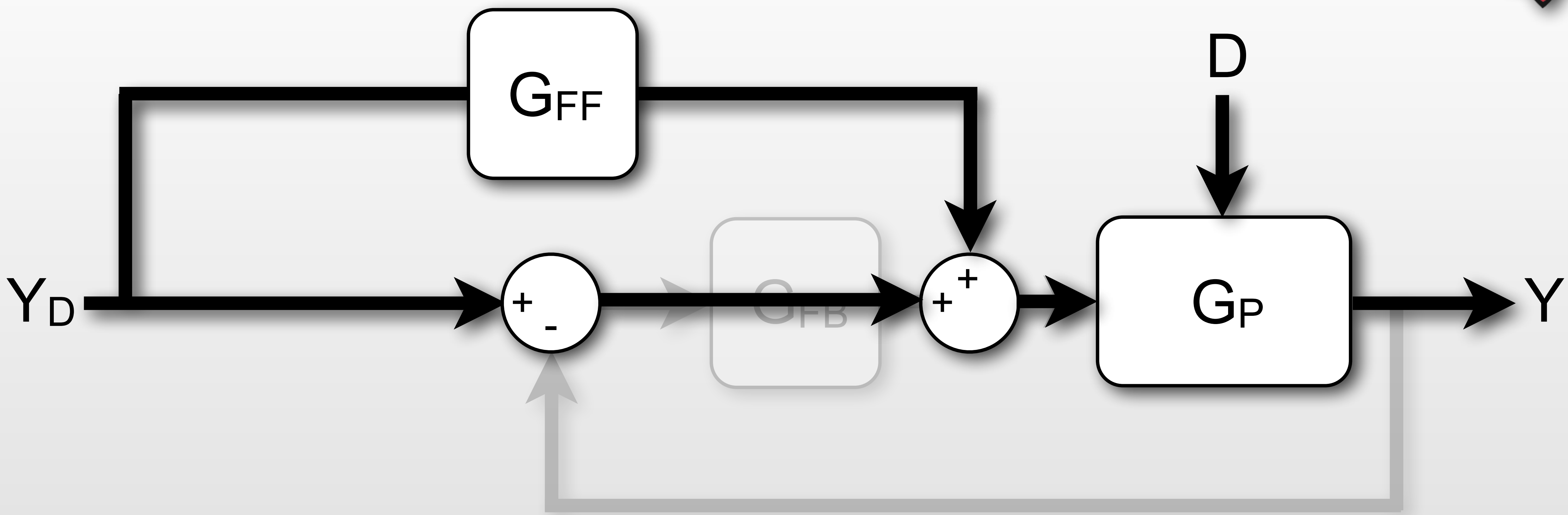

## Pros

- Eliminate $Y_D$-Y errors
- Disturbance rejection
- ...

## Cons

- Stability?
- Need sensors, etc.
- ...

# Feedforward Control



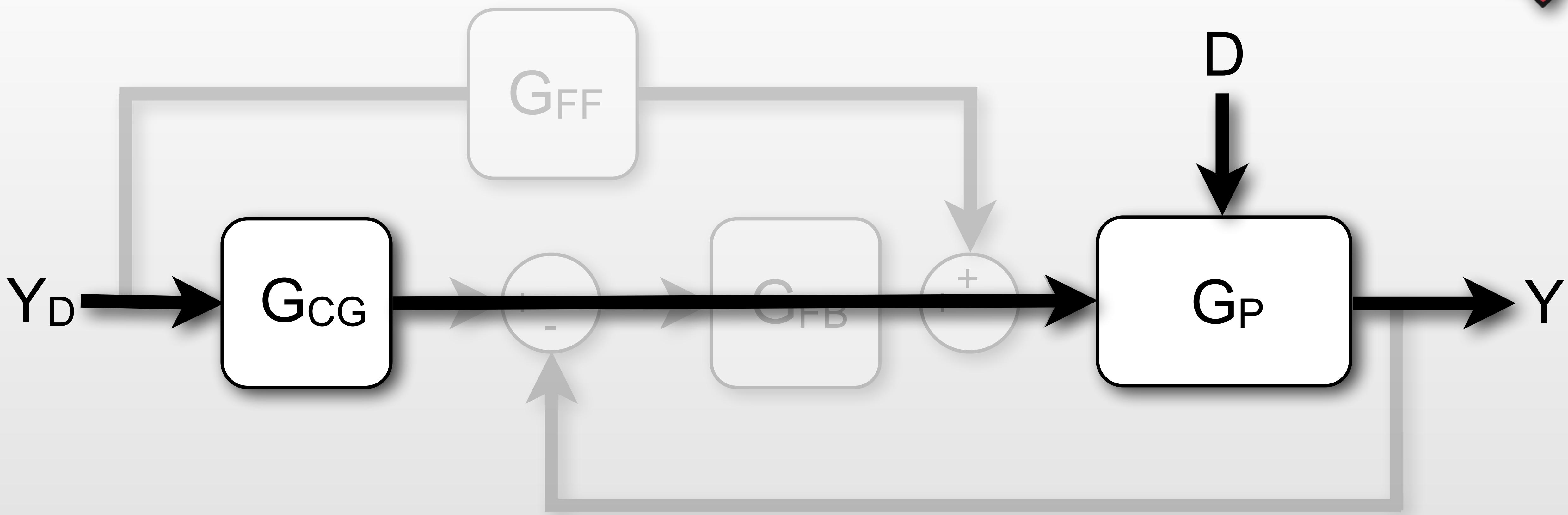

## Pros

- Faster motion
- Compensate for delays
- ...

## Cons

- No disturbance rejection
- High actuator demands
- ...

# Command Generation



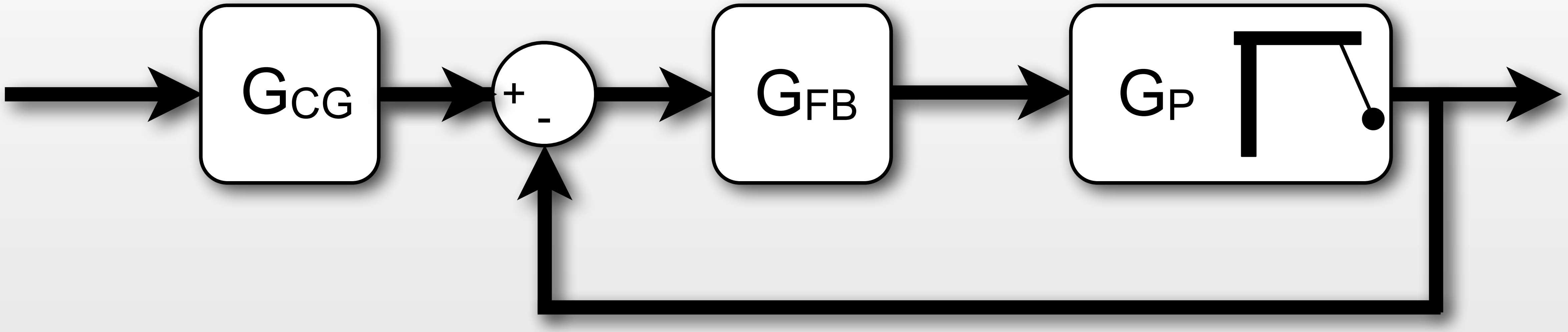

## Pros

- Simple implementation
  - No sensors needed
  - Full model not needed
- Human compatible
- ...

## Cons

- No disturbance rejection
- Increases rise time
- ...

# Open-Loop Vibration Control



# Open-Loop Vibration Control

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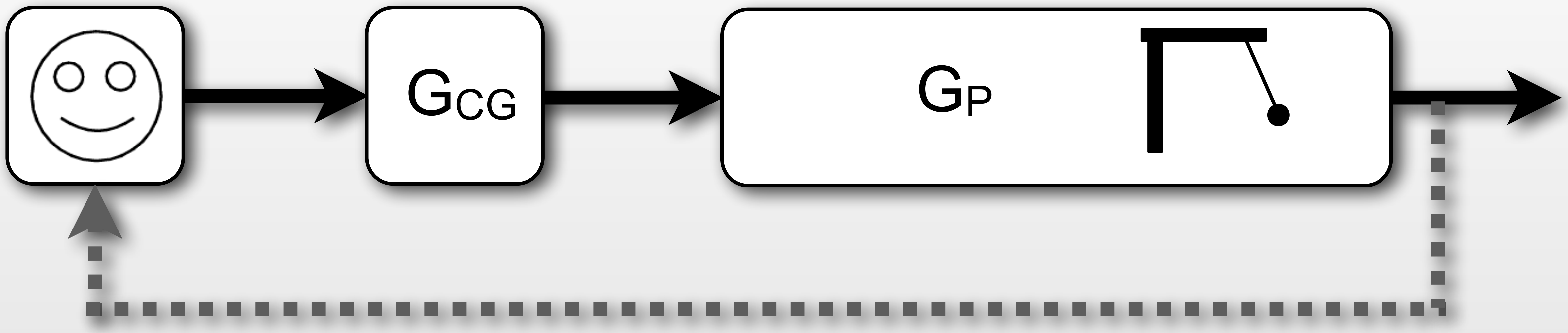
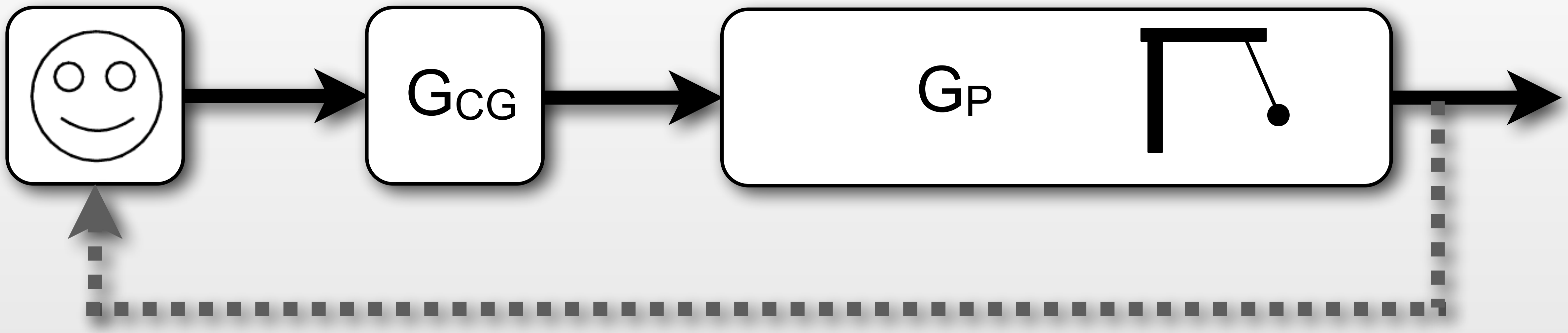


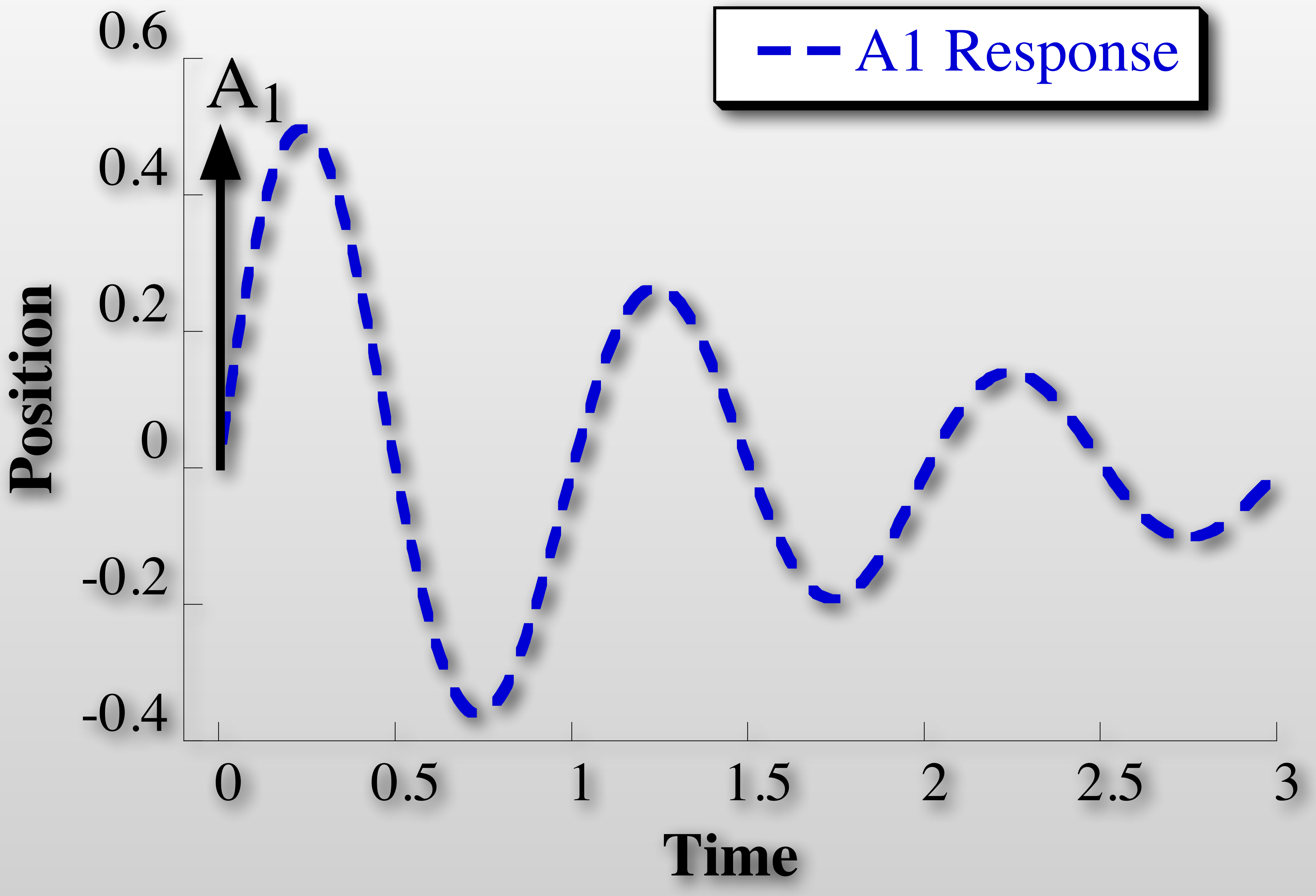
# Open-Loop Vibration Control



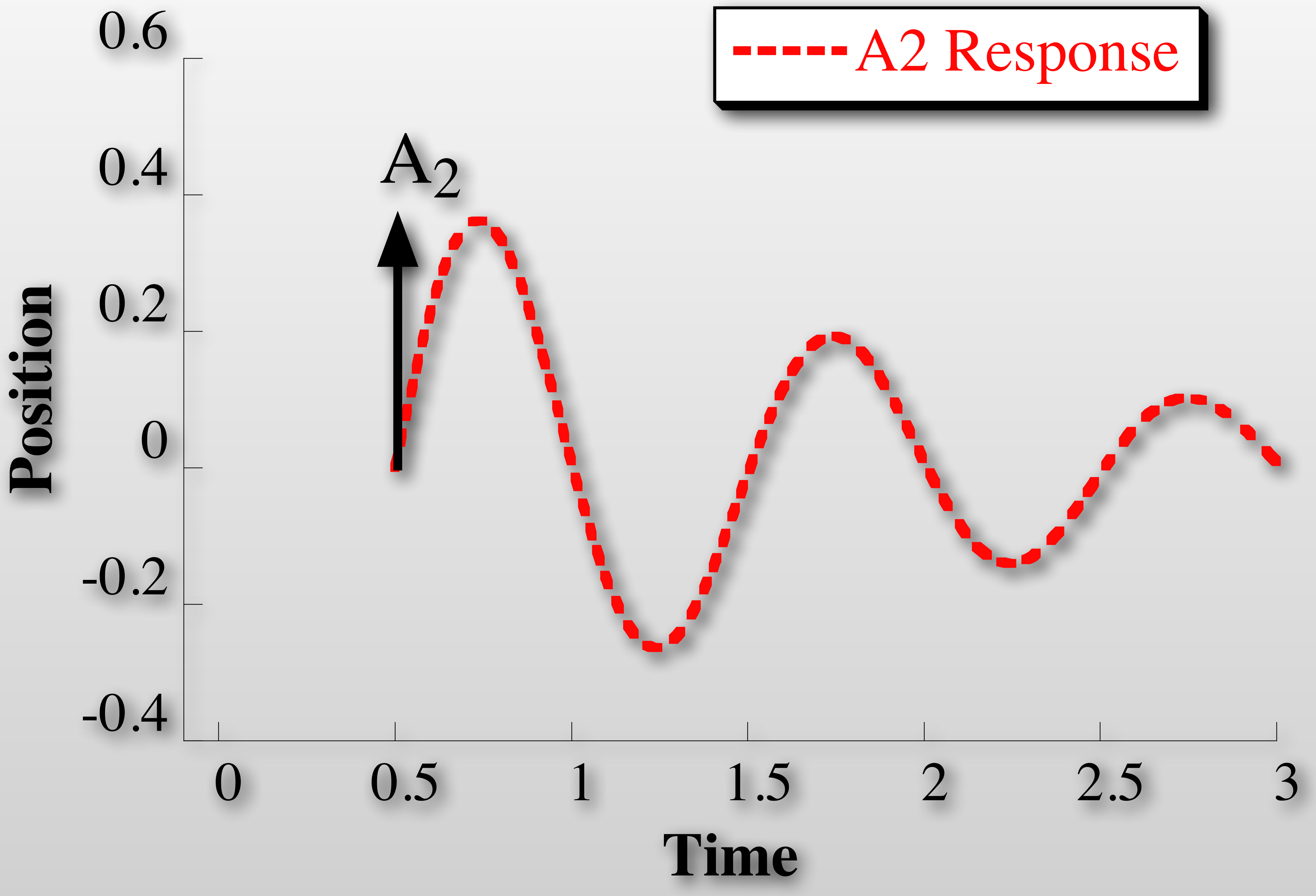

**Options for $G_{CG}$**

- Plant/Model Inversion
- Traditional Filters
- Input Shaping

# Input Shaper Design



# Input Shaper Design



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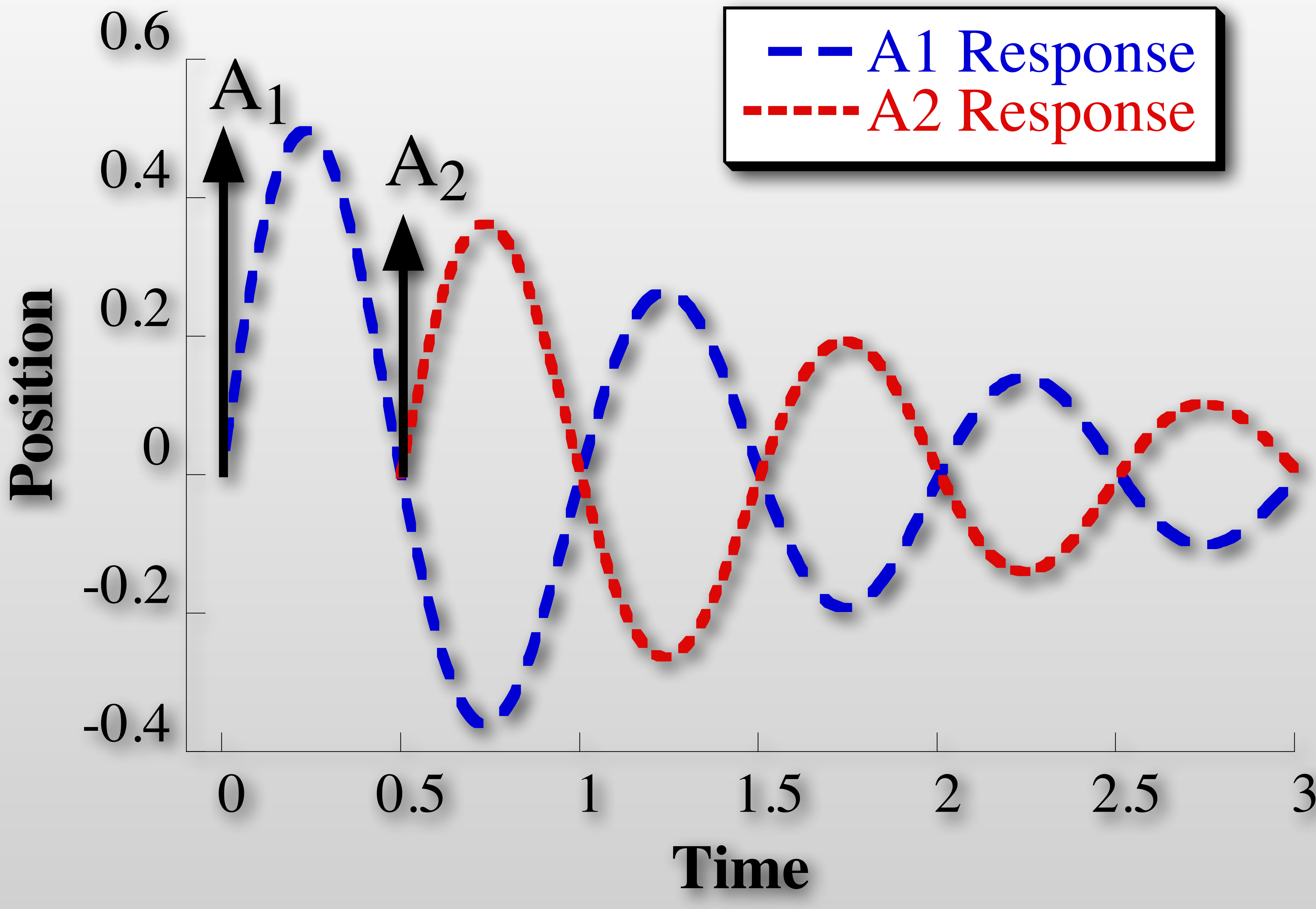
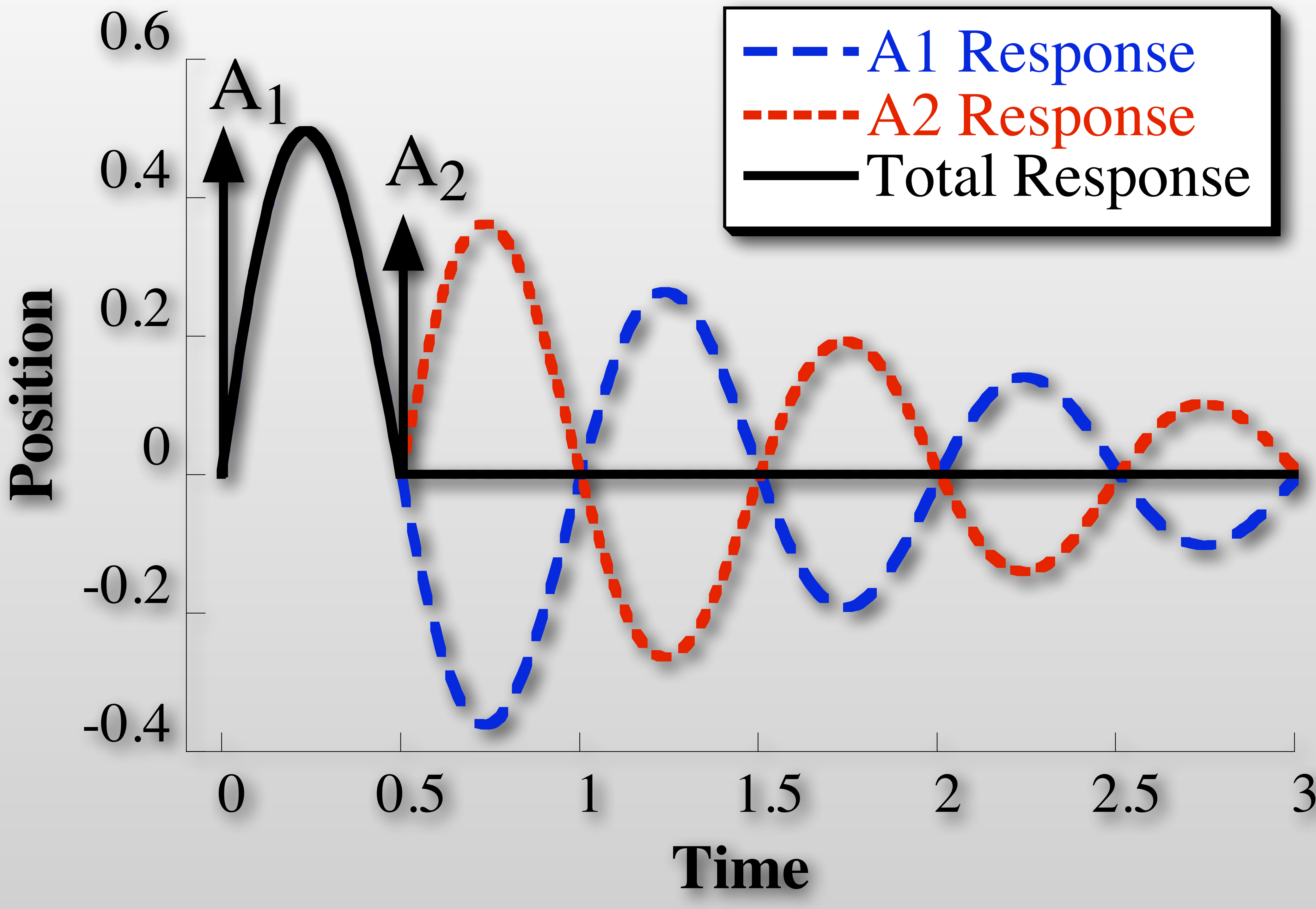
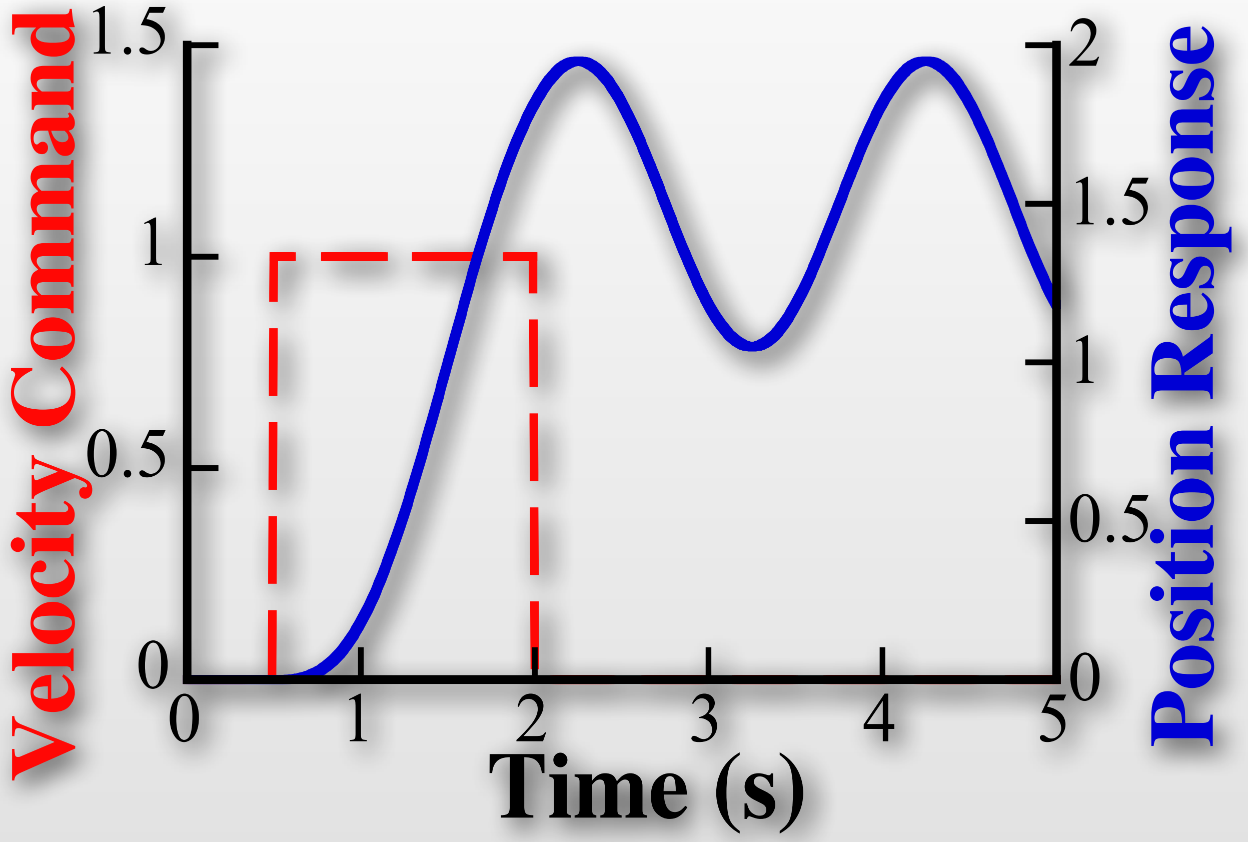
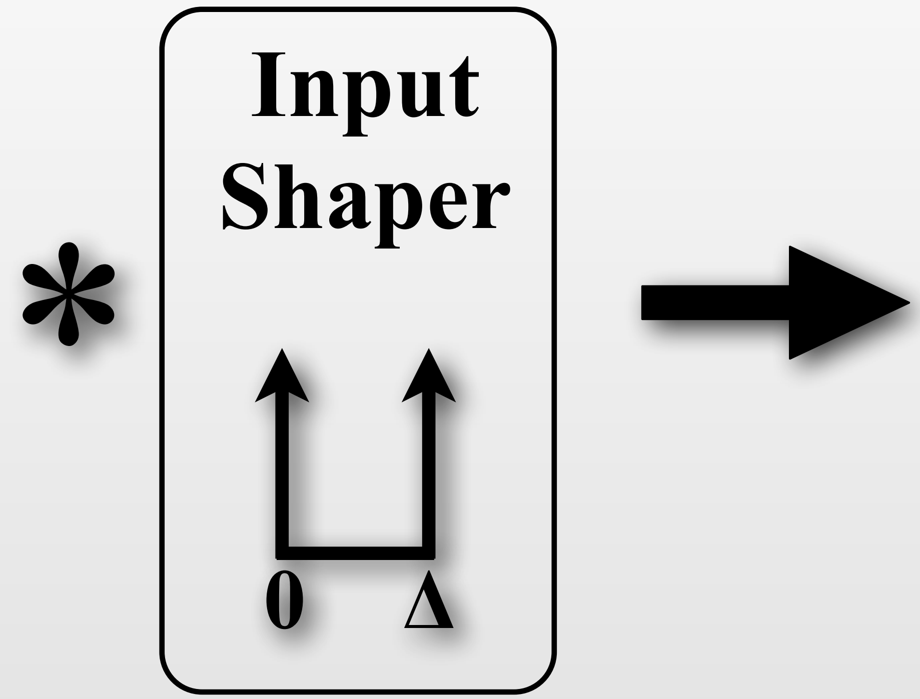


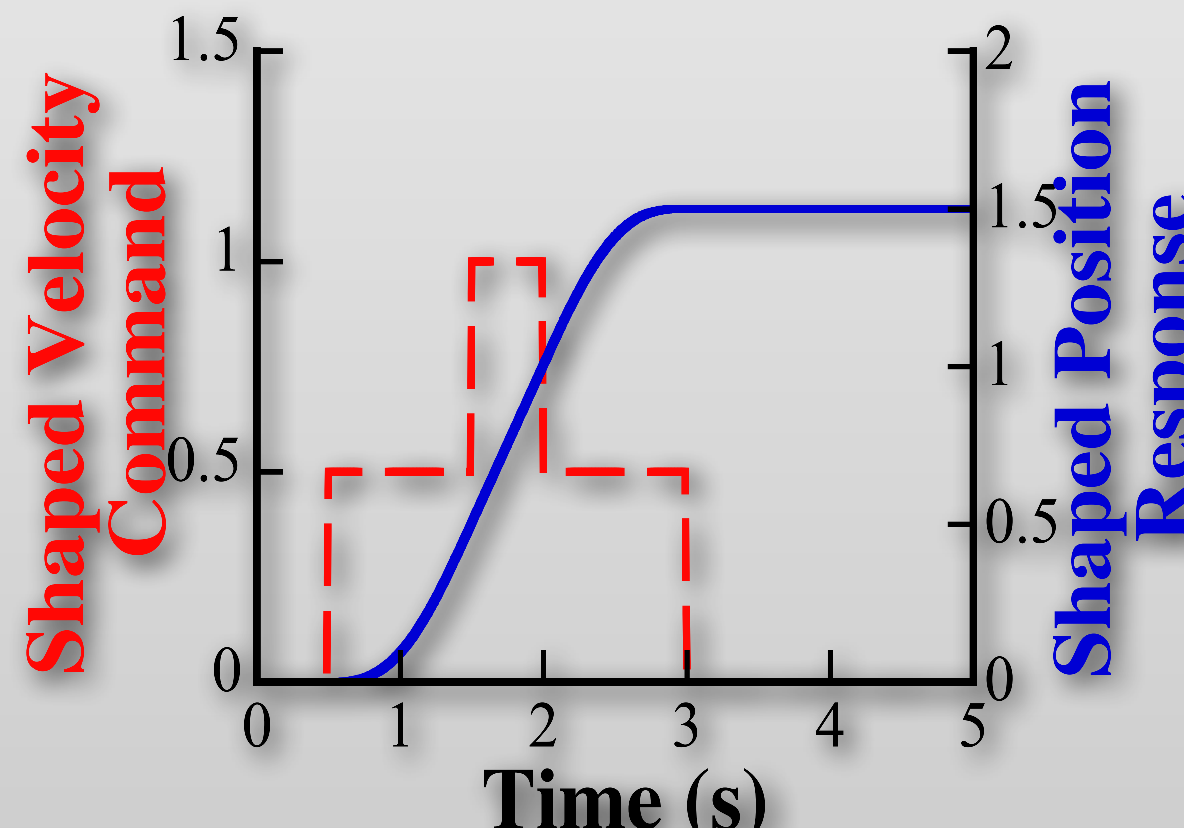
# Input Shaper Design



# Input Shaping Process

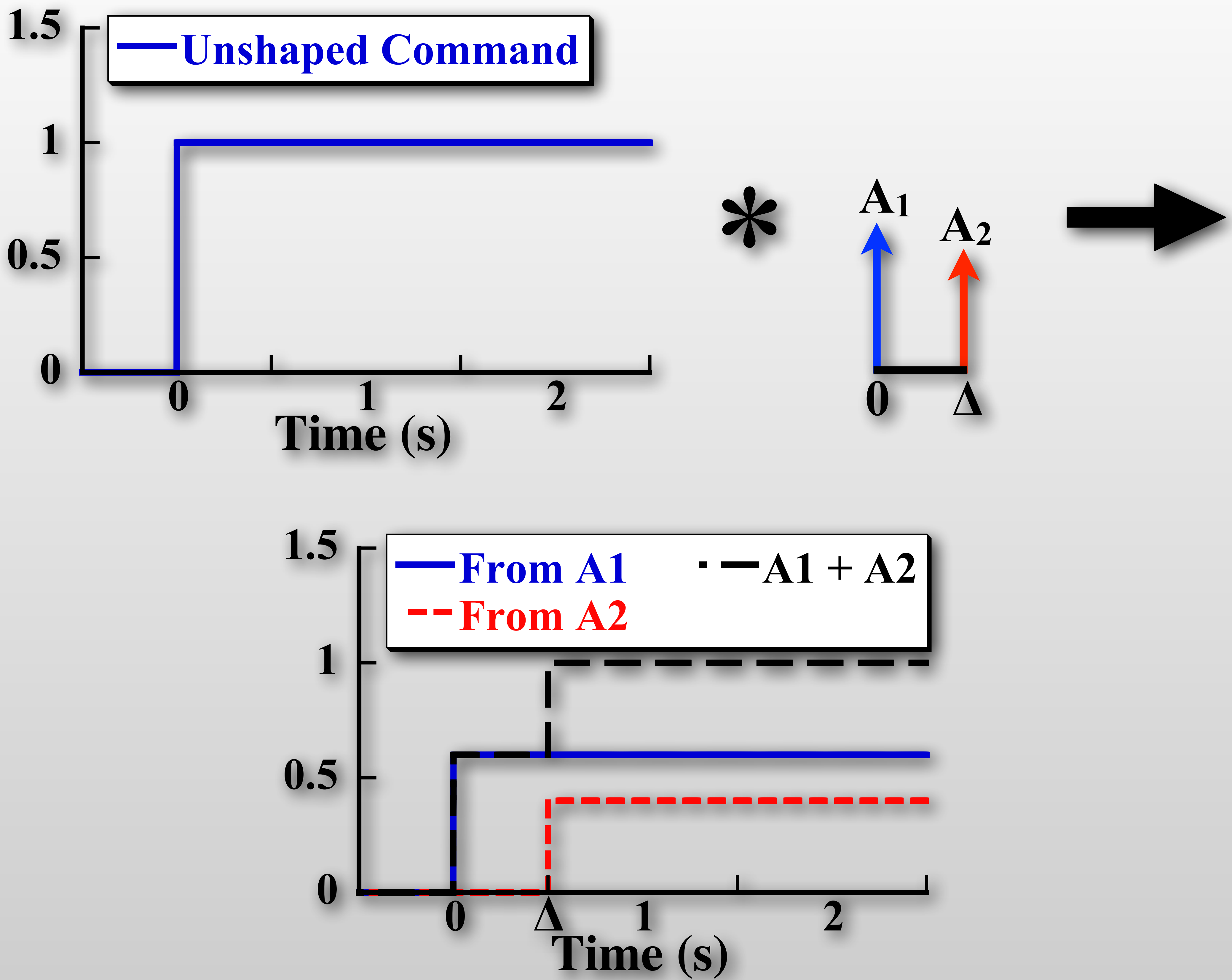


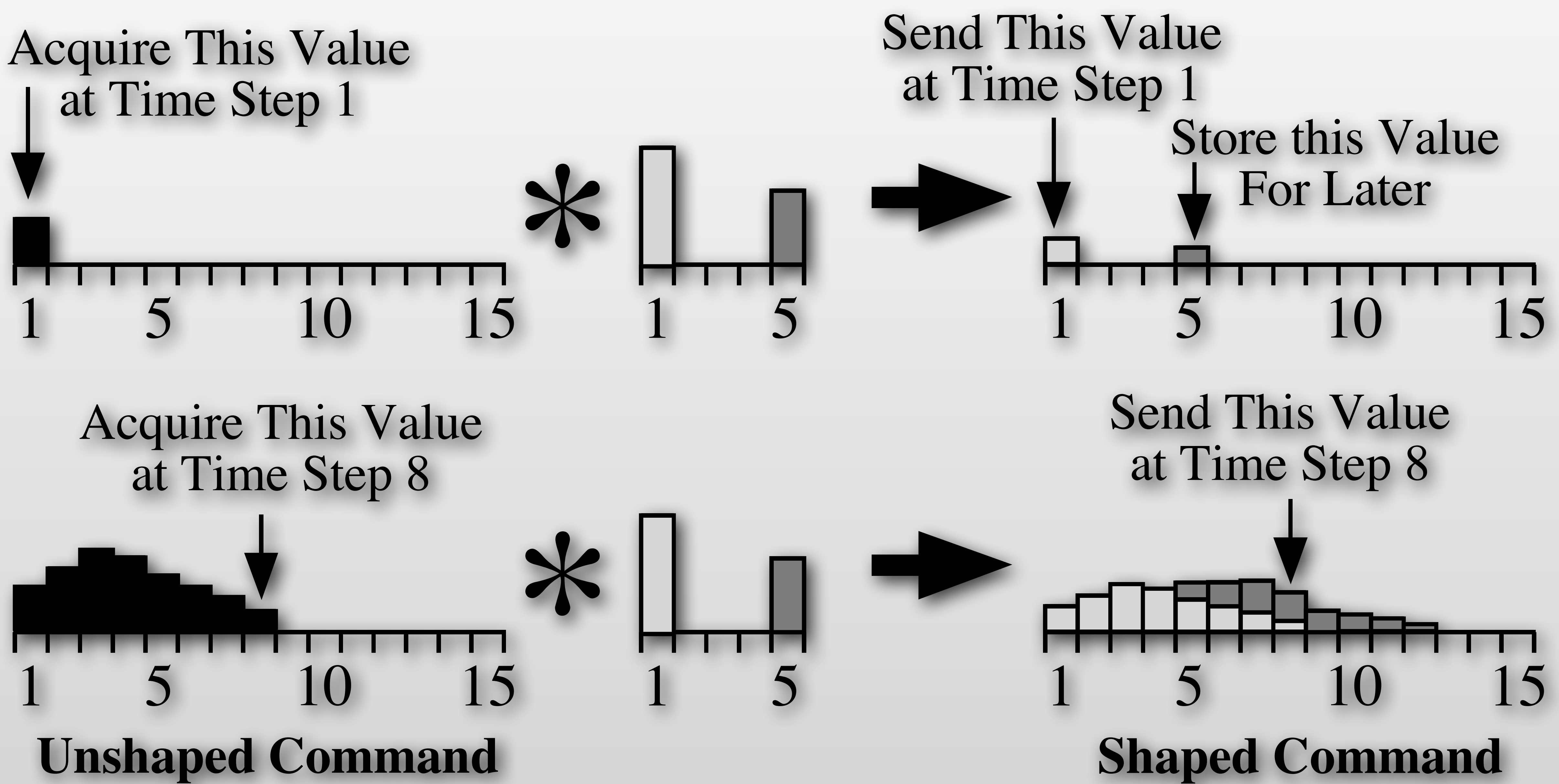




- Shaper design:
  - Natural Freq.
  - Damping Ratio
- Slight increase in command duration

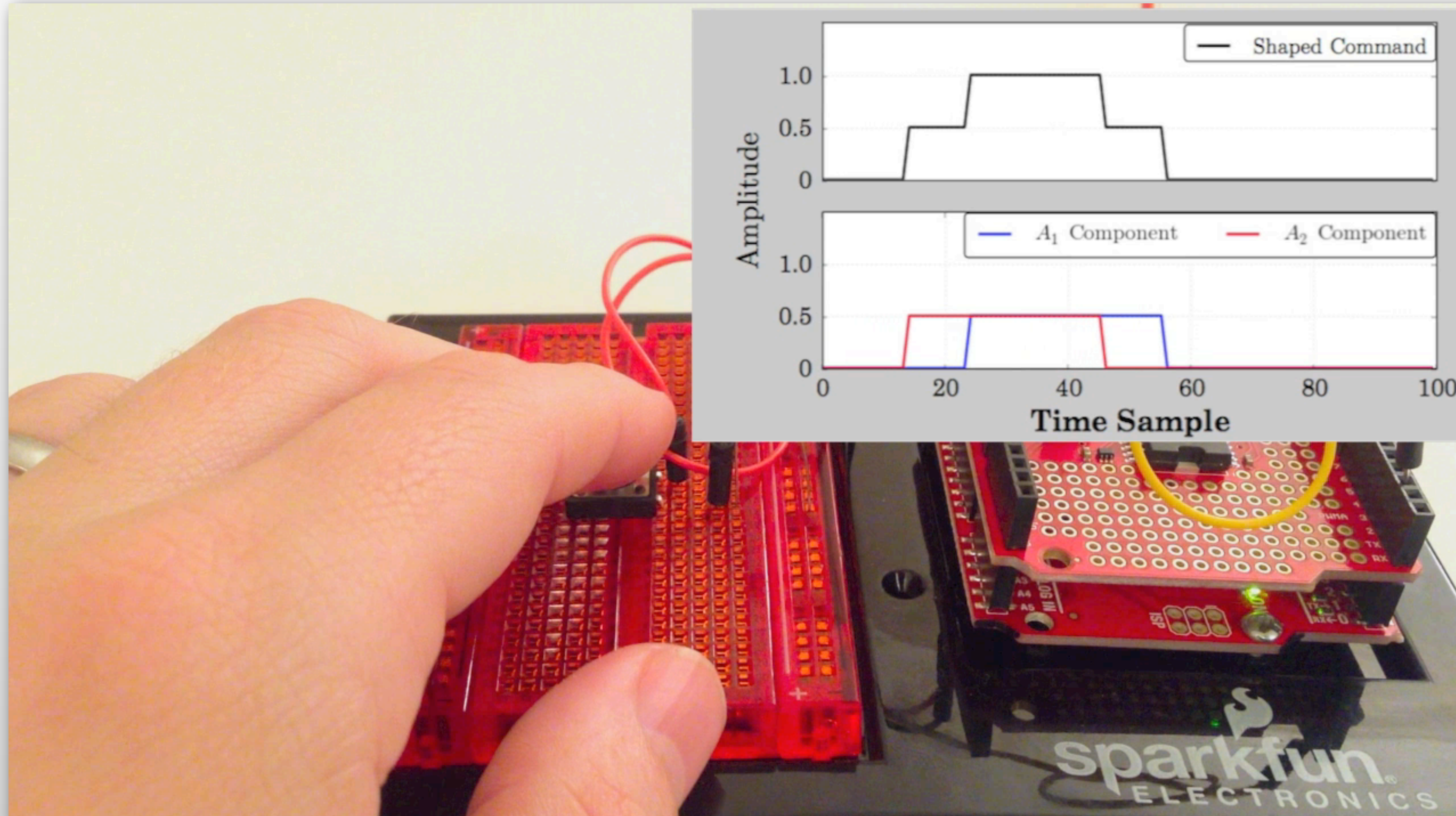
# Convolution with Impulses



# Implementation



# Implementation



# Vibration Equation

$$V(\omega,\zeta) = e^{-\zeta\omega t_n}\sqrt{[C(\omega,\zeta)]^2 + [S(\omega,\zeta)]^2}$$

$$C(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\cos(\omega t_i\sqrt{1-\zeta^2})$$

$$S(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\sin(\omega t_i\sqrt{1-\zeta^2})$$

$V(\omega,\zeta)$ is the vibration excited by *n*-impulses.

$V(\omega,\zeta) \le V_{tol}$ **Constraint is that vibration less than $V_{tol}$**

# Impulse Amplitude Constraints

<u>All impulses sum to one</u>

$$\sum A_i = 1, \qquad i = 1, \ldots, n$$

This ensures we reach our desired state.

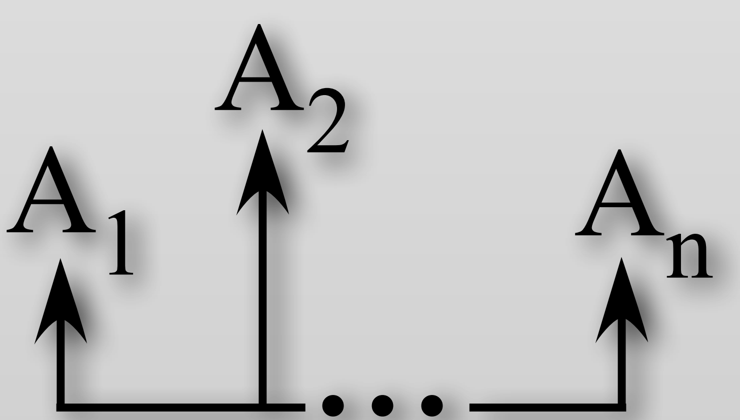
# Impulse Amplitude Constraints

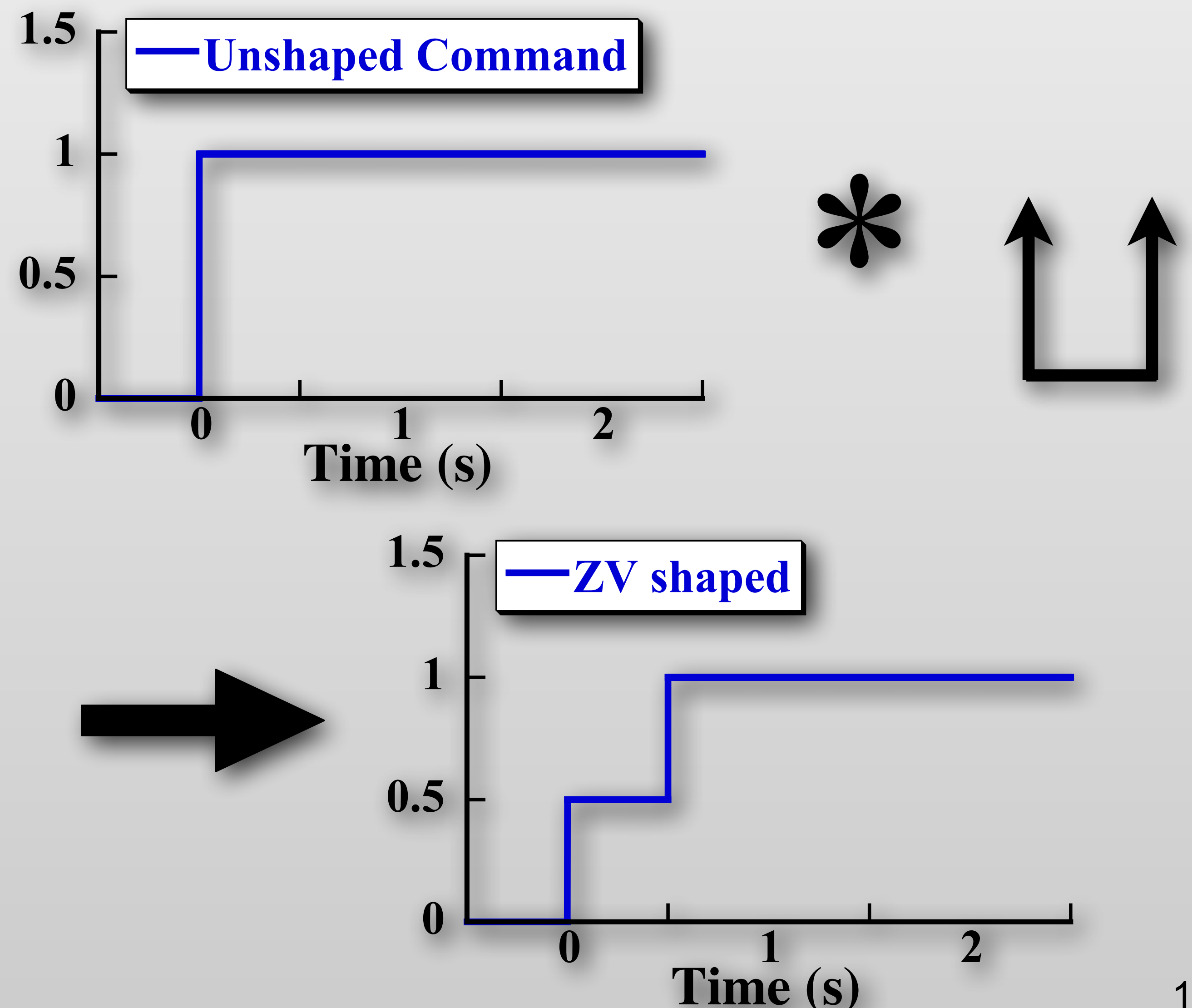
All impulses sum to one

$$\sum A_i = 1, \qquad i = 1, \ldots, n$$

Positive Shapers

$$\begin{aligned} A_i &\geq 0 \\ i &= 1, \ldots, n \end{aligned}$$



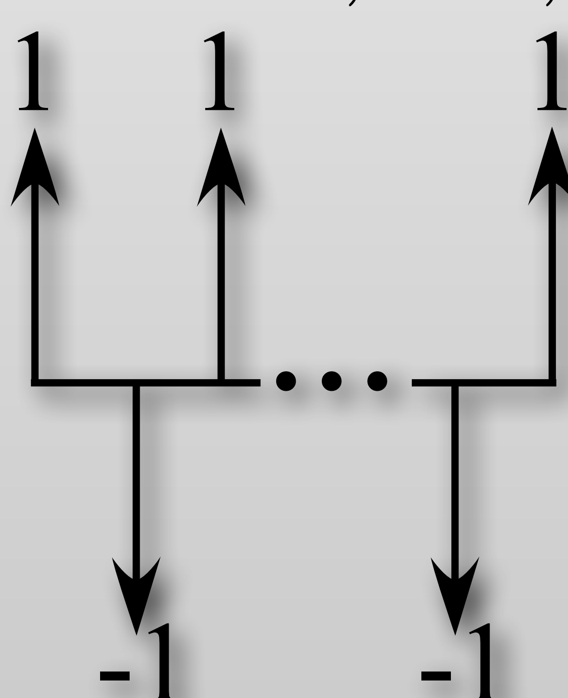
# Impulse Amplitude Constraints

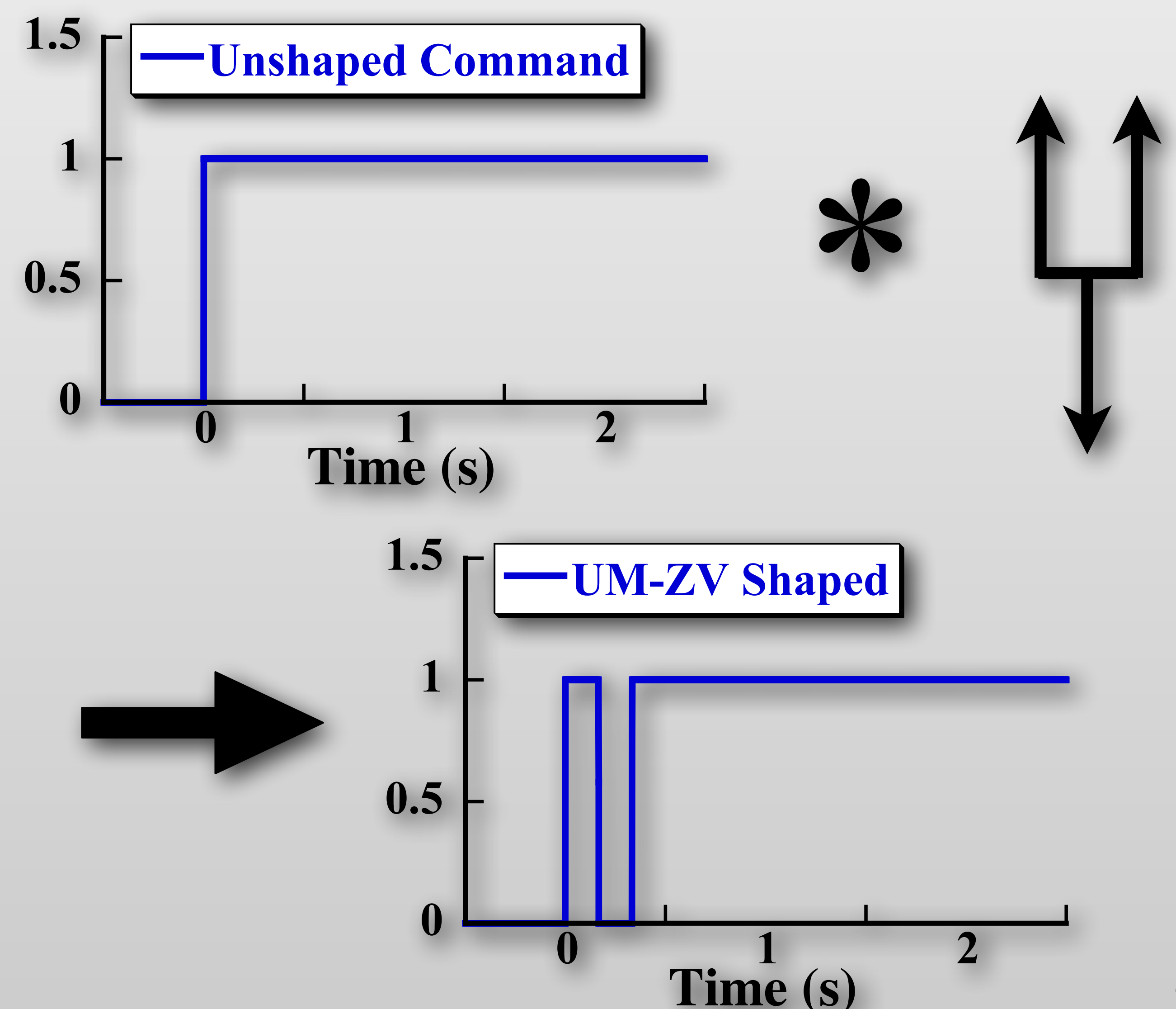
All impulses sum to one

$$\sum A_i = 1, \qquad i = 1, \ldots, n$$

Unity Magnitude (UM)

$$\begin{aligned} A_i &= (-1)^{i+1} \\ i &= 1, \ldots, n \end{aligned}$$



# Impulse Amplitude Constraints

All impulses sum to one

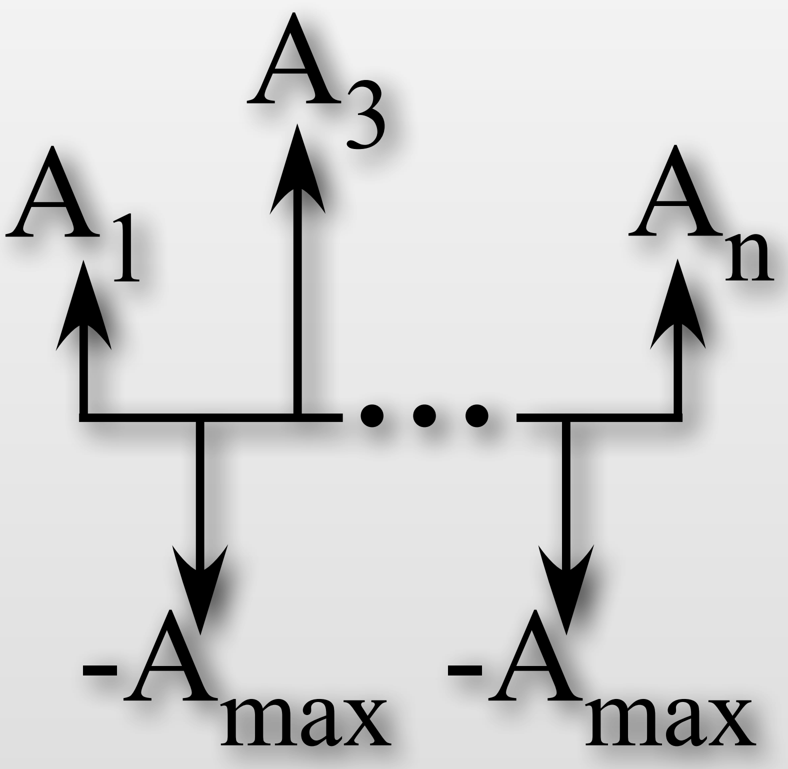
$$\sum A_i = 1, \quad i = 1, \ldots, n$$

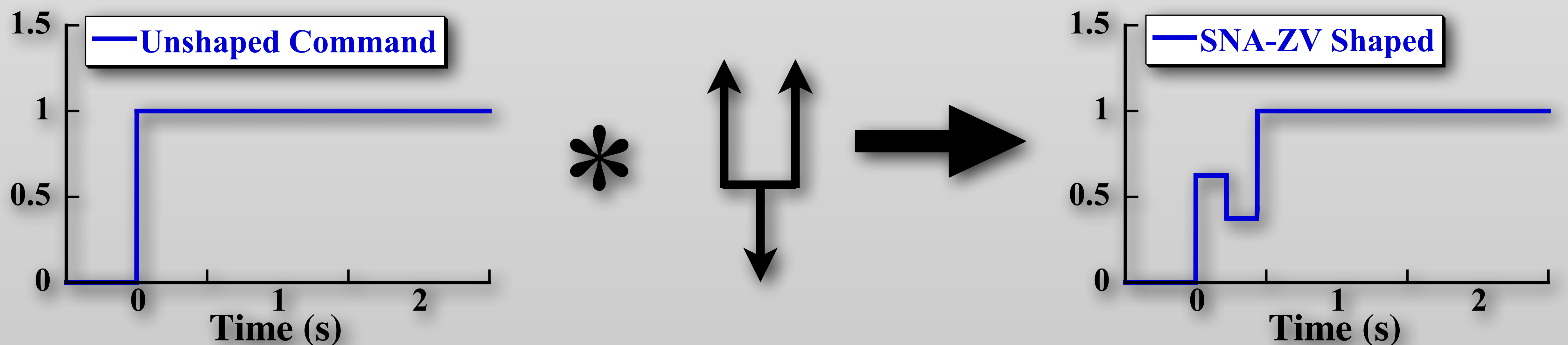
Specified Negative Amplitude (SNA)

$$0 < A_i \leq 1 \quad \text{when } i \text{ is odd}$$

$$A_i = -A_{max} \quad \text{when } i \text{ is even}$$

$$0 \leq \sum_{i=1}^{k} A_i \leq 1 \quad k = 1, \ldots, n$$



# Example Closed-Form Shapers

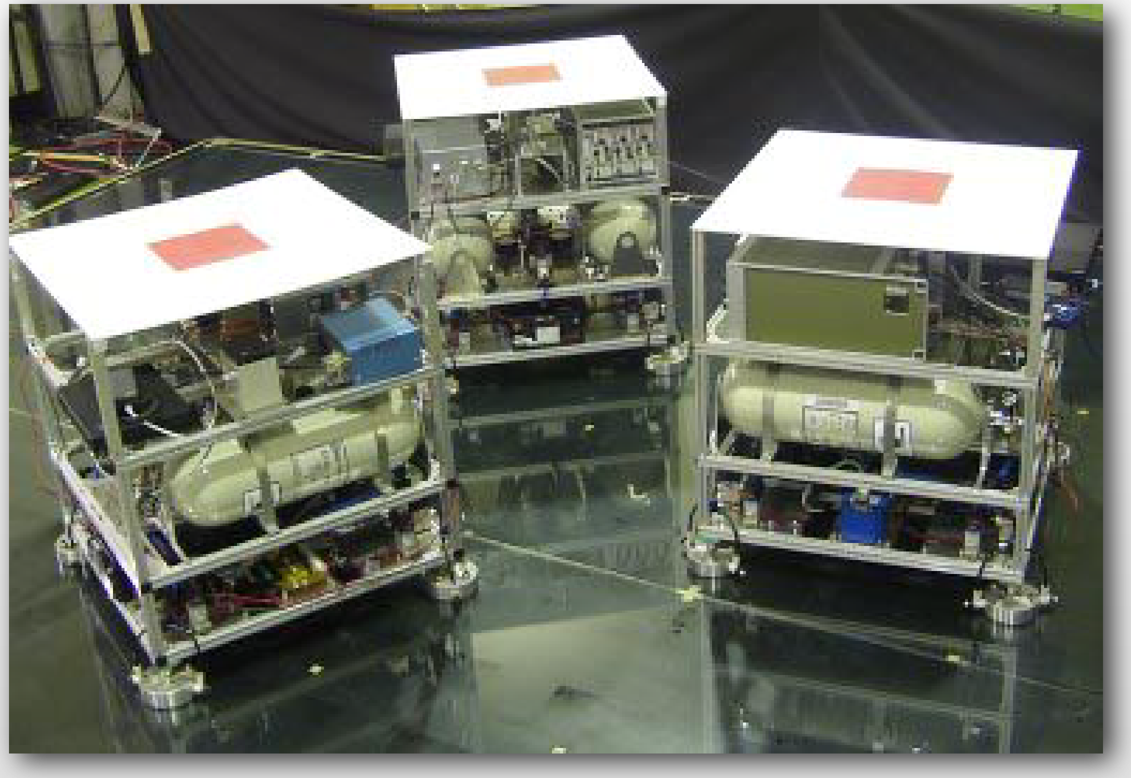
$$\mathrm{ZV} \equiv \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & \frac{\tau_d}{2} \end{bmatrix}$$

$$\mathrm{ZVD} \equiv \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & \frac{\tau_d}{2} & \tau_d \end{bmatrix}$$

where

- $\tau_d$ is the damped vibration period
- $K = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}}$

# Flexible Satellites at Tokyo Inst. of Tech.



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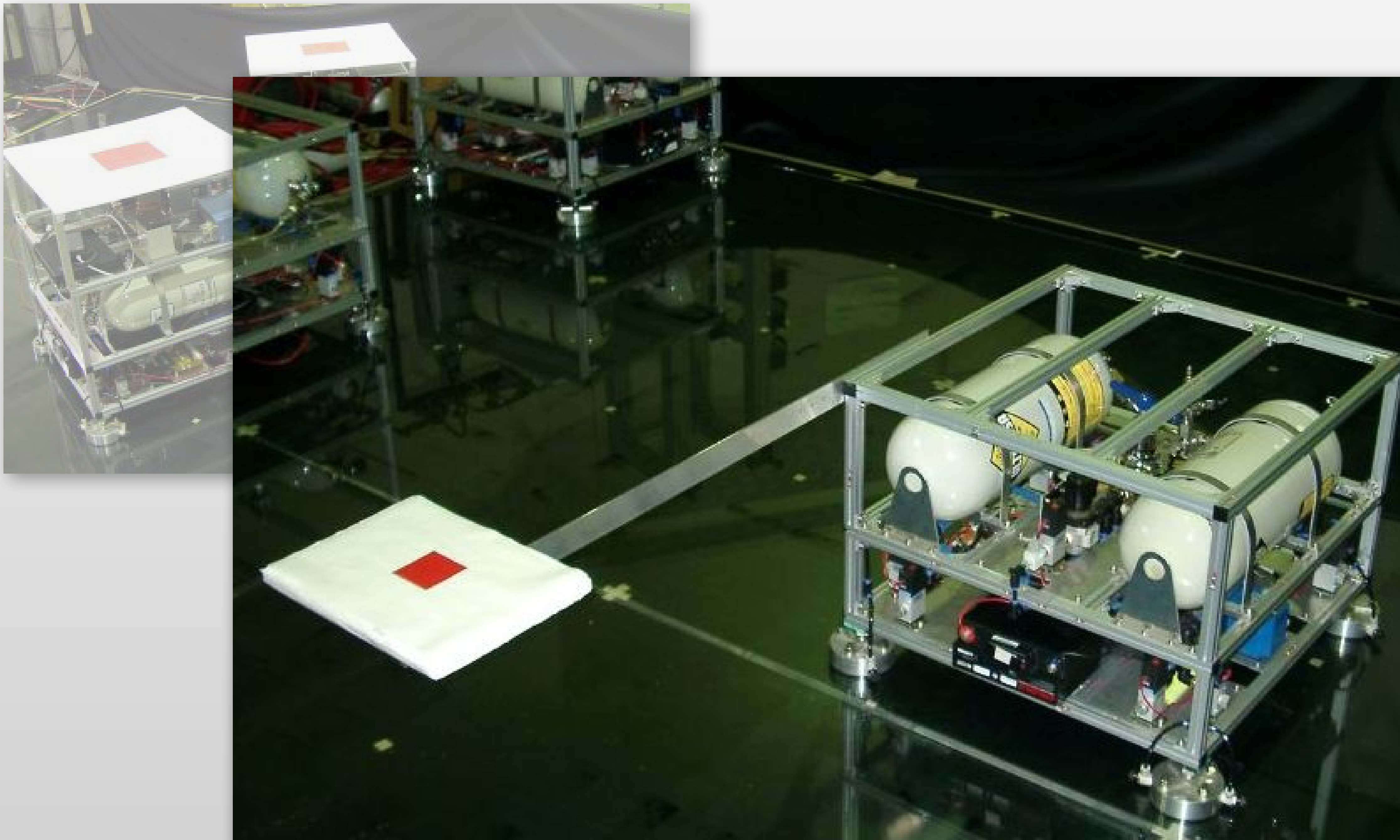
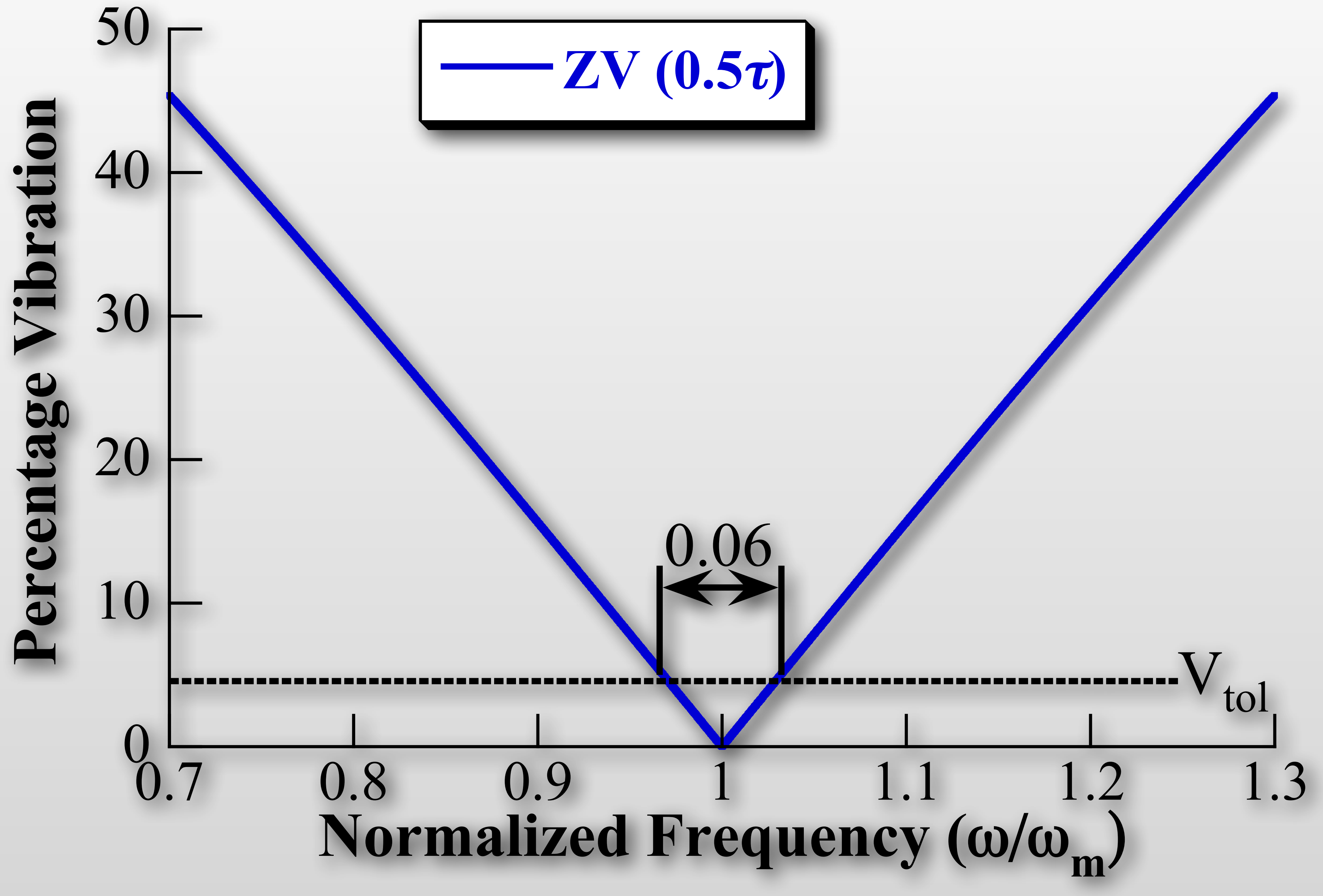
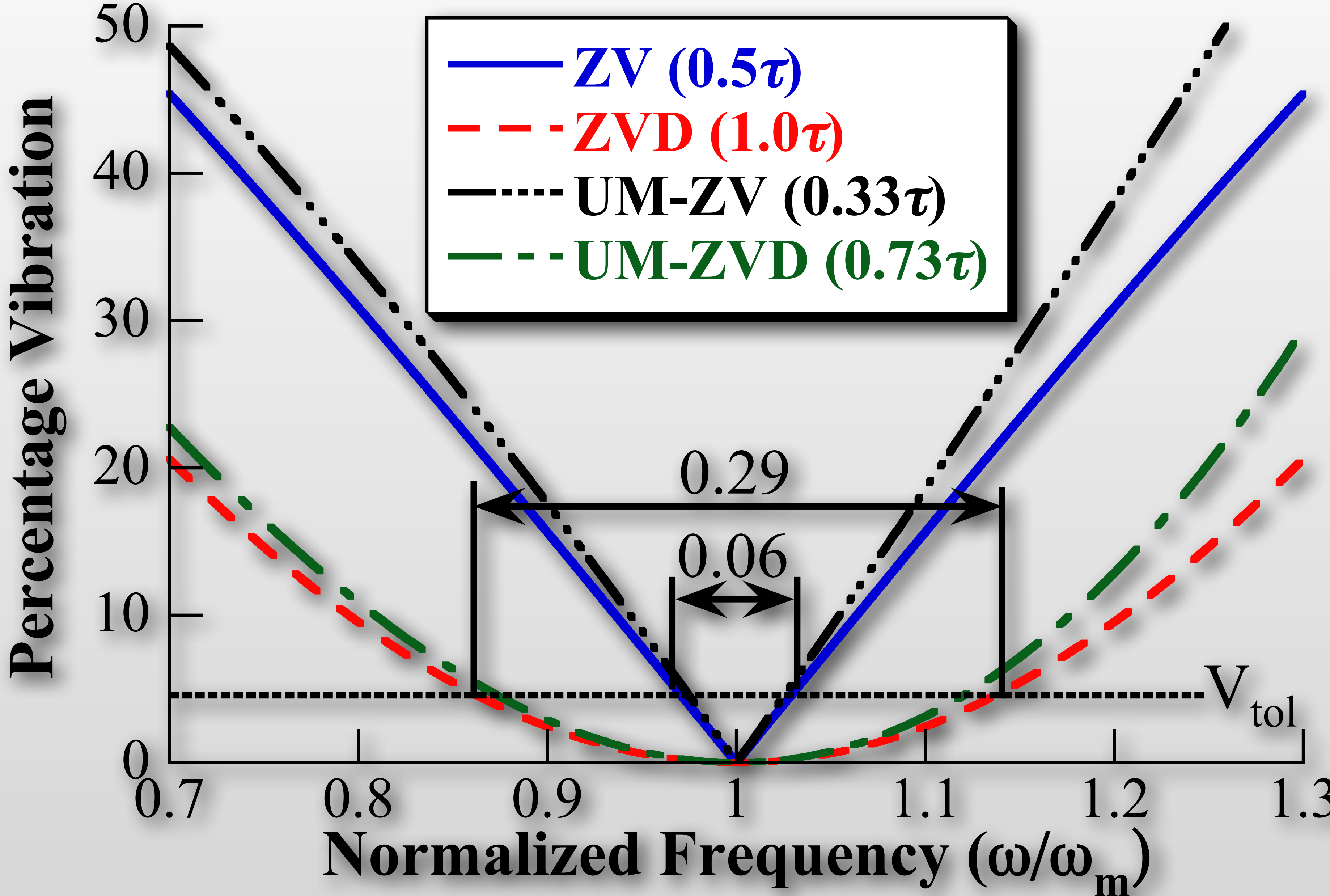


# Measuring Robustness



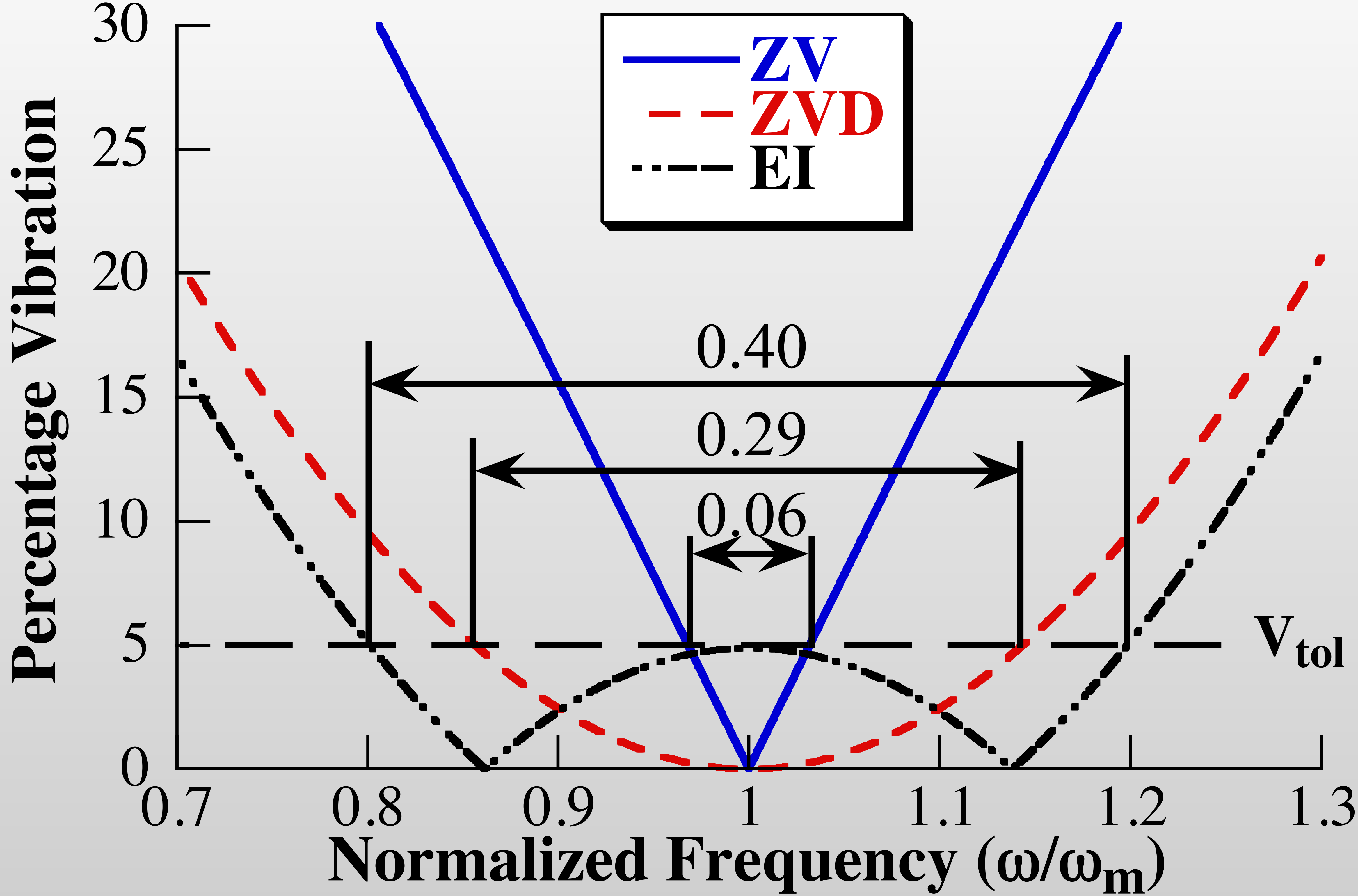

*Insensitivity* - the width of a Sensitivity curve where vibration remains under $V_{tol}$

# Measuring Robustness




*Insensitivity* - the width of a Sensitivity curve where vibration remains under $V_{tol}$

# The Extra-Insensitive (EI) Shaper

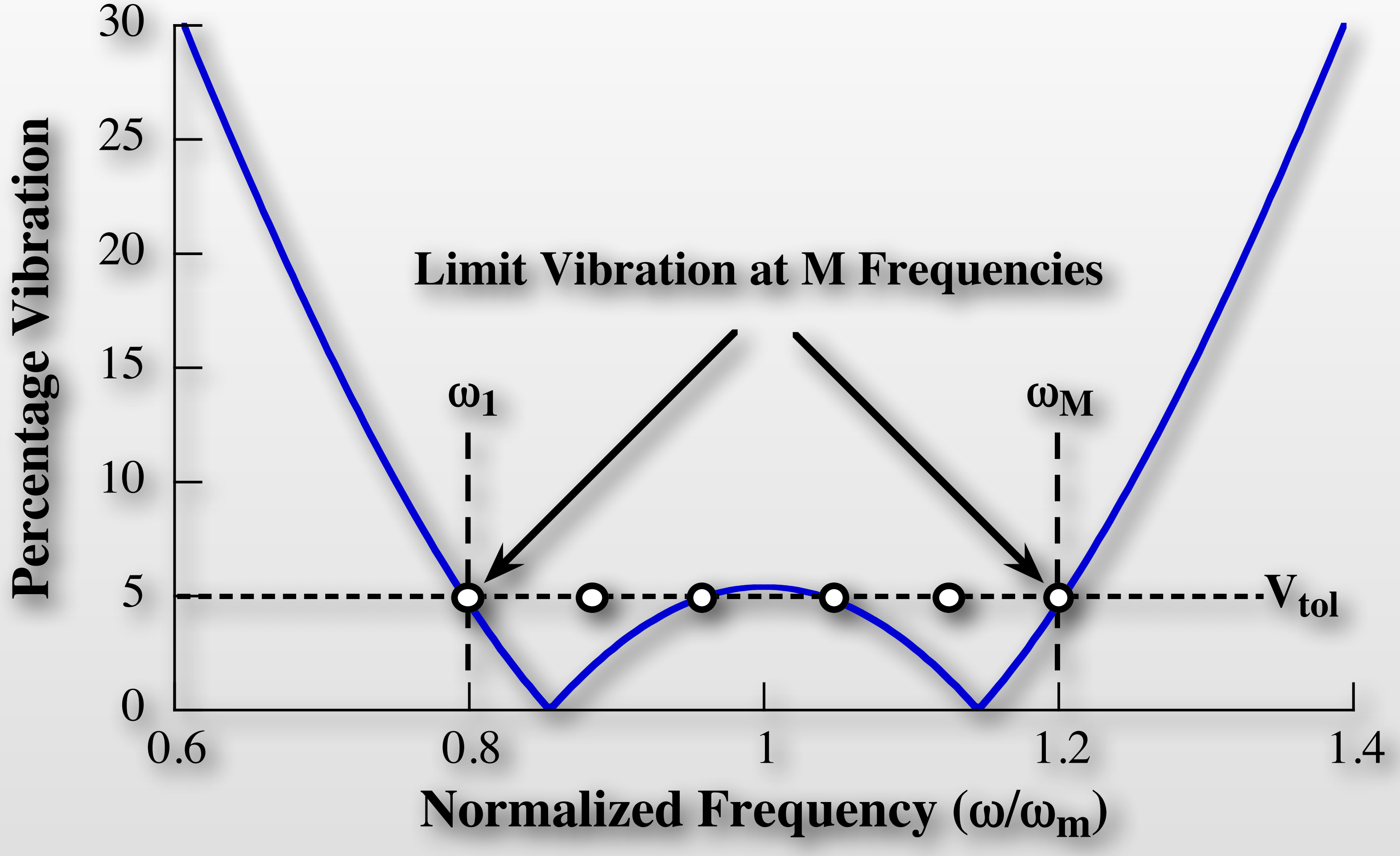


# EI Shaper Form – Undamped Systems

$$\text{Undamped EI} \equiv \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1+V_{tol}}{4} & \frac{1-V_{tol}}{2} & \frac{1+V_{tol}}{4} \\ 0 & \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} & \frac{2\pi}{\omega_n\sqrt{1-\zeta^2}} \end{bmatrix}$$

- $V_{tol}$ is the tolerable level of vibration, 0.05 = 5%

# Specified Insensitivity (SI) Shapers

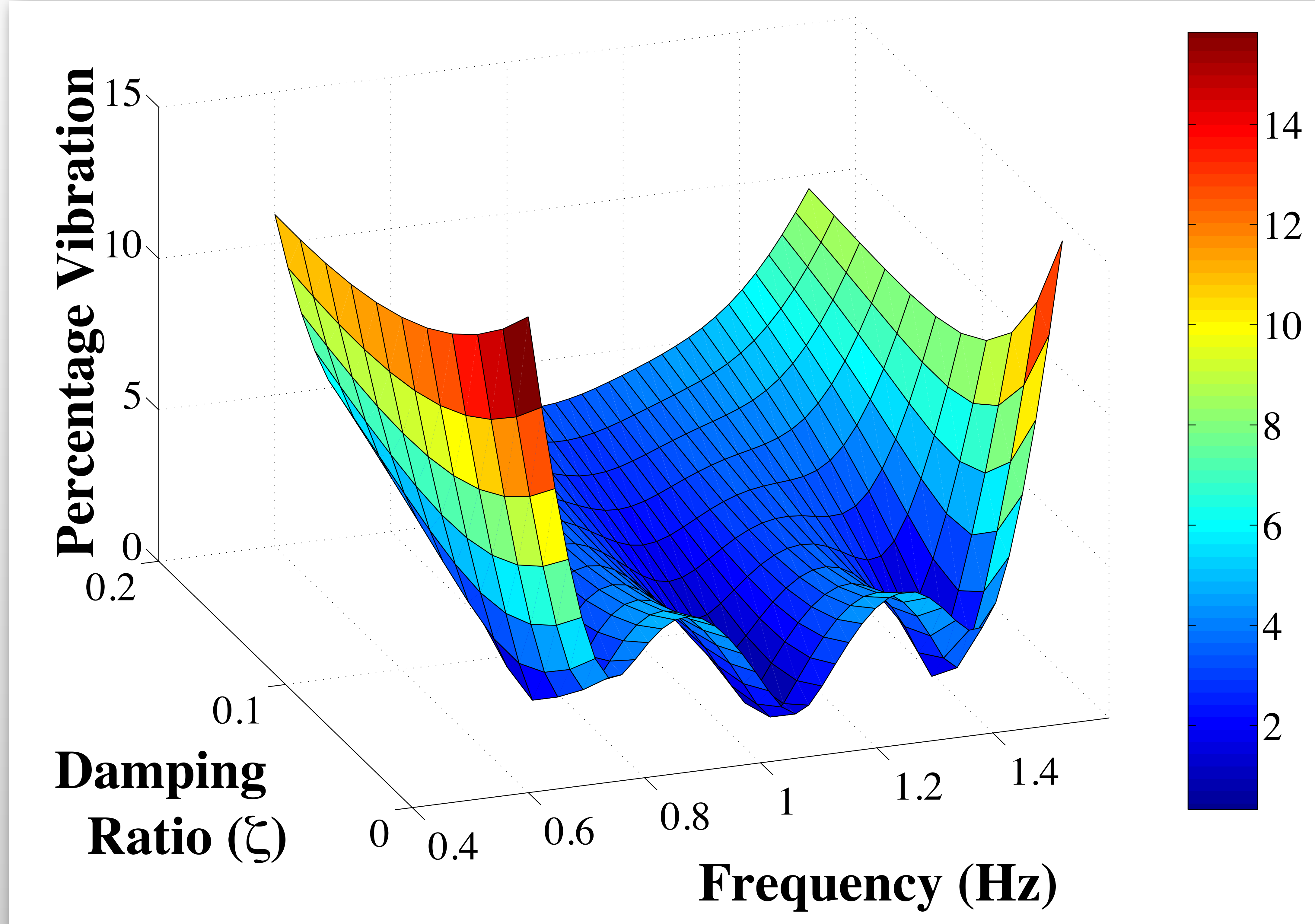



$$V(\omega_k,\zeta) = e^{-\zeta\omega_k t_n}\sqrt{[C(\omega_k,\zeta)]^2 + [S(\omega_k,\zeta)]^2} \le V_{tol}$$

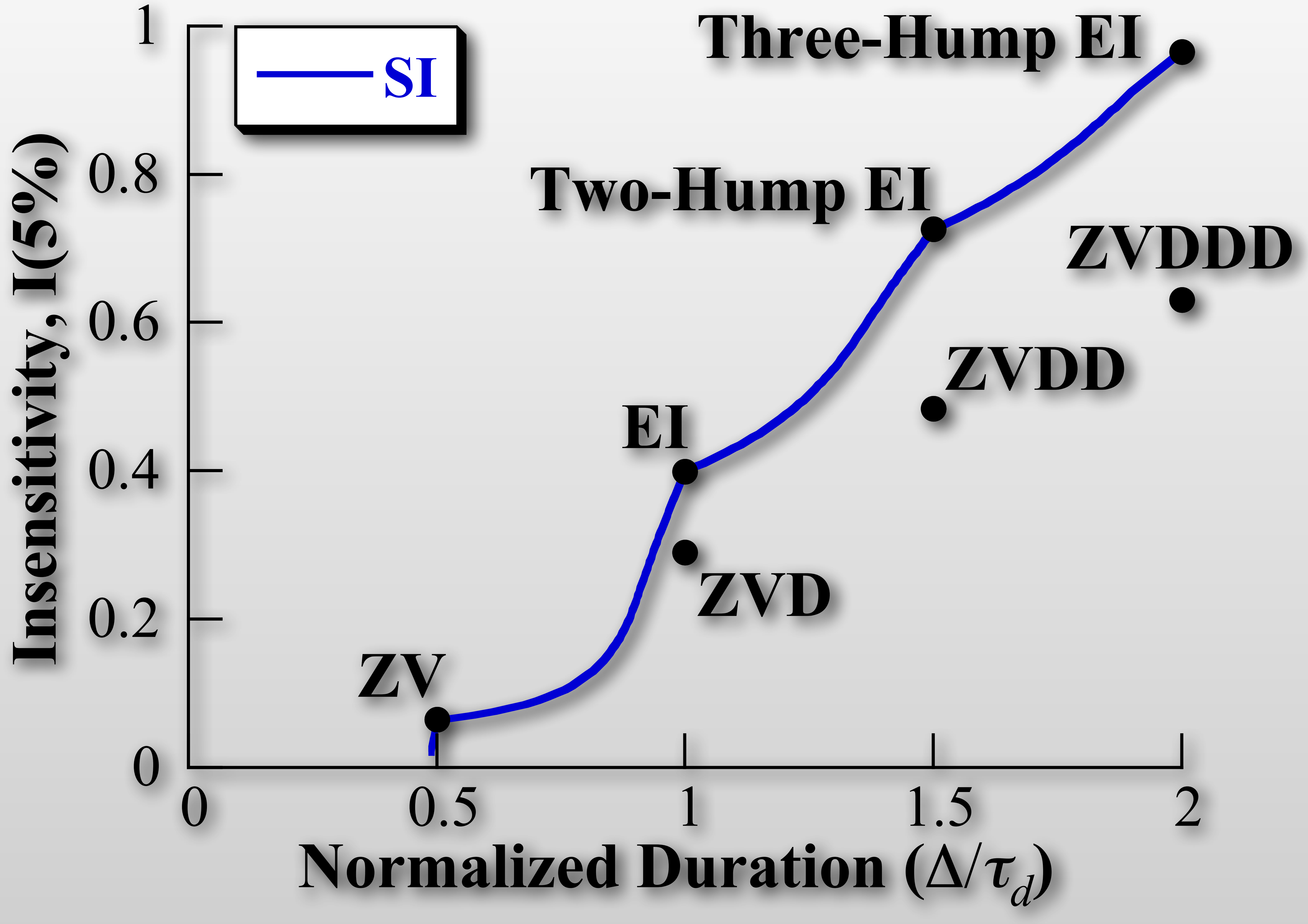
$$k = 1, \ldots, M$$

- Must solve numerically, but can exactly tailor to the system requirements

# Damping Matters, but less than Freq.



# Shaper Duration v. Insensitivity



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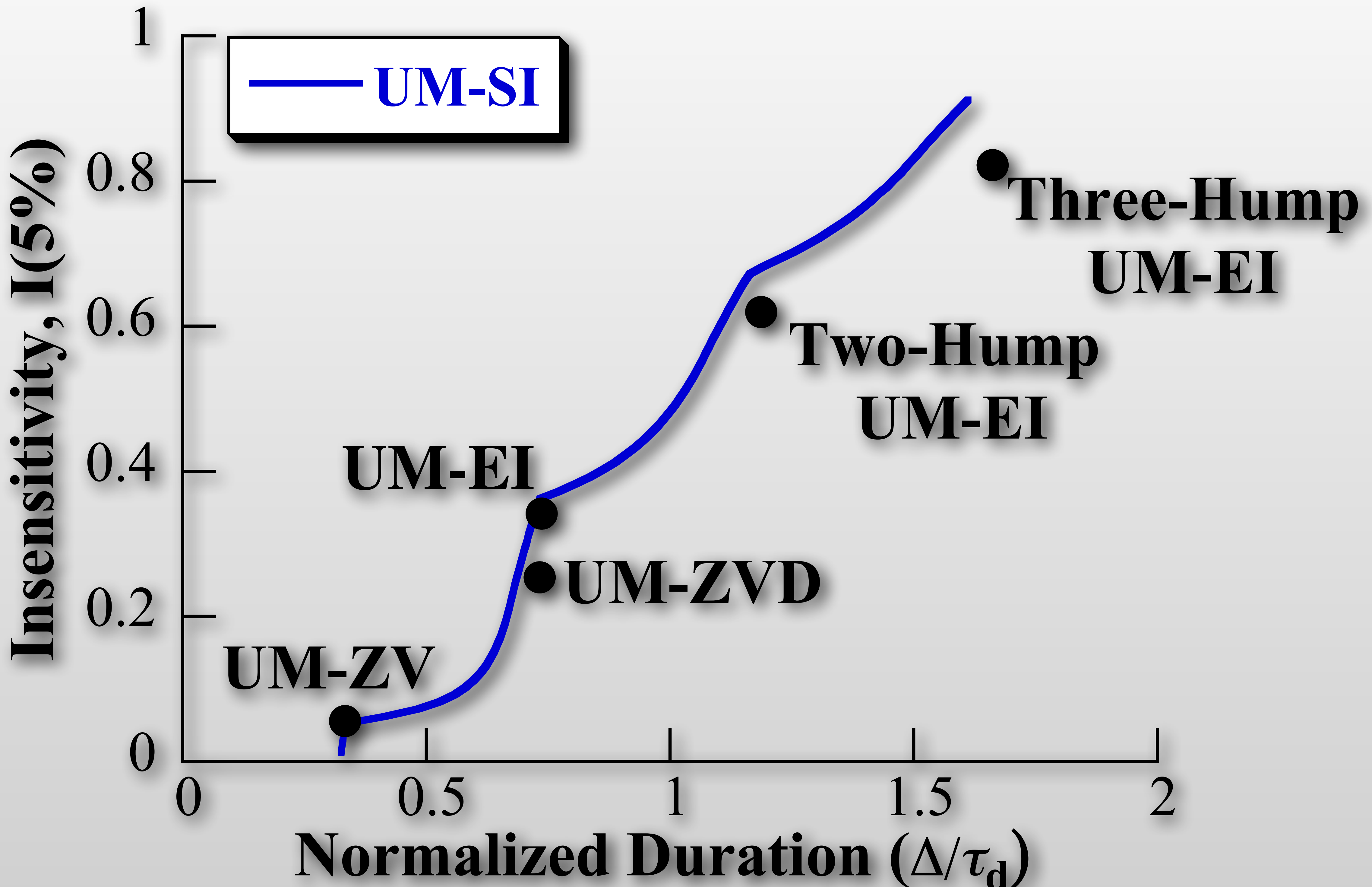
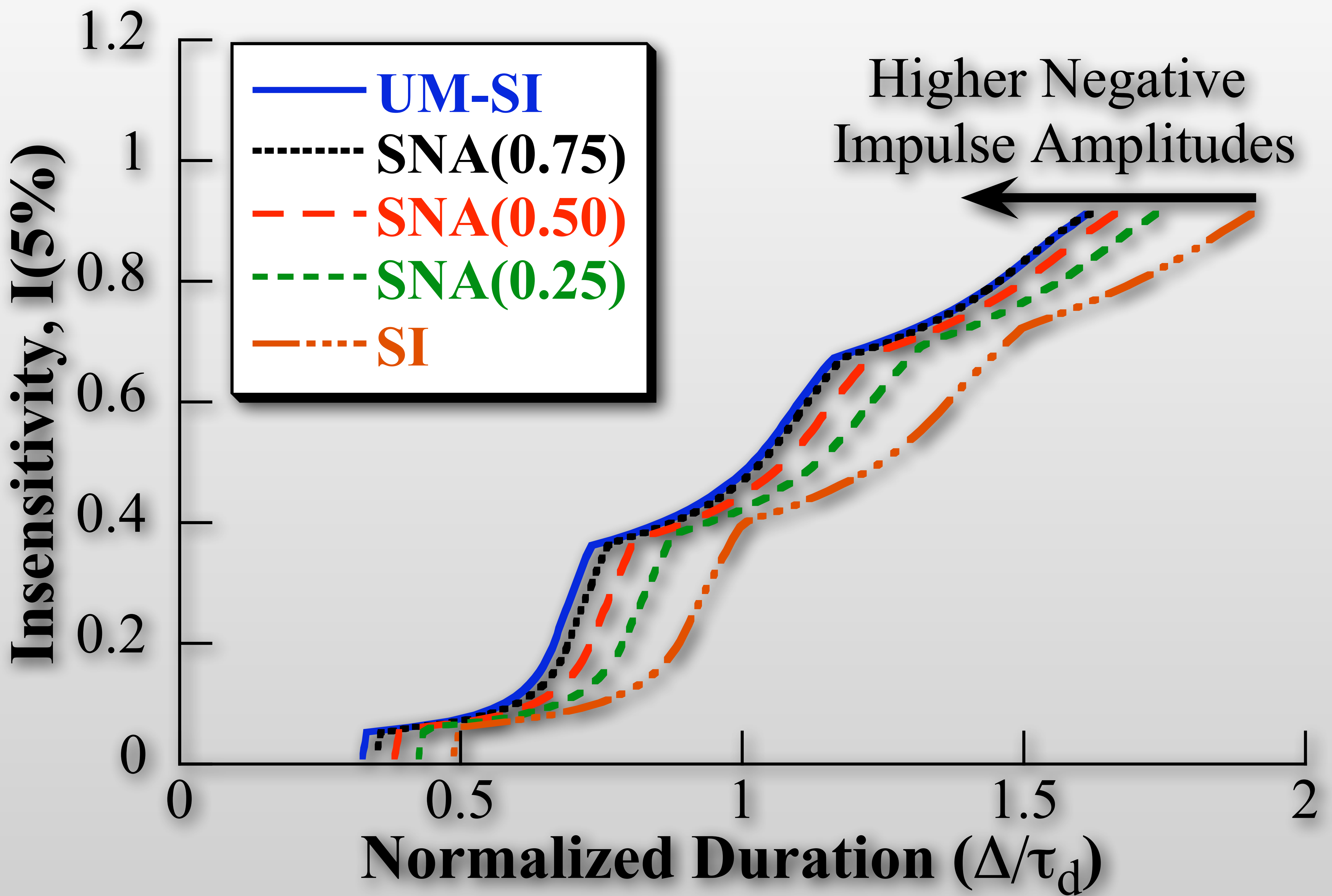


# Shaper Duration v. Insensitivity



# General Design Procedure

- Determine nominal system parameters
  - Dominant vibration frequencies (often only 1)
  - Associated damping ratios

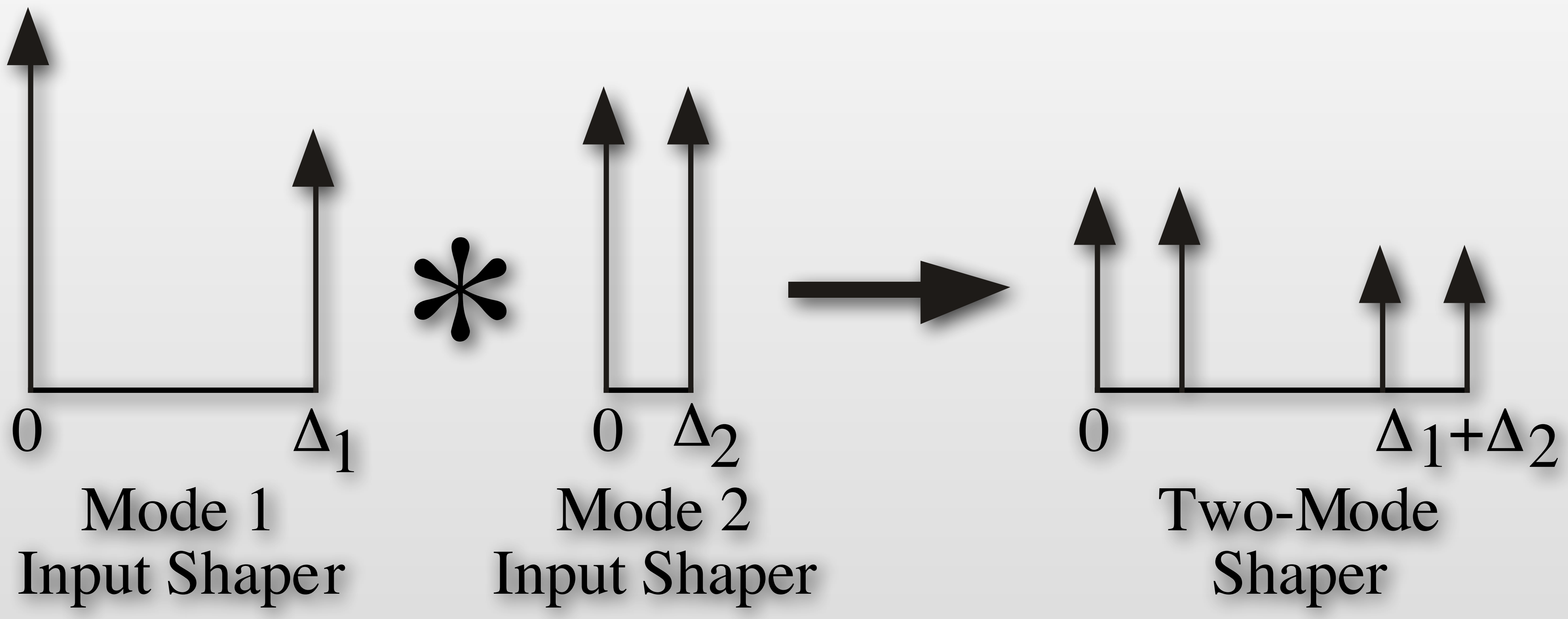
- Determine variation of parameters
  - How must robustness is needed?

- Pick shaper or shapers to use

- Plug in frequency and damping to get:
  - Impulse amplitudes
  - Impulse times

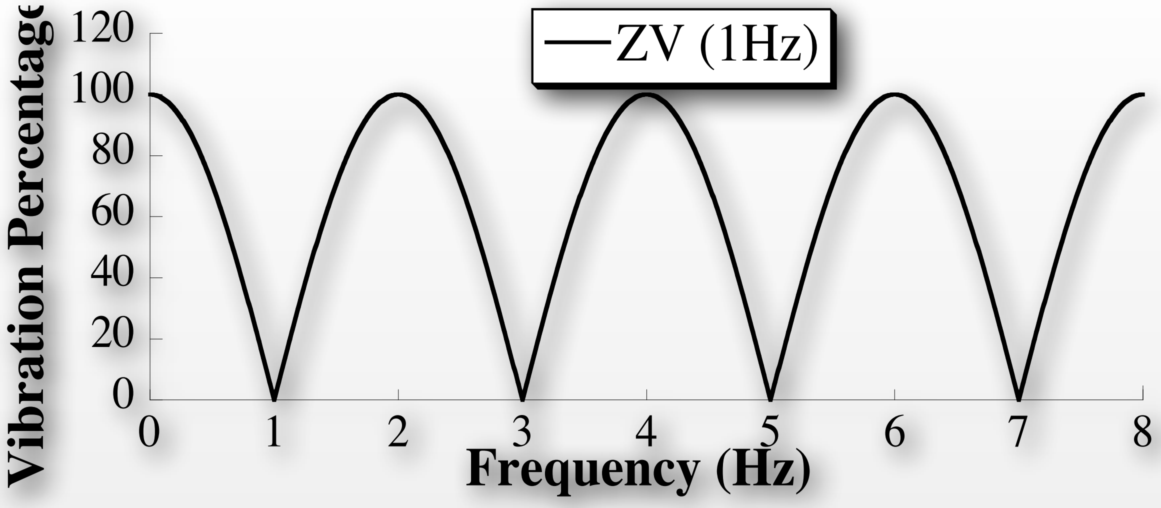
# Example Multi-mode Crane Oscillation

# Convolved Two-Mode Shaper



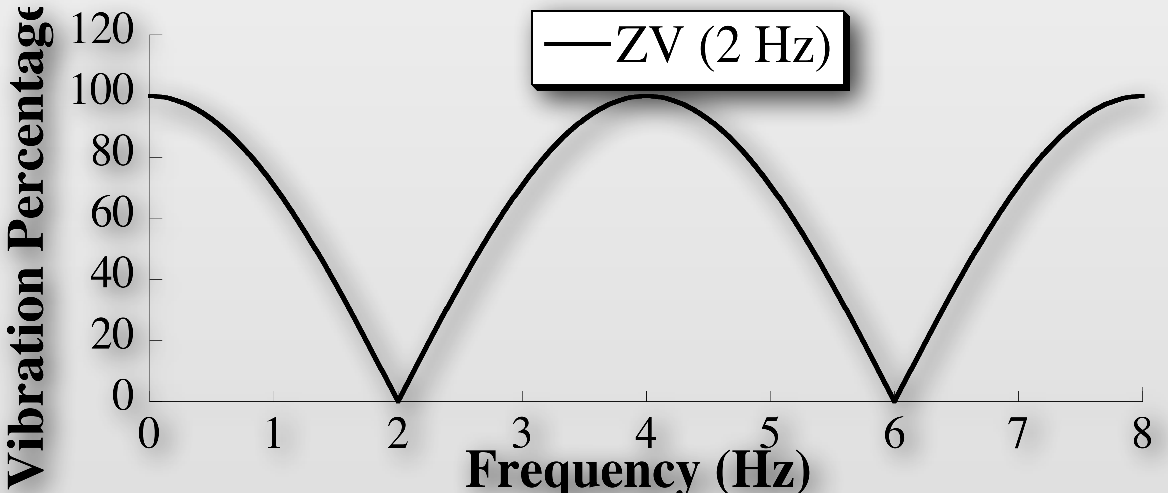

- Design shaper for each mode, then convolve to get a shaper that eliminates both modes

# ZV Shaper for 1 Hz

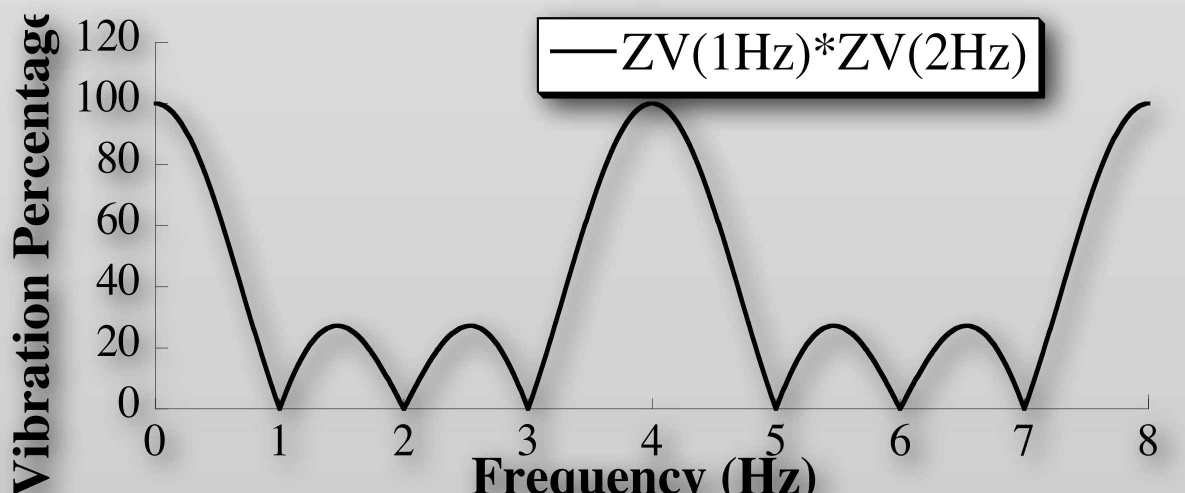



*

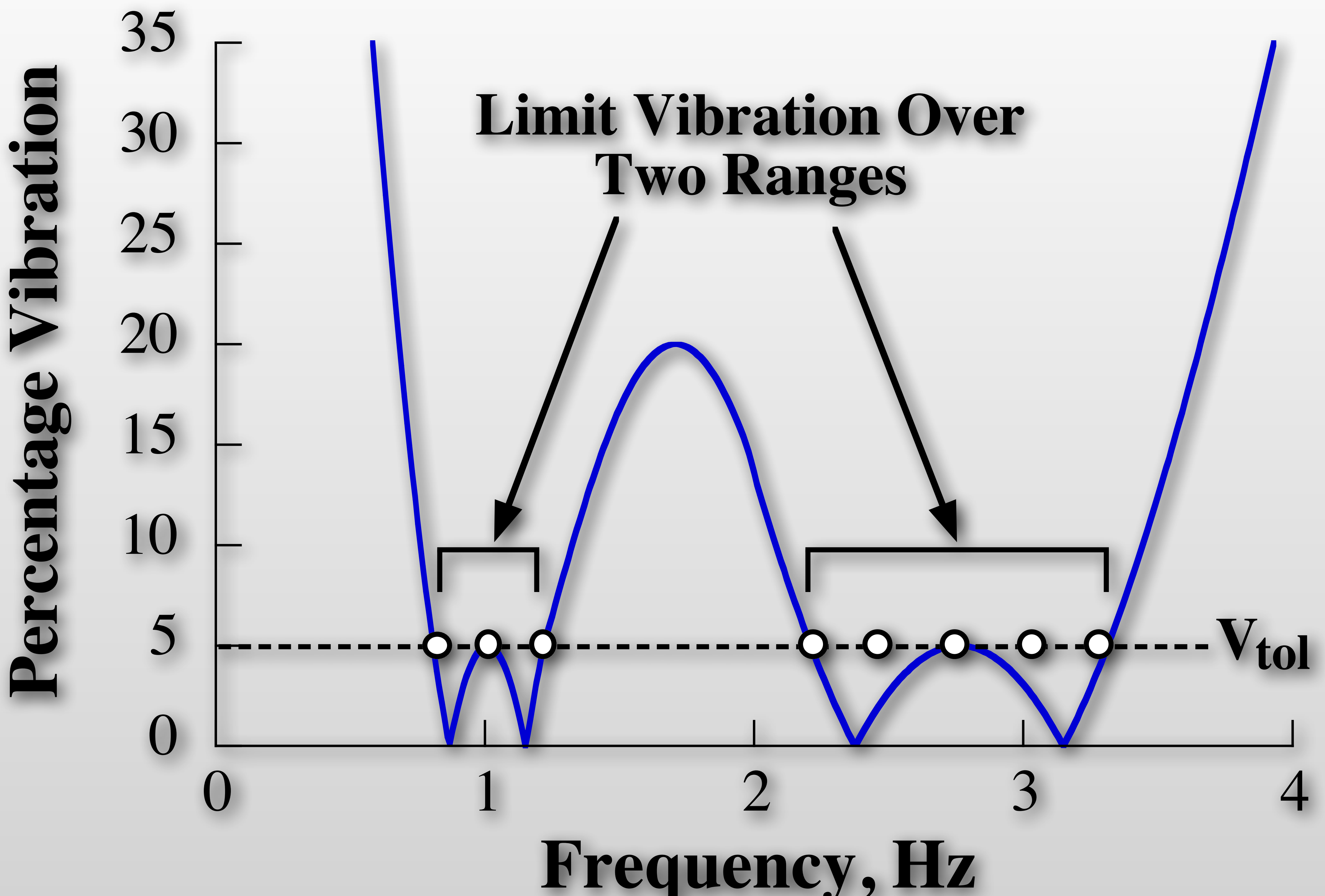
# ZV Shaper for 2 Hz




# ZV Shaper for 1 Hz and 2 Hz



# Multi-mode SI Shapers



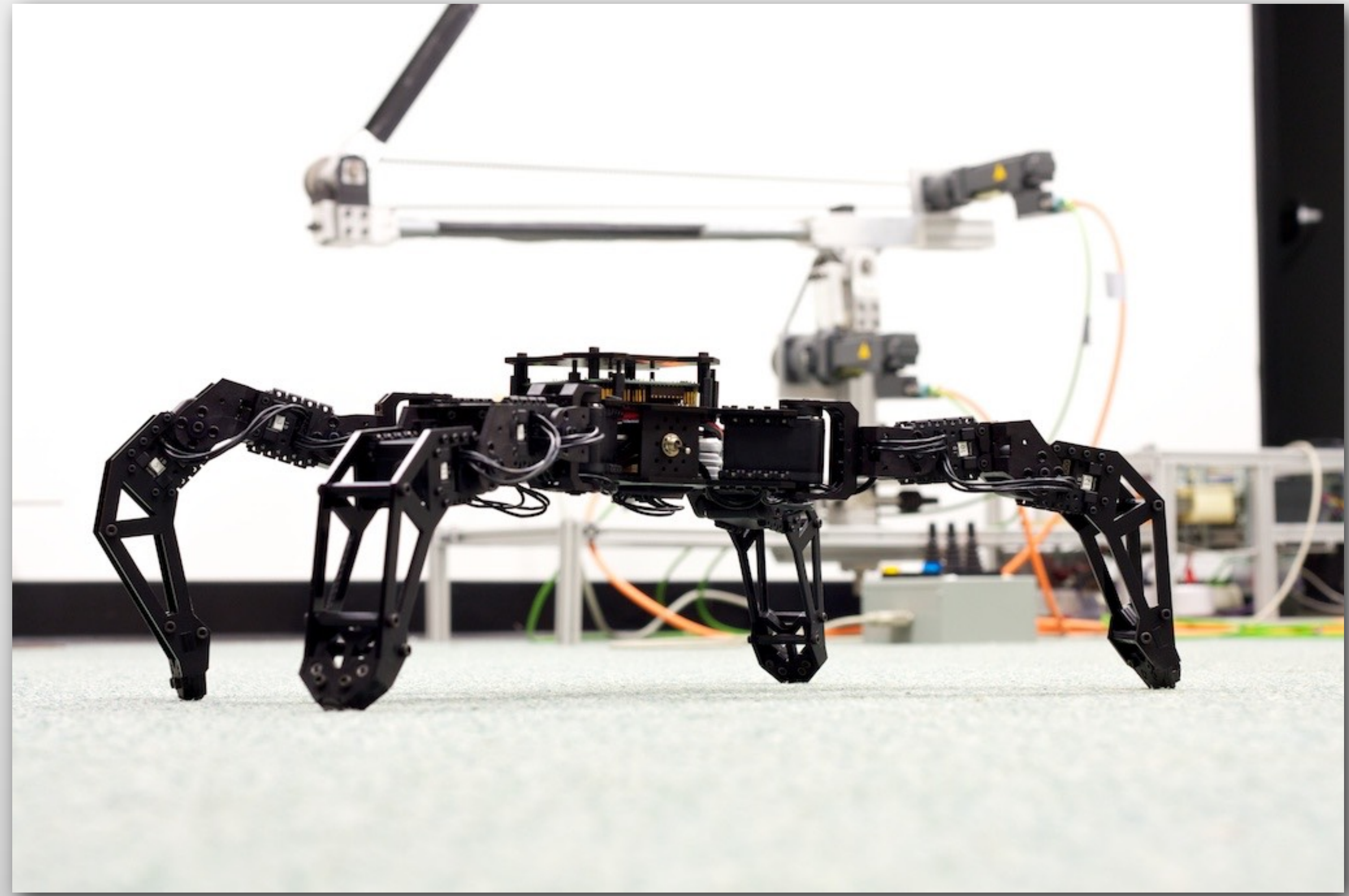

- Solve for all modes simultaneously → faster shapers

# Example Multi-mode Crane Oscillation

# Cooperative Crane Control

# Robot Jumping

- Replacing legs with compliant versions
- Concurrent design of the legs and jumping/running commands



# Jumping

- Can be an efficient way to travel:
  - on rough terrain
  - in low gravity environments

Astronauts used on moon walks

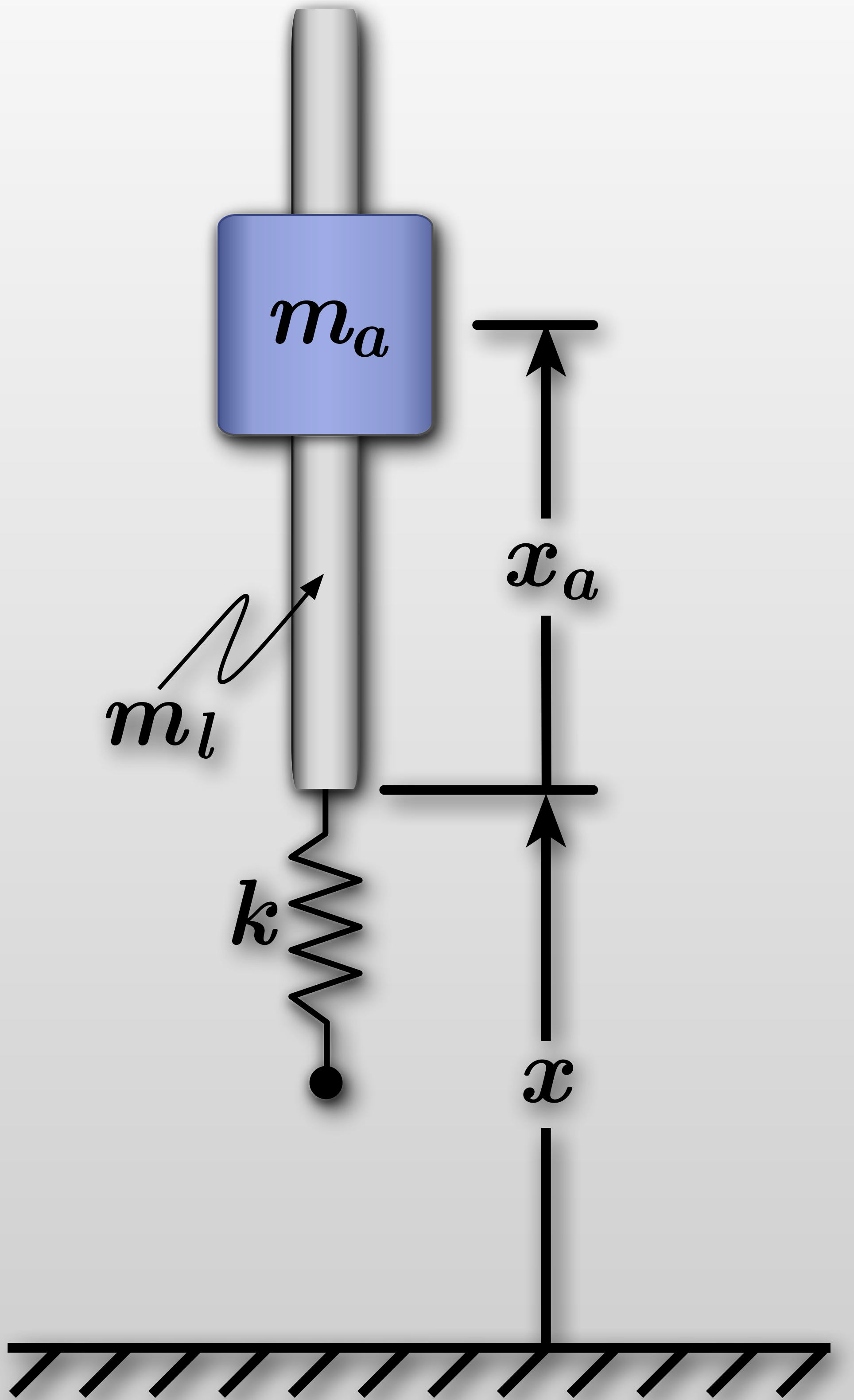
# A Simple Jumping Robot

- Rod mass $m_l$
- Actuator mass $m_a$
- Spring, $k$, and damper, $c$ (not shown)

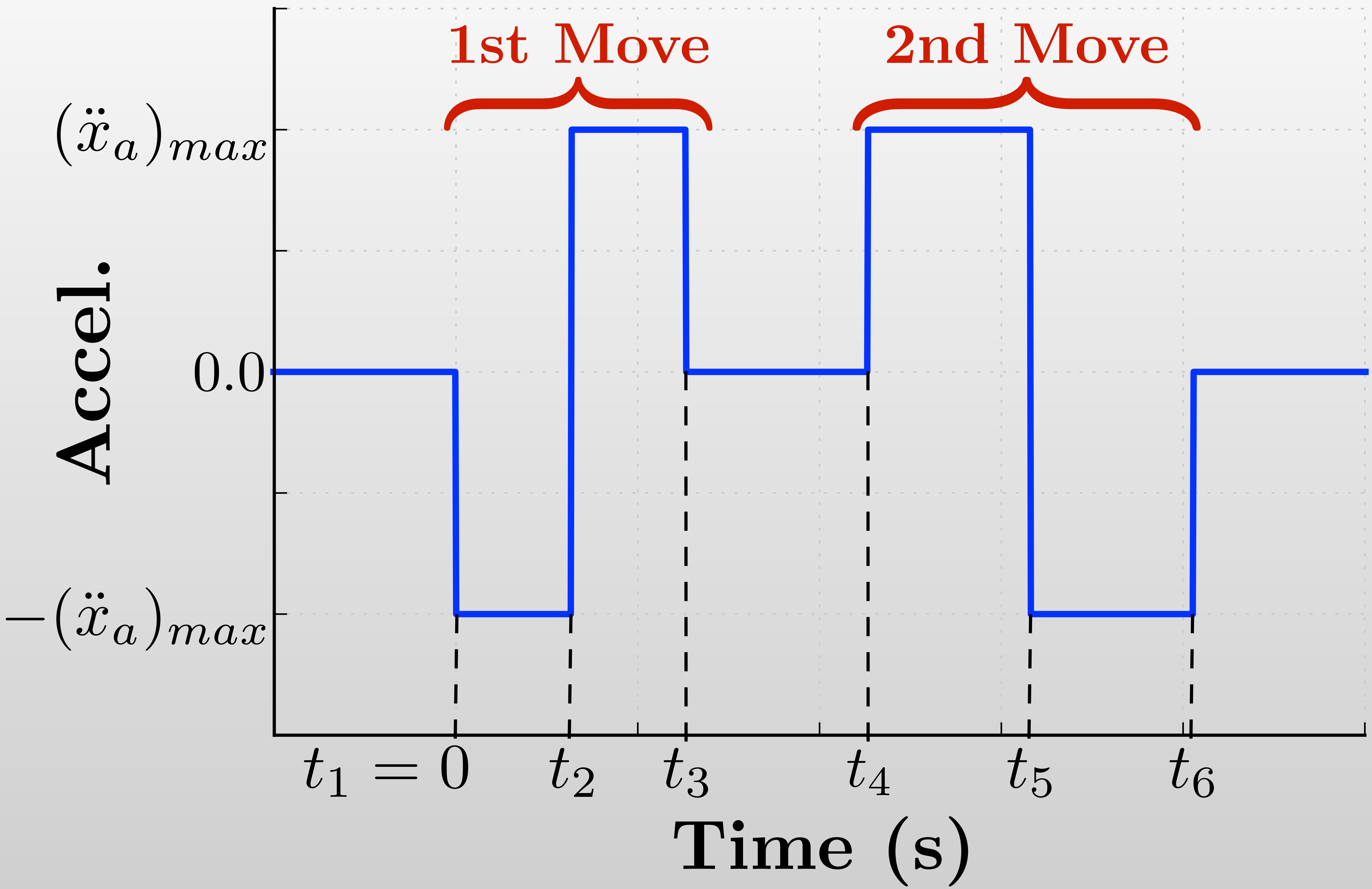
$$\ddot{x} = -\alpha\left(\frac{k}{m}x + \frac{c}{m}\dot{x}\right) - \frac{m_a}{m}\ddot{x}_a - g$$

$$\alpha = \begin{cases} 1, & x \leq 0 \\ 0, & \text{otherwise} \end{cases}$$

**Goal:** Design the motion of $m_a$ to optimize jump height



# Jumping Commands



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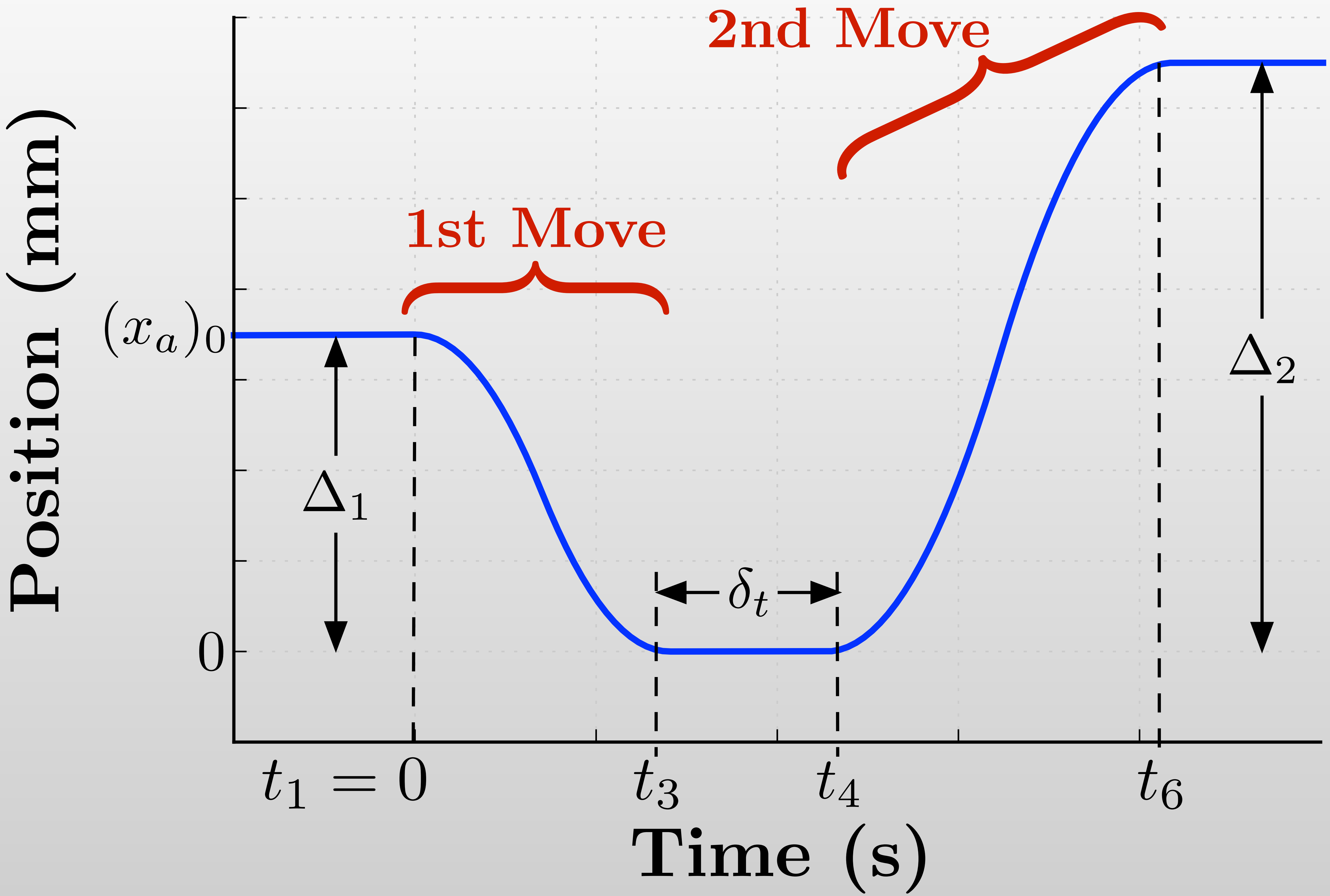
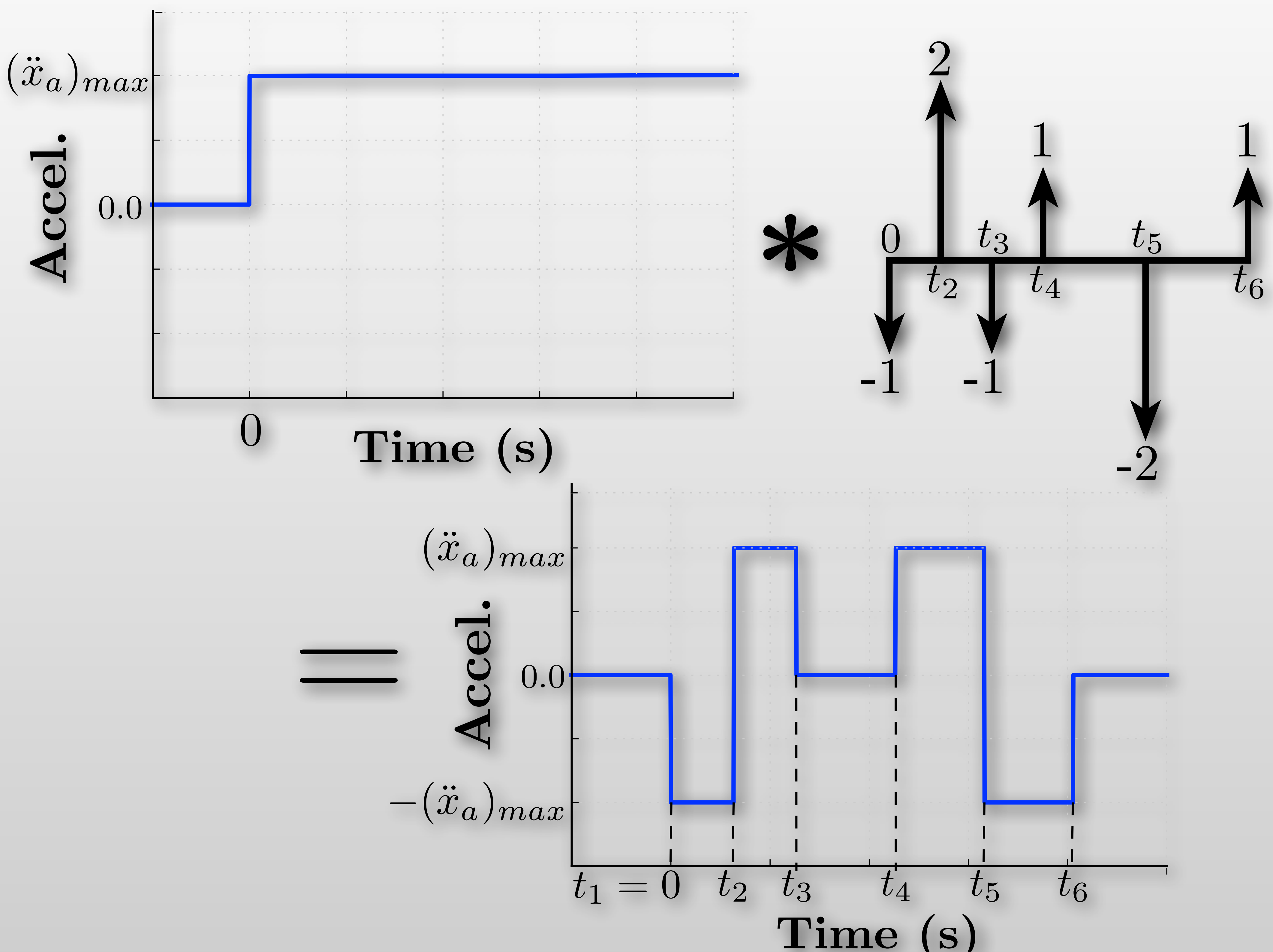
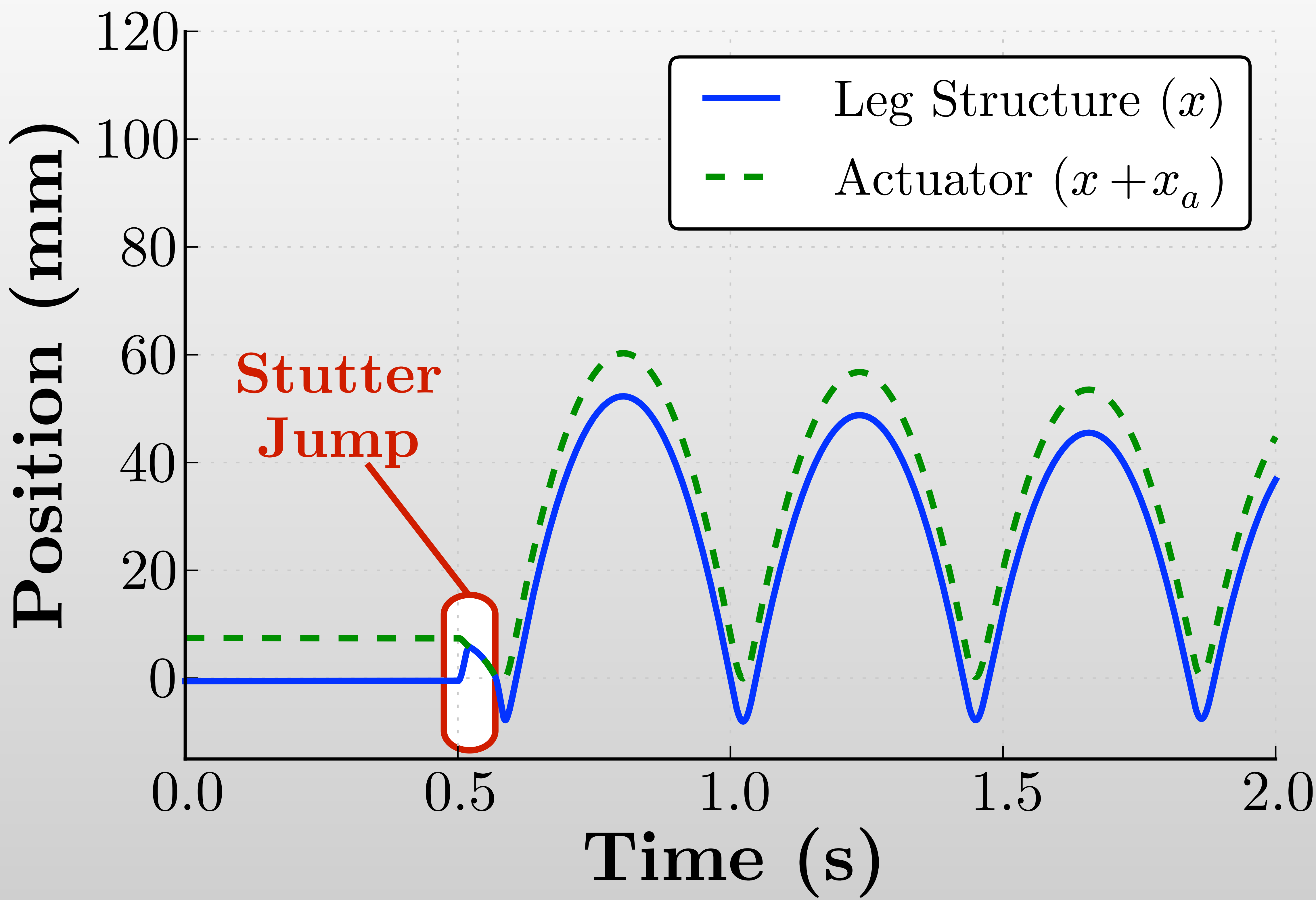


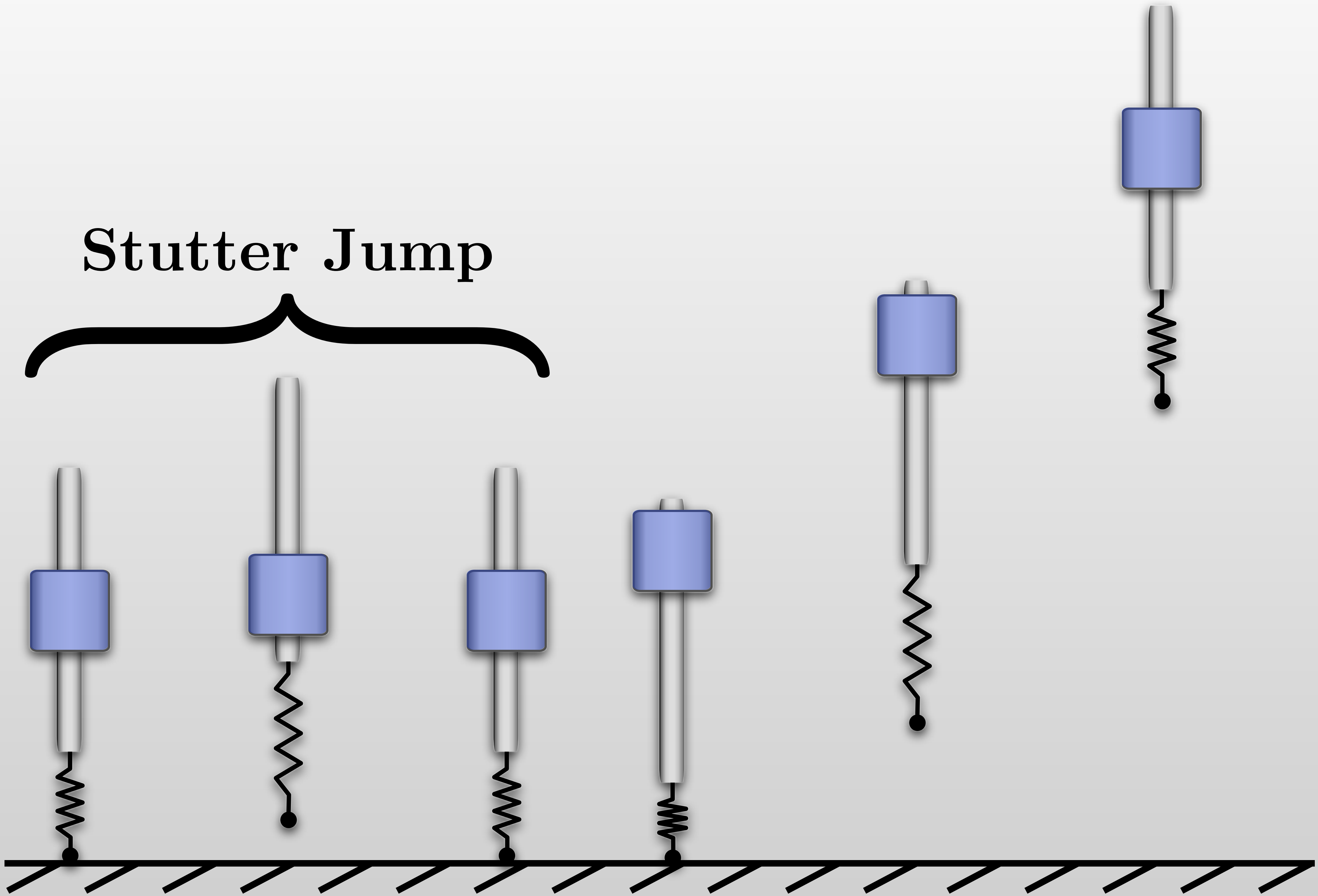
# Input-Shaped Jumping



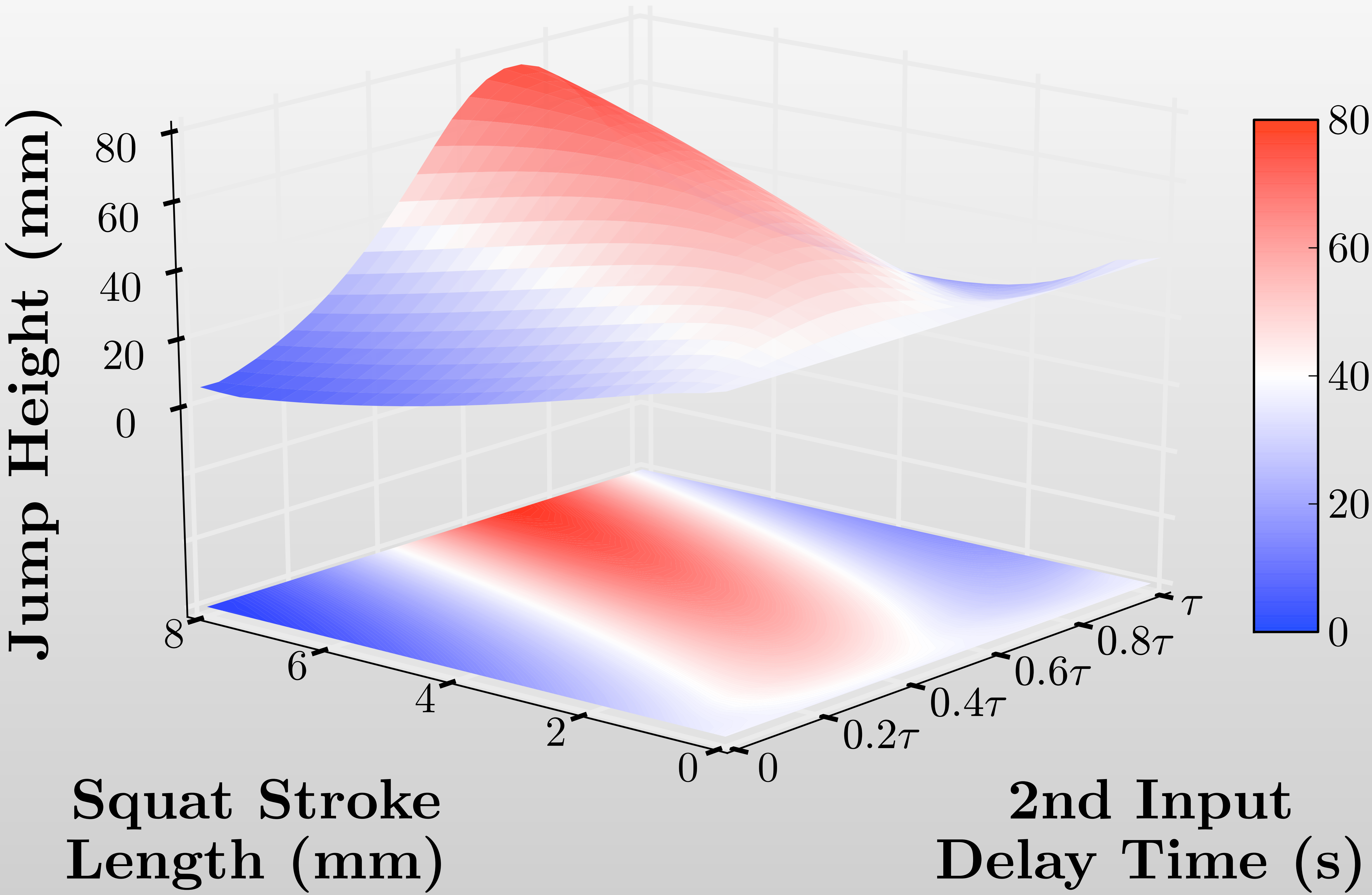
# Jumping Response



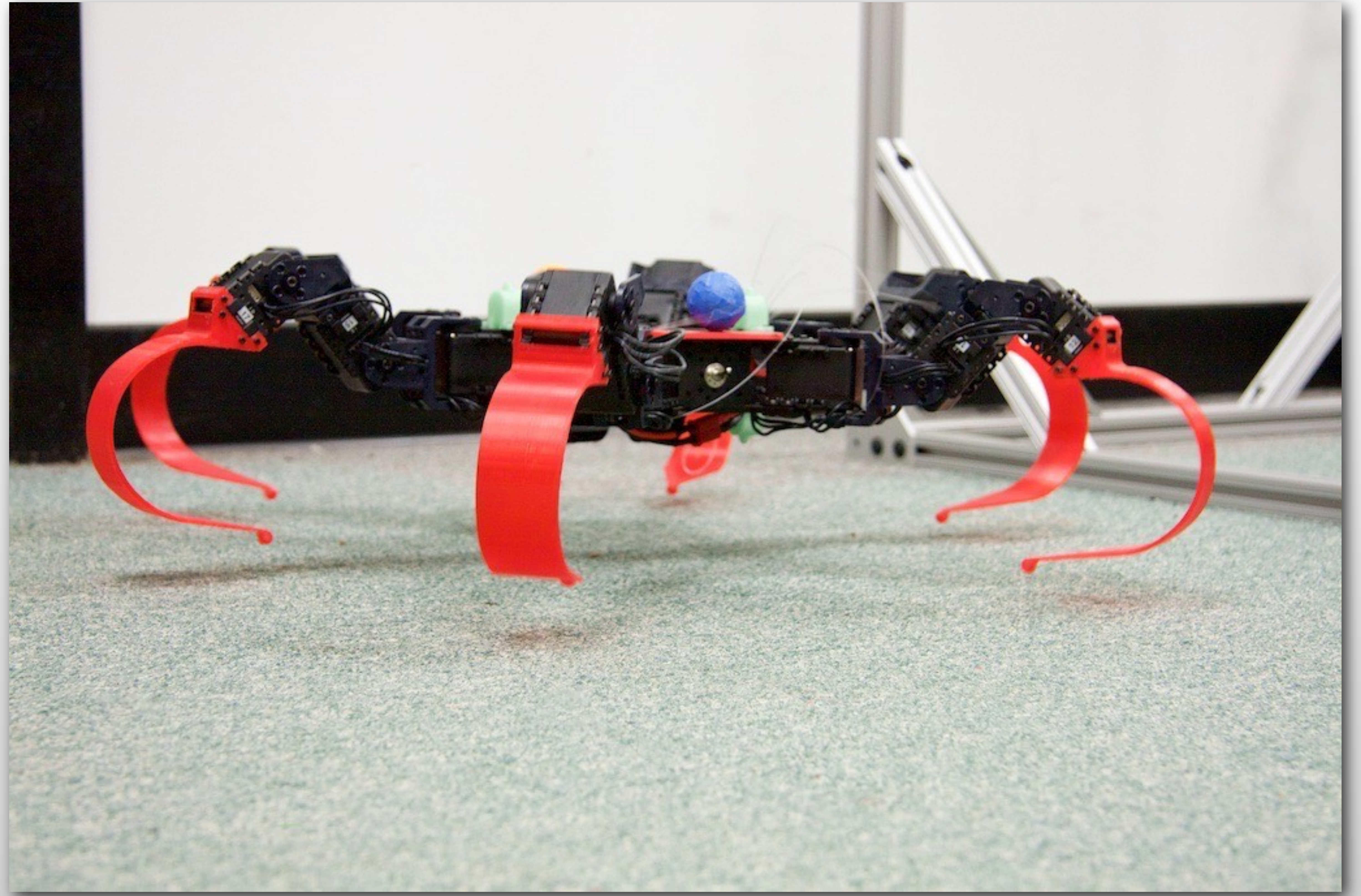
# Stutter Jumping



# Jump Timing


Jump Height (mm)
80
60
40
20
0
8
6
4
2
0
0
0.2τ
0.4τ
0.6τ
0.8τ
τ
80
60
40
20
0
Squat Stroke Length (mm)
2nd Input Delay Time (s)

# Applied to a Hexapod



# Thank You.

# Contact Information

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@doc_vaughan

http://github.com/docvaughan

http://github.com/crawlab