Fractional PID Consensus Control Protocols for Second-Order Multiagent Systems

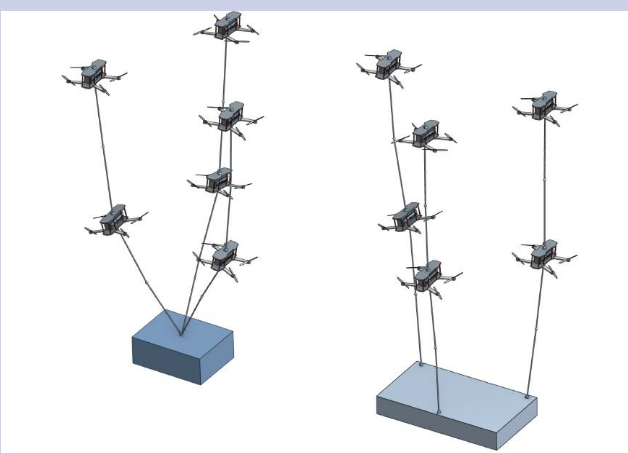
David Yaylali
Coauthored by:
Eric Butcher (UArizona)
Arman Dabiri (Eastern Michagan U)

University of Arizona,
Department of Aerospace and Mechanical Engineering

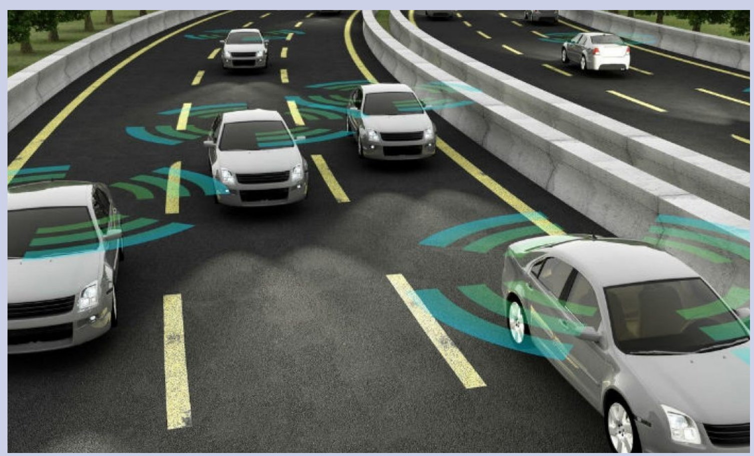
Cooperative Control of Multivehicle Systems

Winter Olympics, 2018 – Opening Ceremony

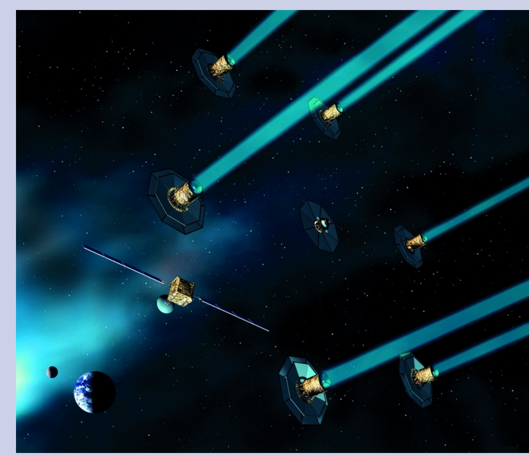
Intel® Shooting Star drones



Cooperative drone transport



Automated transportation

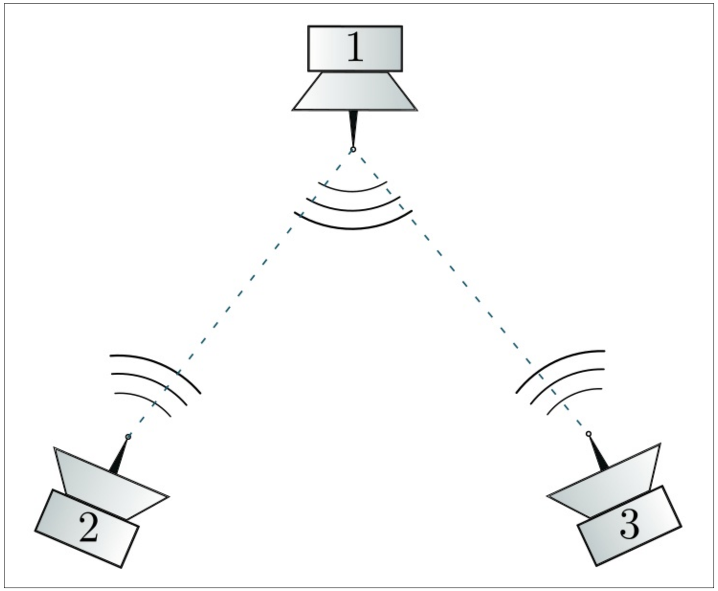


Distributed telescopes

Imagine a system of N agents, each described by linear dynamics as:

$$\dot{x}_1 = Ax_1 + Bu_1$$
$$\dot{x}_2 = Ax_2 + Bu_2$$
$$\vdots$$
$$\dot{x}_N = Ax_N + Bu_N$$

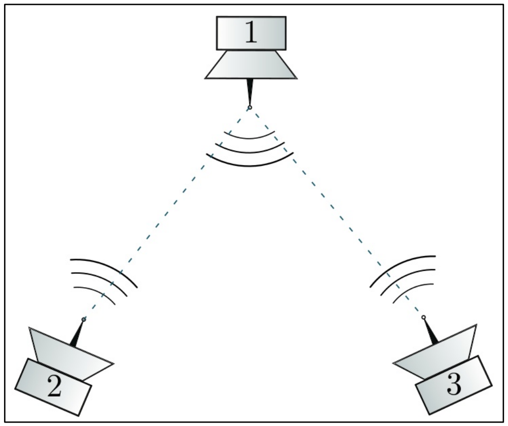
If the agents can communicate their states to one another, the control for agent i can involve states of all other agents.



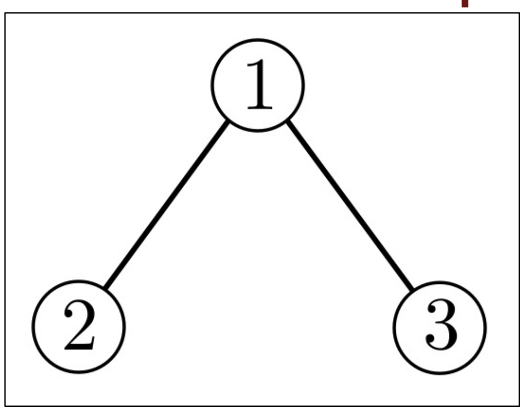
Example

In the 3-agent system illustrated at left, agents 2 and 3 can only communicate with agent 1. Agent 1 can communicate with both. The control laws can therefore have the functional form

$$\boldsymbol{u}_1 = \boldsymbol{u}_1(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3)$$
$$\boldsymbol{u}_2 = \boldsymbol{u}_2(\boldsymbol{x}_2, \boldsymbol{x}_1)$$
$$\boldsymbol{u}_3 = \boldsymbol{u}_3(\boldsymbol{x}_3, \boldsymbol{x}_1)$$



Communication Graph



We can represent the communication topology by a **communication graph** and its **graph Laplacian matrix**:

Graph Laplacian Matrix

$$L = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

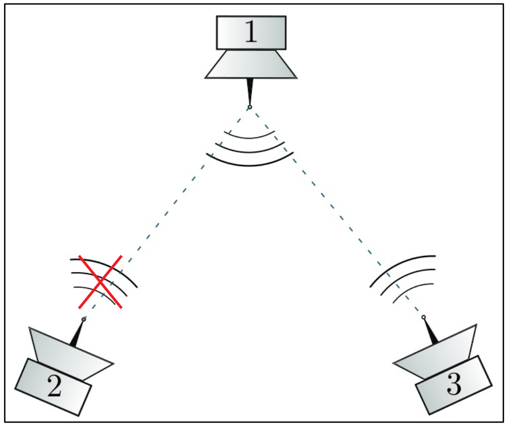
Diagonal elements: $[L]_{ii}$

Number of agents communicating with agent i

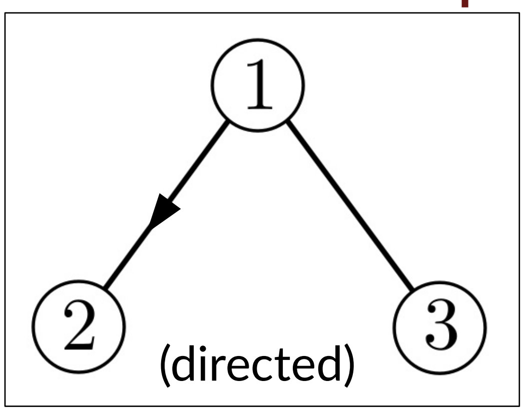
Off-diagonal elements: $-[L]_{ij} \equiv a_{ij}$

Nonzero if agent j communicates with agent i

Eigenvalues μ_i of L ⟷ Stability of the system under cooperative control



Communication Graph



We can represent the communication topology by a **communication graph** and its **graph Laplacian matrix**:

Graph Laplacian Matrix

$$L = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Diagonal elements: $[L]_{ii}$

Number of agents communicating with agent *i*

Off-diagonal elements: $-[L]_{ij} \equiv a_{ij}$

Nonzero if agent *j* communicates with agent *i*

Eigenvalues μ_i of L ⟺ Stability of the system under cooperative control

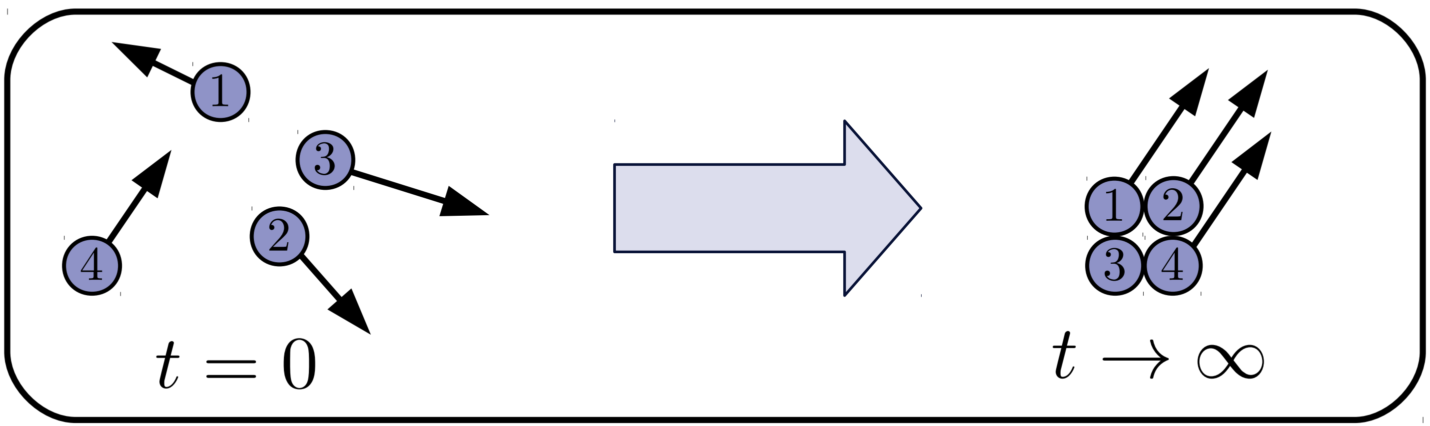
- **Individual Agent Dynamics:** $\dot{x}_i = Ax_i + Bu_i$

- **System-Wide State:**

$$x_i = \begin{bmatrix} r_i \\ v_i \end{bmatrix} \Rightarrow \boldsymbol{r} = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_N \end{bmatrix}, \; \boldsymbol{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} \Rightarrow \boldsymbol{x}_G = \begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{v} \end{bmatrix}$$

"Global" system state

- **PD Consensus Control:** $u_i = -\sum_{j=1}^{N} a_{ij}\Big(k_P(r_i - r_j) + k_D(v_i - v_j)\Big)$



e.g., rendezvous, formation flying, *etc.*

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- **System-Wide State:**

$$x_i = \begin{bmatrix} r_i \\ v_i \end{bmatrix} \Rightarrow \boldsymbol{r} = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_N \end{bmatrix}, \ \boldsymbol{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} \Rightarrow \boldsymbol{x}_G = \begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{v} \end{bmatrix}$$

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Closed-Loop EOM – ***Multiagent Consensus***

$$\dot{\boldsymbol{x}}_G = \big(A \otimes I_N - BK \otimes L\big)\boldsymbol{x}_G$$

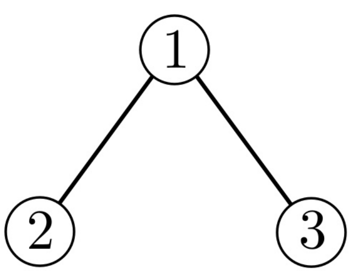
Closed-Loop EOM: $$\dot{\boldsymbol{x}}_G = \big(A \otimes I_N - BK \otimes L\big)\boldsymbol{x}_G = \Gamma \boldsymbol{x}_G$$

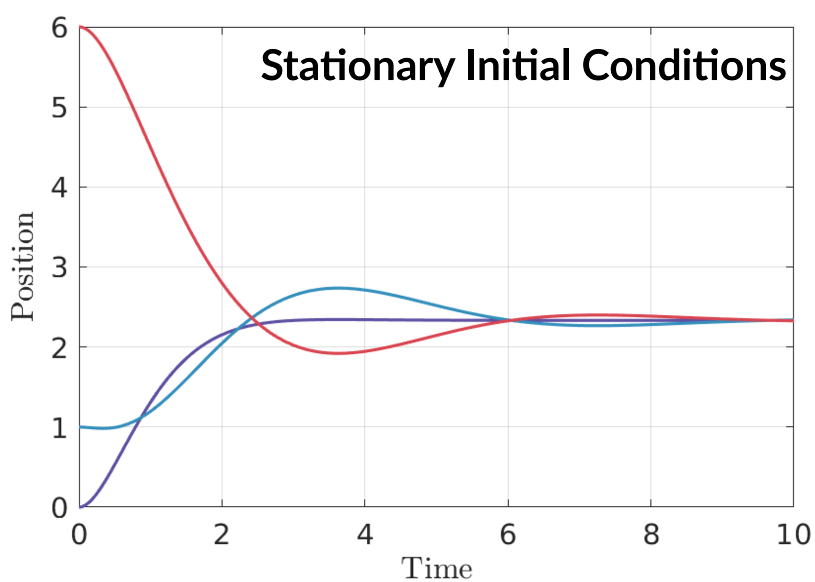
Stability of PD Consensus Control – Ren/Beard/Atkins (2005)

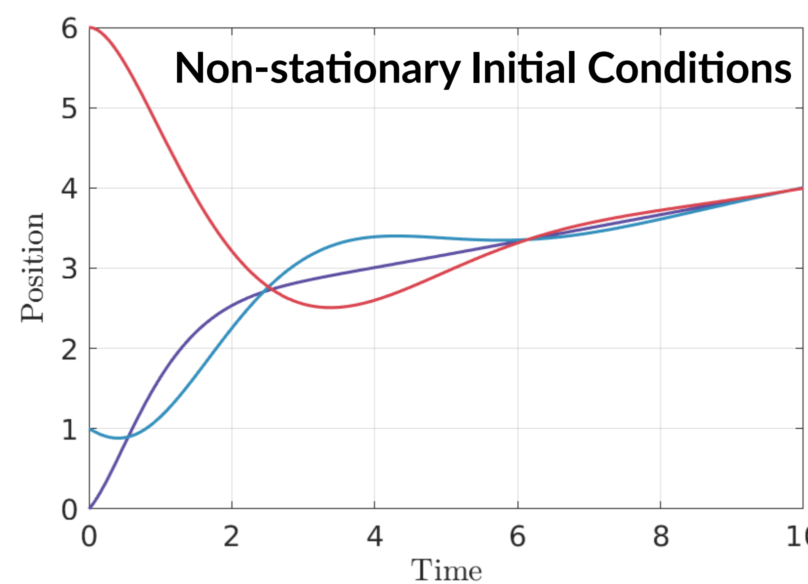
The closed-loop system will asymptotically reach consensus iff

$$\operatorname{eig}\Gamma = \begin{cases} \text{Exactly 2 zero-eigenvalues} \\ \text{Remaining } 2N-2 \text{ eigenvalues in LHP} \end{cases}$$

3-Body Example







What we have done…

- Generalized the control law in two ways:
  - Introduced ***integral control***: PD → PID
  - Utilized ***fractional derivatives***: PID → PID$^{\alpha}$

(increases the ***tunability*** of the controller, and helps eliminate steady-state error)

- Proven stability of the PID$^{\alpha}$ controlled system

- Established conditions on gains for stability

- Shown numerically that PID$^{\alpha}$ can **outperform** PD/PID

(This will be a rough outline for the rest of the talk)

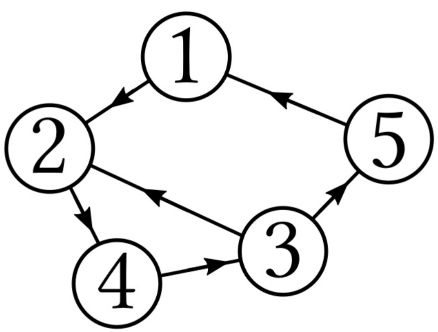
Adding **integral control...**

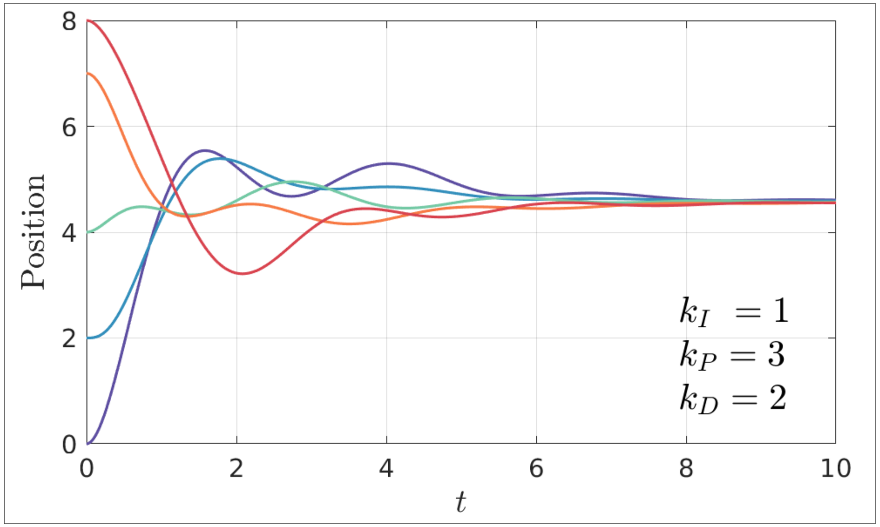
$$\xi_i \equiv \int_0^t r_i(\tau)d\tau \quad \Rightarrow \quad u_i = -\sum_{j=1}^{N} a_{ij}\Big(\boldsymbol{k_I(\xi_i - \xi_j)} + k_P(r_i - r_j) + k_D(v_i - v_j)\Big)$$

Single-agent dynamics: $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \; B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$ N-agent state: $\boldsymbol{x}_G = \begin{bmatrix} \boldsymbol{\xi} \\ \boldsymbol{r} \\ \boldsymbol{v} \end{bmatrix}$

PID Consensus: Closed-Loop EOM

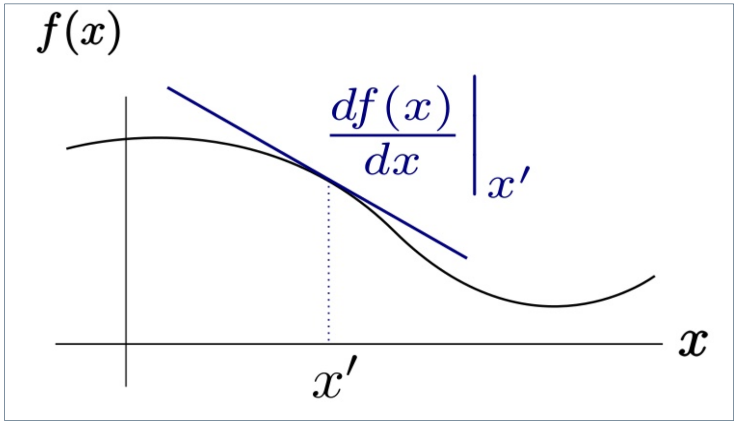
$$\dot{\boldsymbol{x}}_G = \big(A \otimes I_N - BK \otimes L\big)\boldsymbol{x}_G = \begin{bmatrix} \mathbf{0} & I_N & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & I_N \\ -k_I L & -k_P L & -k_D L \end{bmatrix} \boldsymbol{x}_G,$$



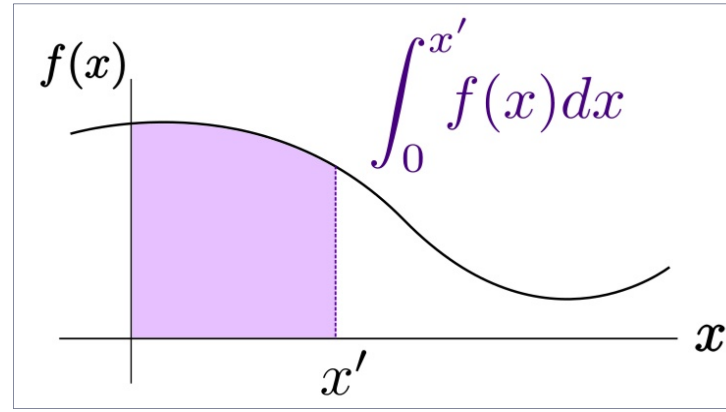


Integrals and derivatives of common experience can only be “wholly” applied:

A “whole” derivative of $f(x)$



A “whole” integral of $f(x)$



Similarly, we can apply derivatives or integrals any (natural) number of times:

$$\underbrace{\frac{d}{dx}\frac{d}{dx}\cdots\frac{d}{dx}}_{n \text{ times}} f(x) = D^n f(x) \qquad \underbrace{\int dx'' \int dx' \cdots \int dx}_{n \text{ times}} f(x) = D^{-n} f(x)$$

Common derivative and integral operators are **integer-ordered:**

$$D^n, \quad n \in \mathbb{Z}$$

*Can we generalize to **real-ordered** derivatives?*

Derivatives of a power function:

$$\frac{d}{dx}(x^m) = mx^{m-1}$$
$$\frac{d^2}{dx^2}(x^m) = m(m-1)x^{m-2}$$
$$\vdots$$
$$\frac{d^n}{dx^n}(x^m) = m(m-1)\cdots(m-n+1)x^{m-n}$$

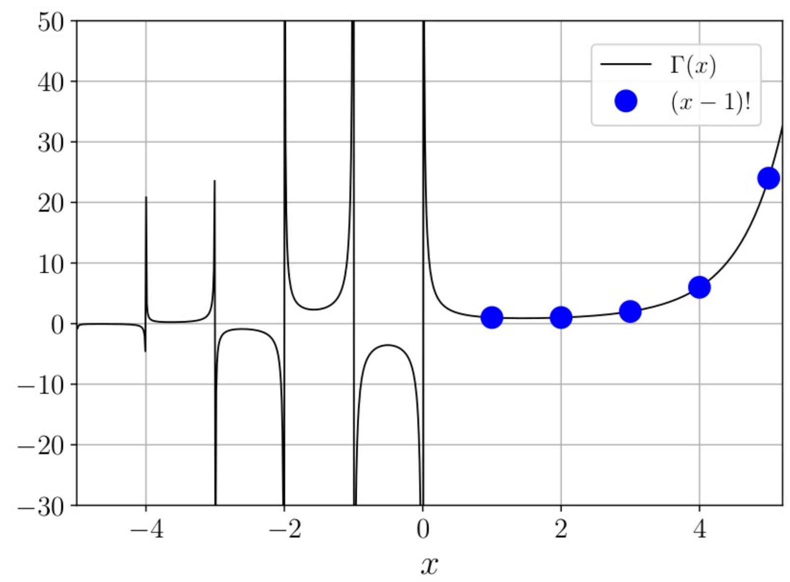
In general, this can be written

$$\boxed{\frac{d^n}{dx^n}(x^m) = \frac{m!}{(m-n)!}x^{m-n} \quad \text{for } m,n \in \mathbb{Z}, \quad m \geq n}$$

Euler's *generalization* of the factorial function:

$$(n-1)! \quad \longrightarrow \quad \Gamma(z) = \int_0^\infty x^{z-1}e^{-x}dx = (z-1)!$$

Valid for all real numbers z
(excluding the negative integers)

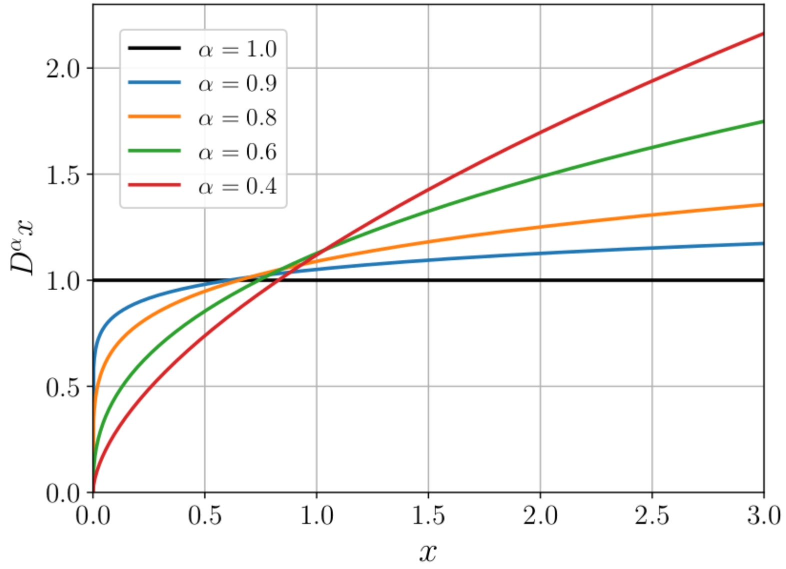


We can therefore *continue* the derivative of a power function to **any real order**!

"Fractional" derivative:

$$\frac{d^\alpha}{dx^\alpha}\left(x^m\right) = \frac{\Gamma(m+1)}{\Gamma(m-\alpha+1)}x^{m-\alpha}, \quad m \in \mathbb{Z},\ \alpha \in \mathbb{R}$$

Example: Fractional derivatives of x



e.g., half-derivative of x

$$\frac{d^{1/2}}{dx^{1/2}}x = \frac{\Gamma(2)}{\Gamma(3/2)}x^{1/2} = \frac{2}{\sqrt{\pi}}x^{1/2}$$

Details aside...

Fractional calculus ⇒ Fractional derivatives and integrals of **general functions**

Derivatives can now be "continued" to non-integer order

$$\frac{d^n f(x)}{dx^n}, \ n \in \mathbb{Z} \quad \Rightarrow \quad D^\alpha f(x) \equiv \frac{d^\alpha f(x)}{dx^\alpha}, \ \alpha \in \mathbb{R}$$

...which we can use to build the...

Fractional PID$^\alpha$ consensus controller:

$$u_i = -\sum_{j=1}^{N} a_{ij}\Big(k_I(\xi_i - \xi_j) + k_P(r_i - r_j) + k_D D^{\alpha_D}(r_i - r_j)\Big)$$

Outline

- Generalizing the control law in two ways:
  - Introduced ***integral control***: PD → PID
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- Proving stability of the PID$^\alpha$ controlled system
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Stability of Fractional Fractional PID$^{\alpha}$ Consensus

Proof of standard consensus control stability relied on the **state transition matrix** derived from the **state equations**

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + Bu$$

For fractional control, we need the ***pseudostate equations***

Single agent:

$$u = -k_P r - k_D D^{0.5} r$$

$$\boldsymbol{X} = \begin{bmatrix} r \\ D^{0.5} r \\ D^{1} r \\ D^{1.5} r \end{bmatrix}$$

$$D^{0.5}\boldsymbol{X} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix} \boldsymbol{X} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u$$

Number of components in pseudostate:

PD Control: $n = 2/\alpha$

PID Control: $n = 3/\alpha$

Pseudostate equation

$$D^{\alpha}\boldsymbol{X} = \tilde{A}\boldsymbol{X} + \tilde{B}u$$

Now, for *N* agents...

- Fractional PID$^\alpha$ Consensus

$$u_i = -\sum_{j=1}^{N} a_{ij}\Big(k_I(\xi_i - \xi_j) + k_P(r_i - r_j) + k_D D^{\alpha_D}(r_i - r_j)\Big)$$

- Closed-Loop EOM from Pseudostate Equation

$$D^\alpha \boldsymbol{X} = \underbrace{(\tilde{A} \otimes I_N - \tilde{B}\tilde{K} \otimes L)}_{(nN \times nN)\text{-dimensional},\ n = 3/\alpha}\boldsymbol{X} = \Gamma \boldsymbol{X}$$

- Solutions/stability found through the ***pseudostate transition matrix***

$$\Phi(t,0) = e^{\Gamma t} \quad \longrightarrow \quad \Phi(t,0) = E_\alpha[\Gamma t^\alpha]$$

Mittag-Leffler function

Closed-loop EOM:
(fractional PID consensus)

$$D^{\alpha}\boldsymbol{X} = (\tilde{A} \otimes I_N - \tilde{B}\tilde{K} \otimes L)\boldsymbol{X} = \Gamma\boldsymbol{X}$$

Theorem: Stability of Fractional PID$^{\alpha}$ Consensus Control

The closed-loop system will asymptotically reach consensus iff

1) Γ has exactly *n* zero-eigenvalues

2) All other eigenvalues satisfy $|\arg \lambda_i| > \alpha \frac{\pi}{2}$

Closed-loop EOM:
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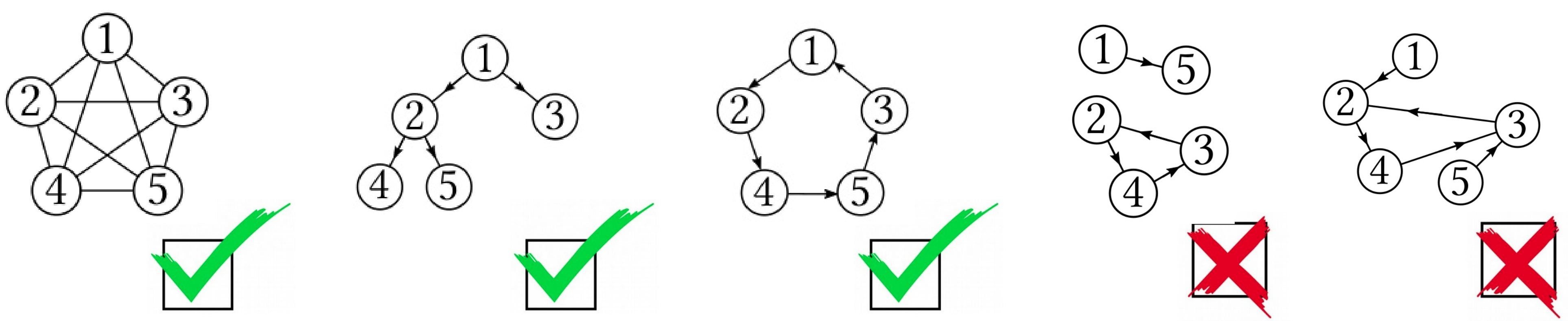
Condition 1 is satisfied as long as the communication topology is "connected"



Stability of Fractional Fractional PID$^\alpha$ Consensus

Closed-loop EOM:
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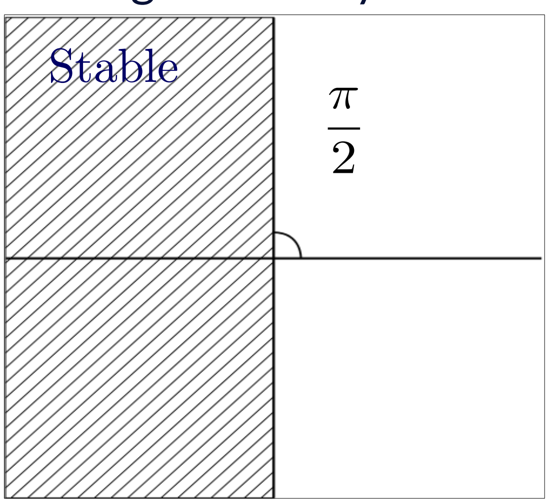
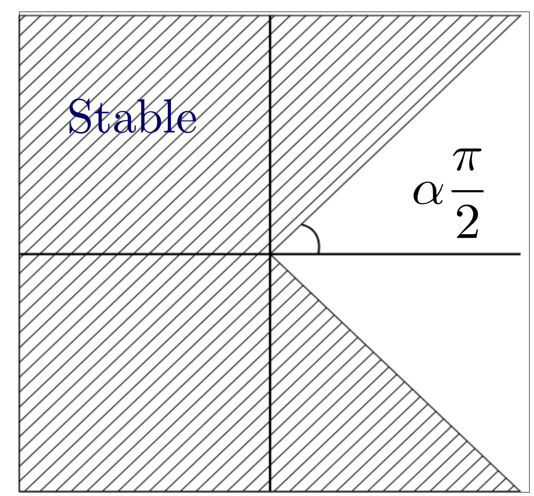
Integer order system



Condition 2 is an instance of ***Matignon's Theorem***

Fractional order system



Outline

- Generalizing the control law in two ways:
  - Introduced ***integral control***: PD $\rightarrow$ PID
  - Utilized ***fractional derivatives***: PID $\rightarrow$ PID$^{\alpha}$
- Proving stability of the PID$^{\alpha}$ controlled system
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I'll outline for PID control. Procedure for PID$^\alpha$ control is analogous.

Eigenvalues of Γ are solutions to the **characteristic equation**

$$\det(\lambda I_{3N} - \Gamma) = \prod_{i=1}^{N} \left(\lambda^3 + k_D\mu_i\lambda^2 + k_P\mu_i\lambda + k_I\mu_i\right) = 0$$

This is a **product of *N* third-order polynomials** (one for each L eigenvalue).

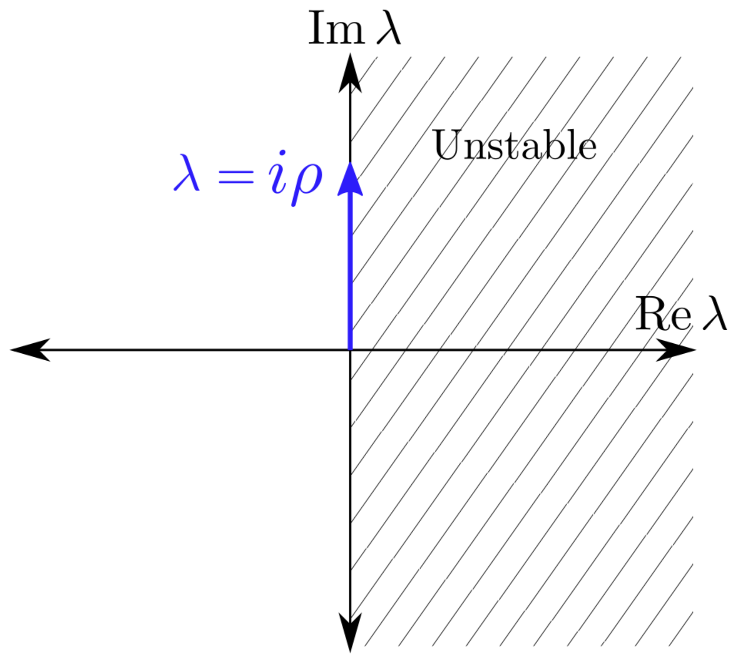
For stability, non-zero eigenvalues λ **must be in the left-half plane**.

Communication topology eigenvalues are in general complex $\Rightarrow$ $\mu_i = a_i + ib_i$

Nonzero closed-loop eigenvalues λ:
(associated with μ_i)

$$\lambda^3 + k_D(a+ib)\lambda^2 + k_P(a+ib)\lambda + k_I(a+ib) = 0$$

Trace the boundary of stability



- At this boundary, characteristic equation provides:

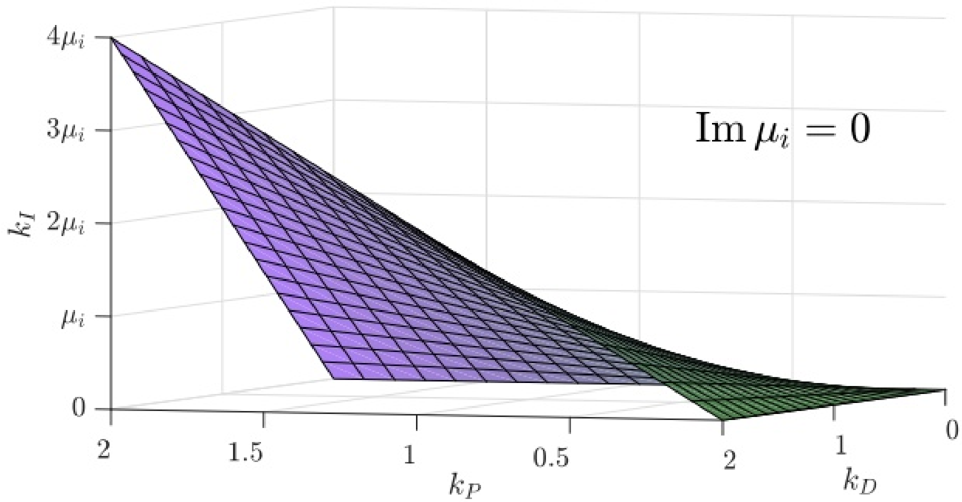
Imaginary part: $$ak_D\rho^2 + bk_P\rho - ak_I = 0$$

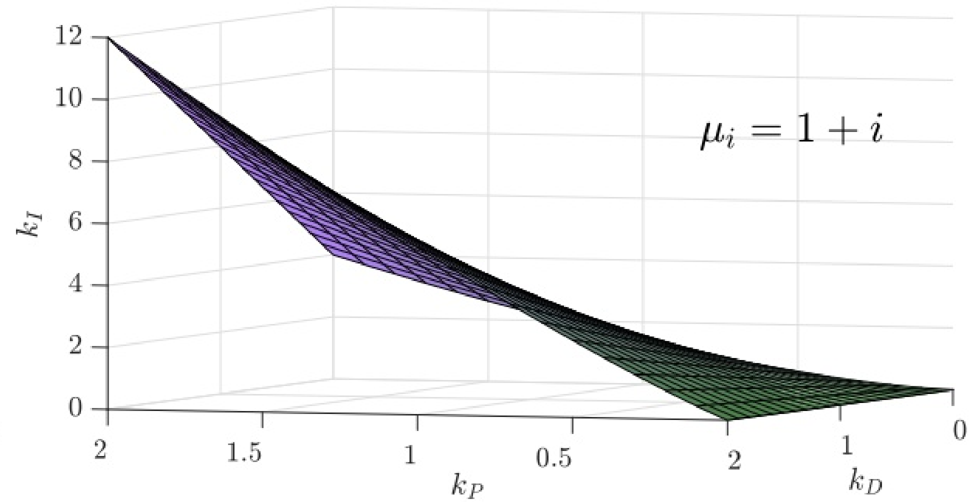
Real part: $$\rho^3 + bk_D\rho^2 - ak_P\rho - bk_I = 0$$

- Equation 1 → eliminate ρ
  Equation 2 → provides **three-dimensional hypersurface** separating stable and unstable regions:

$$S_i(k_P, k_I, k_D) = 0$$

Stability region in **gain-space** corresponding to this non-zero eigenvalue:





Volume V_i **below** the surface corresponds to **stable region of gain-space**.

Since we need the gains to be in this stable volume for **all** eigenvalues $\mu_2,\ \mu_3,\ \ldots,\ \mu_N$,

PID consensus controller for connected system is stable for

$$\{k_P, k_I, k_D\} \in V_2 \cap V_3 \cap \cdots \cap V_N$$

...or, equivalently,

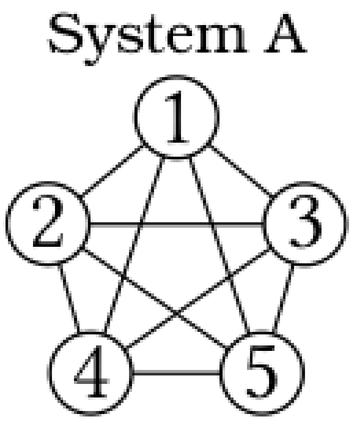
Gain conditions for PID Consensus Control

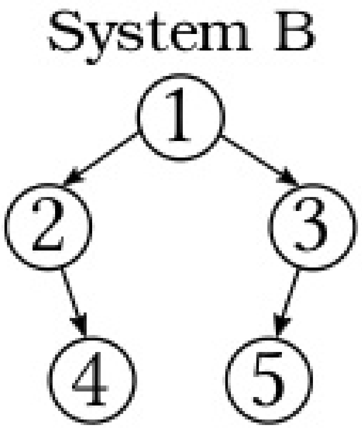
PID consensus control is asymptotically stable iff

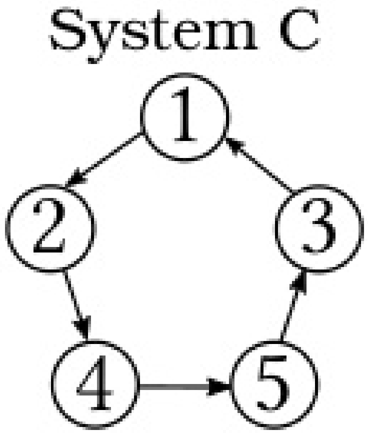
$$k_I < \min_i \left\{ \left(a_i + \frac{b_i^2}{a_i} \right) k_D k_P + \left(\frac{b_i}{a_i} \sqrt{a_i + \frac{b_i^2}{a_i}} \right) k_P^{3/2} \right\}, \quad i = 2, 3, \ldots, N$$

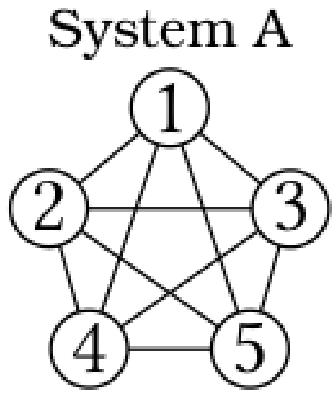
where $a_i = \operatorname{Re} \mu_i,\ b_i = \operatorname{Im} \mu_i.$

We illustrate for a few cases...







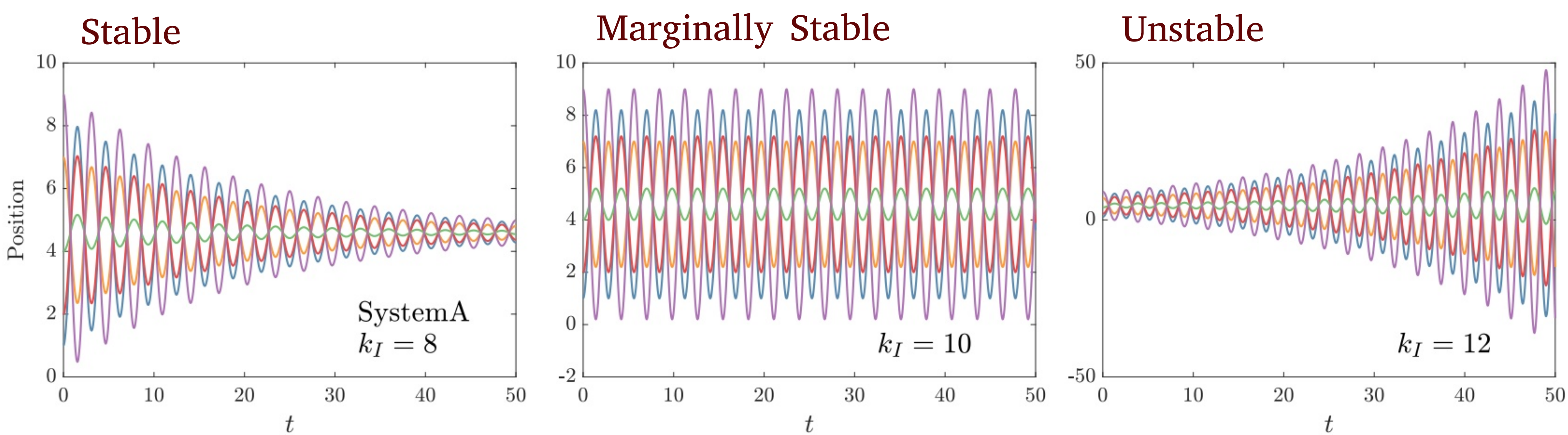


$$\operatorname{eig} L = \{0, 5, 5, 5, 5\}$$

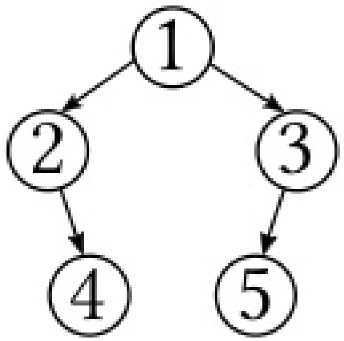
Stability Condition on Gains:

$$k_I < \min_i \left\{ \left(a_i + \frac{b_i^2}{a_i} \right) k_D k_P + \left(\frac{b_i}{a_i} \sqrt{a_i + \frac{b_i^2}{a_i}} \right) k_P^{3/2} \right\}$$

$$\boxed{k_P = 1,\ k_D = 2 \quad \Rightarrow \quad k_I < 10}$$



System B



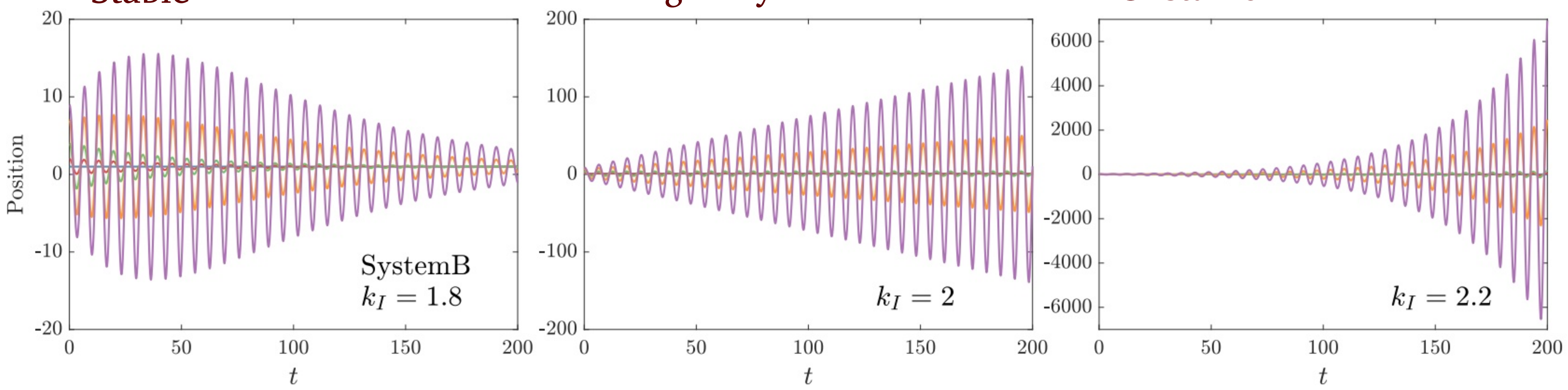
$$\operatorname{eig} L = \{0, 1, 1, 1, 1\}$$

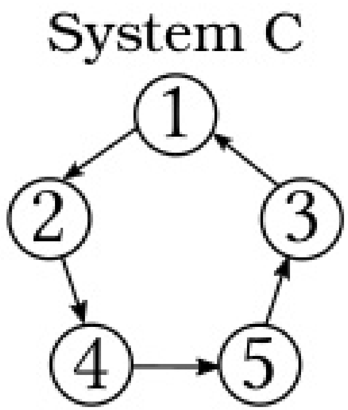
Stability Condition on Gains:

$$k_I < \min_i \left\{ \left(a_i + \frac{b_i^2}{a_i} \right) k_D k_P + \left(\frac{b_i}{a_i} \sqrt{a_i + \frac{b_i^2}{a_i}} \right) k_P^{3/2} \right\}$$

$$k_P = 1,\ k_D = 2 \quad \Rightarrow \quad k_I < 2$$

Stable | Marginally Stable | Unstable



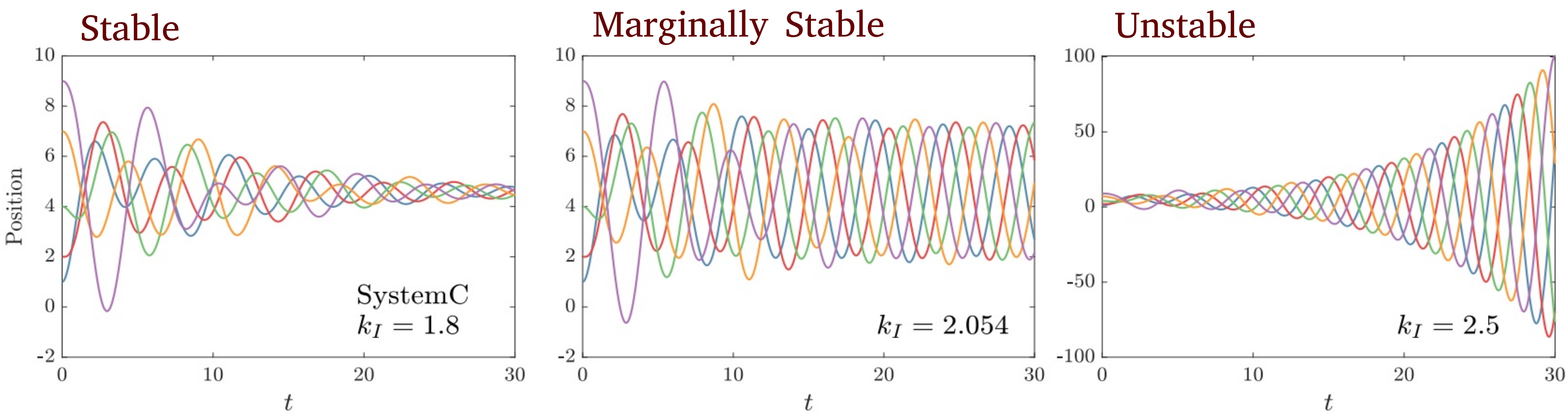


$$\operatorname{eig} L = \begin{cases} 0 \\ 0.69 \pm 0.95i \\ 1.81 \pm 0.59i \end{cases}$$

Stability Condition on Gains:

$$k_I < \min_i \left\{ \left(a_i + \frac{b_i^2}{a_i} \right) k_D k_P + \left(\frac{b_i}{a_i} \sqrt{a_i + \frac{b_i^2}{a_i}} \right) k_P^{3/2} \right\}$$

$$\boxed{k_P = 1, \ k_D = 2 \quad \Rightarrow \quad k_I < 2.054}$$



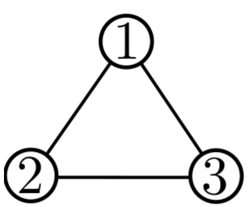
Similar result for fractional PID$^\alpha$ consensus control

$$u_i = -\sum_{j=1}^{N} a_{ij}\Big(k_I(\xi_i - \xi_j) + k_P D^{\delta\alpha}(\xi_i - \xi_j) + k_D D^{q\alpha}(\xi_i - \xi_j)\Big)$$

Gain Conditions for Fractional PID Consensus Stability
(Fully connected topology)

$$k_P > k_I \tan\left(\frac{q\alpha\pi}{2}\right)\left(\frac{-k_I}{k_D\cos\left(\frac{q\alpha\pi}{2}\right)}\right)^{-\frac{1}{q\alpha}} + \frac{1}{N}\left(\frac{-k_I}{k_D\cos\left(\frac{q\alpha\pi}{2}\right)}\right)^{\frac{2}{q\alpha}}$$

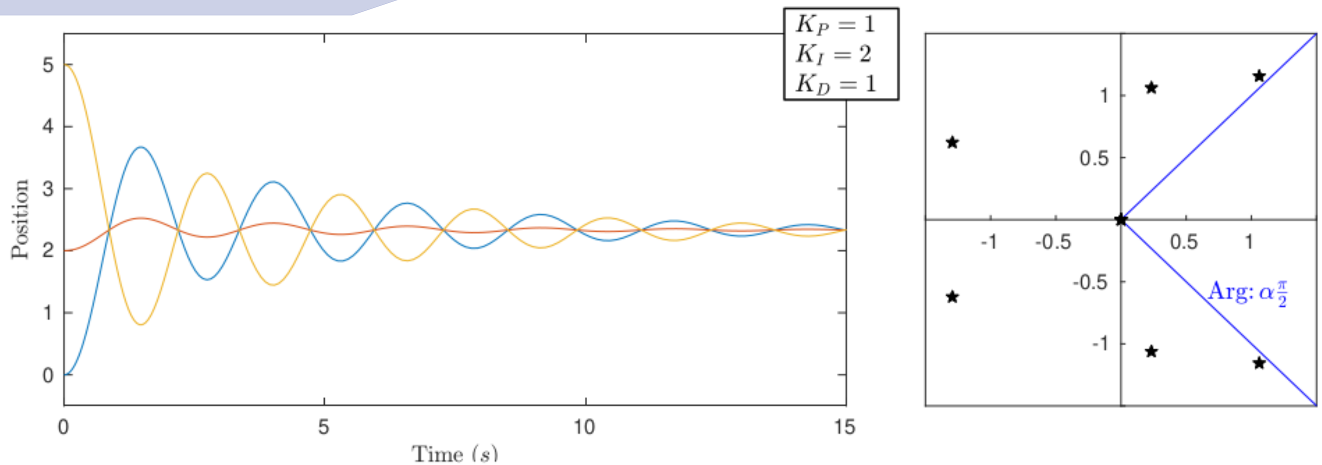
Example: 3-Agent, PID$^{0.5}$ Consensus



Choosing $k_D = 1,\ k_I = 2, \quad \Rightarrow \quad \boxed{k_P > 0.33}$

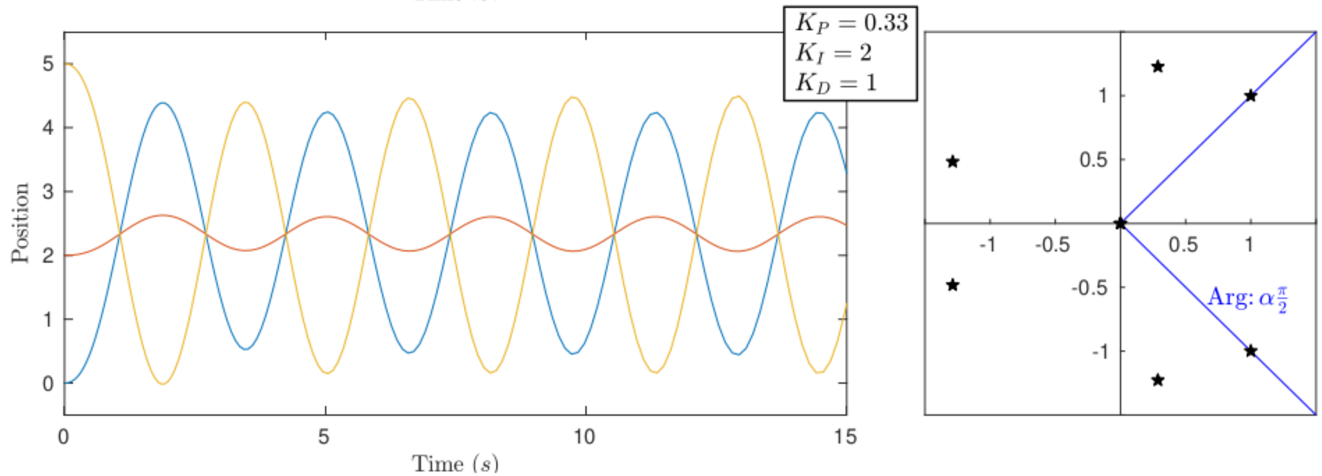
Stable

$$k_P = 1 > 0.33$$



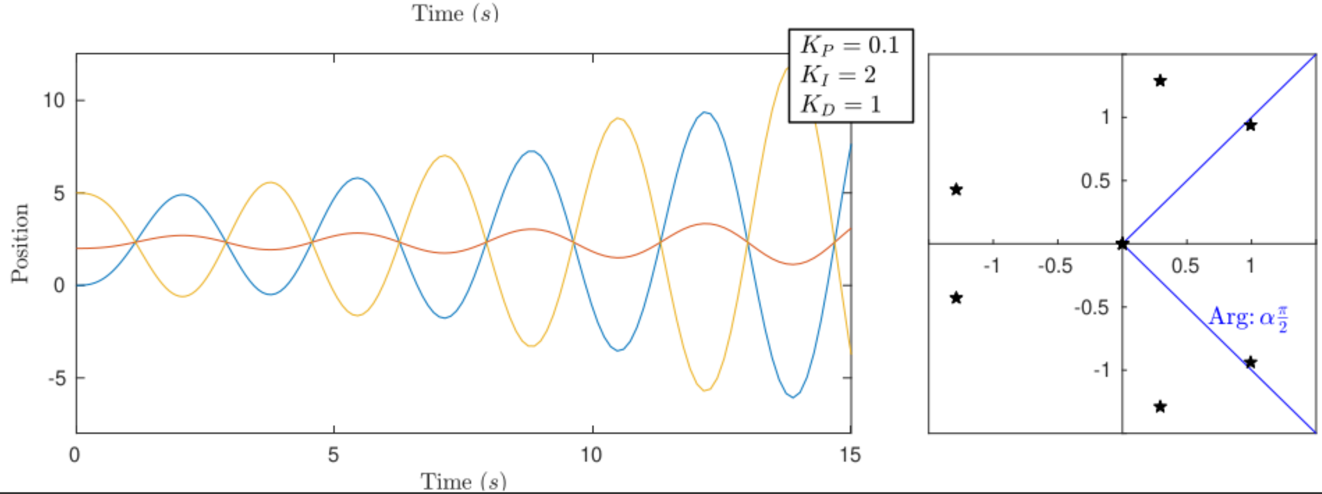
Marginally Stable

$$k_P = 0.33$$



Unstable

$$k_P = 0.1 < 0.33$$

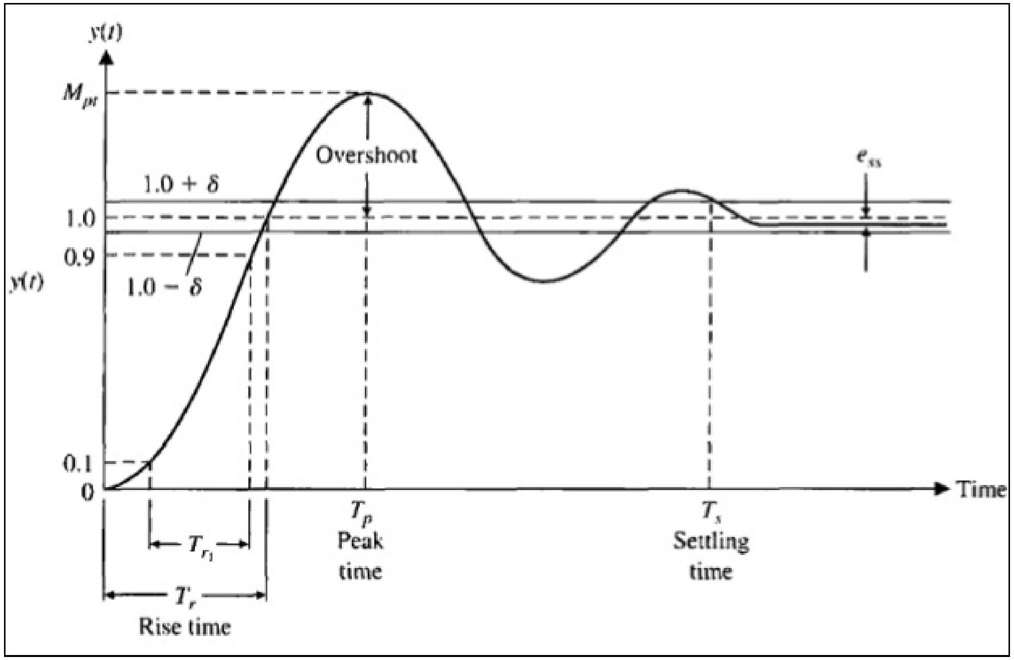


Outline

- Generalizing the control law in two ways:
  - Introduced ***integral control***: PD $\rightarrow$ PID
  - Utilized ***fractional derivatives***: PID $\rightarrow$ PID$^{\alpha}$
- Proving stability of the PID$^{\alpha}$ controlled system
- Establishing conditions on gains for stability
- Demonstrating that PID$^{\alpha}$ can **outperform** PD/PID

To compare controllers, we will consider some common performance measures:

- Settling Time
- Overshoot
- Integrated Control
  ($\propto$ fuel cost)



These can be defined analogously (and in a meaningful way) for consensus systems.

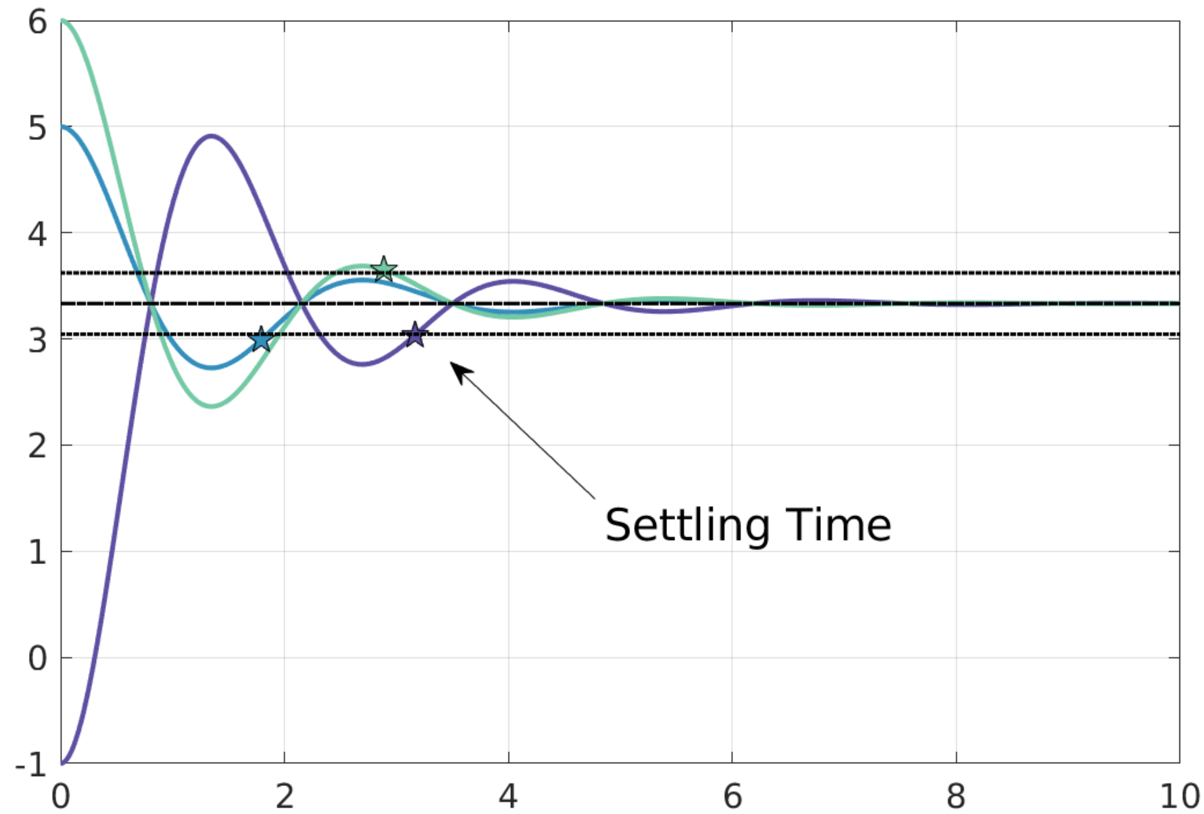
Settling Time

- Find average distance of initial positions from consensus value

$$\overline{\delta x_0}$$

- Define settling time window:

$$x_{\text{consensus}} \pm (10\% \times \overline{\delta x_0})$$



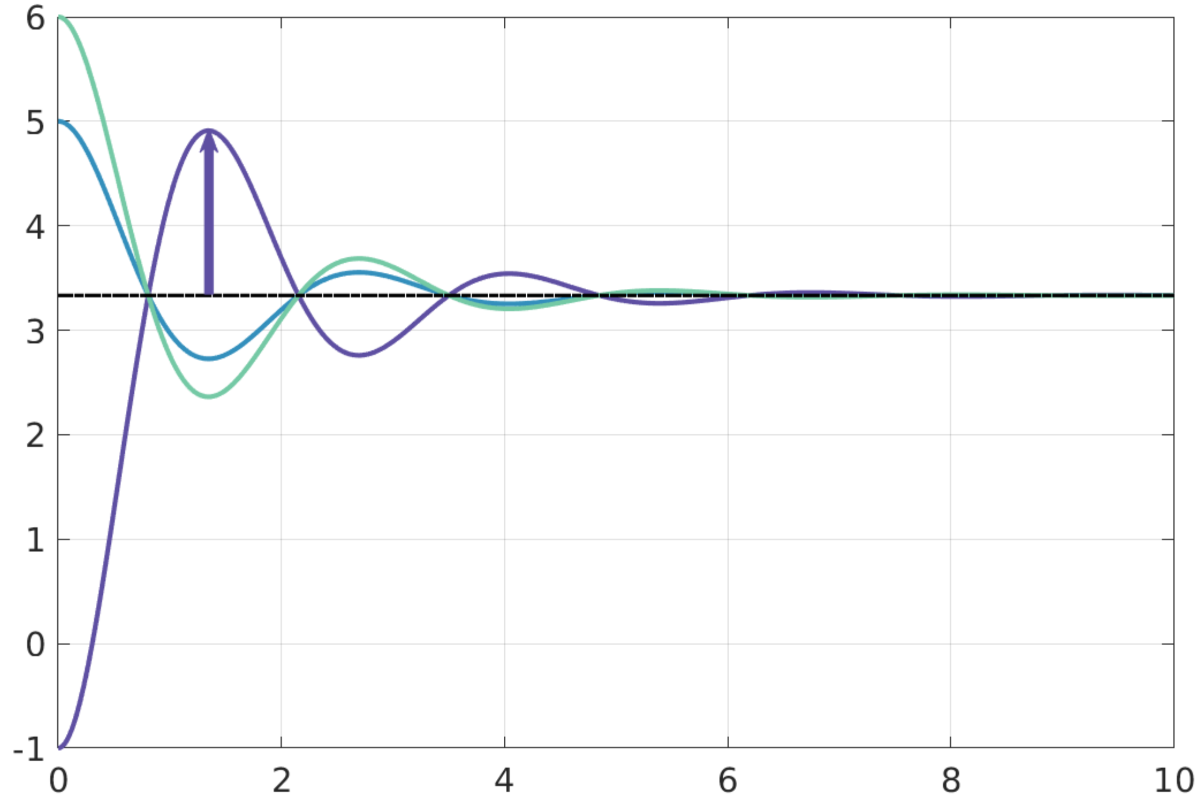
Settling time is time of **last agent** to reach and remain within this window.

Overshoot

- Find **largest** distance between consensus value and agent

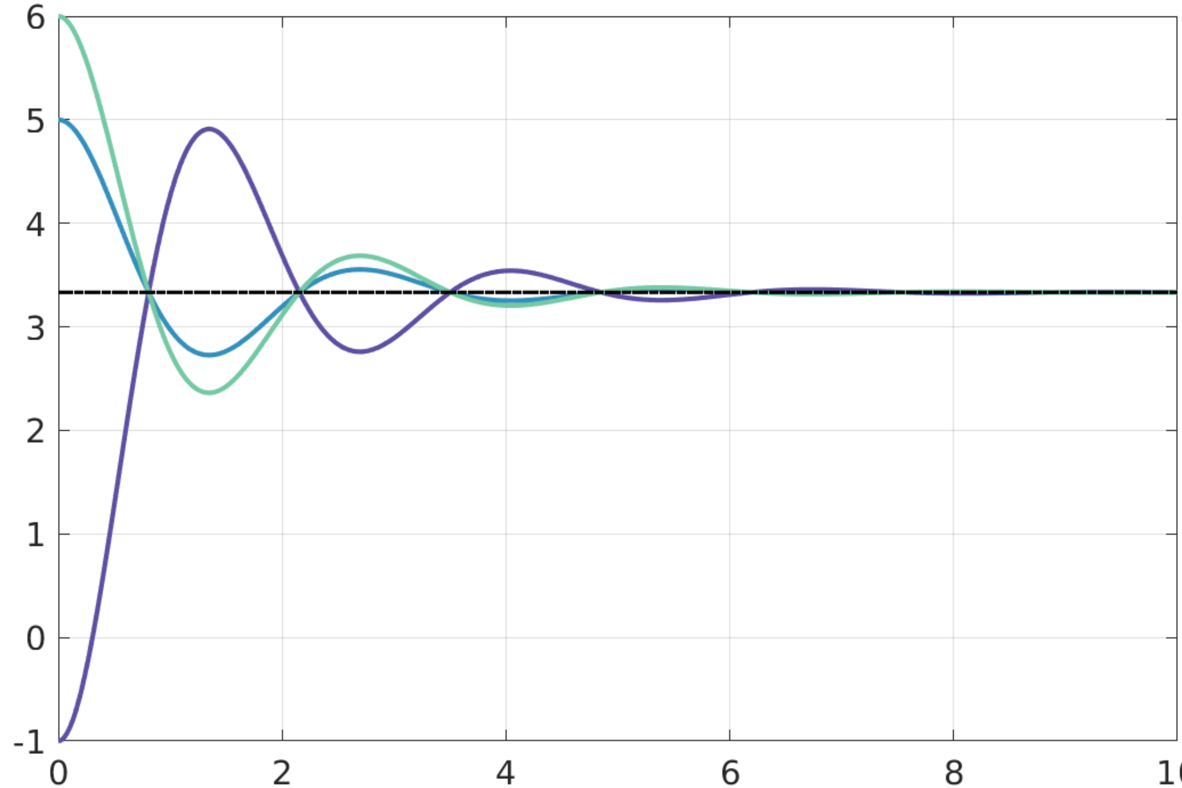
- Normalize this distance by dividing by initial distance to consensus value.

$$\Rightarrow \text{ Percent Overshoot}$$

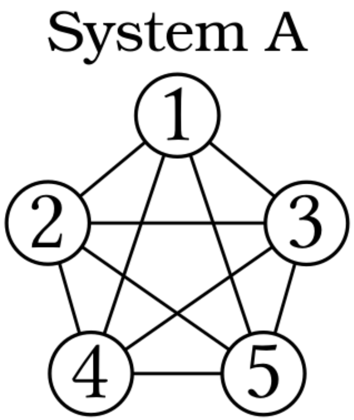


- Integrated Control

$$U = \sum_{i=1}^{N} \int_0^{\infty} |u_i(t)| dt$$

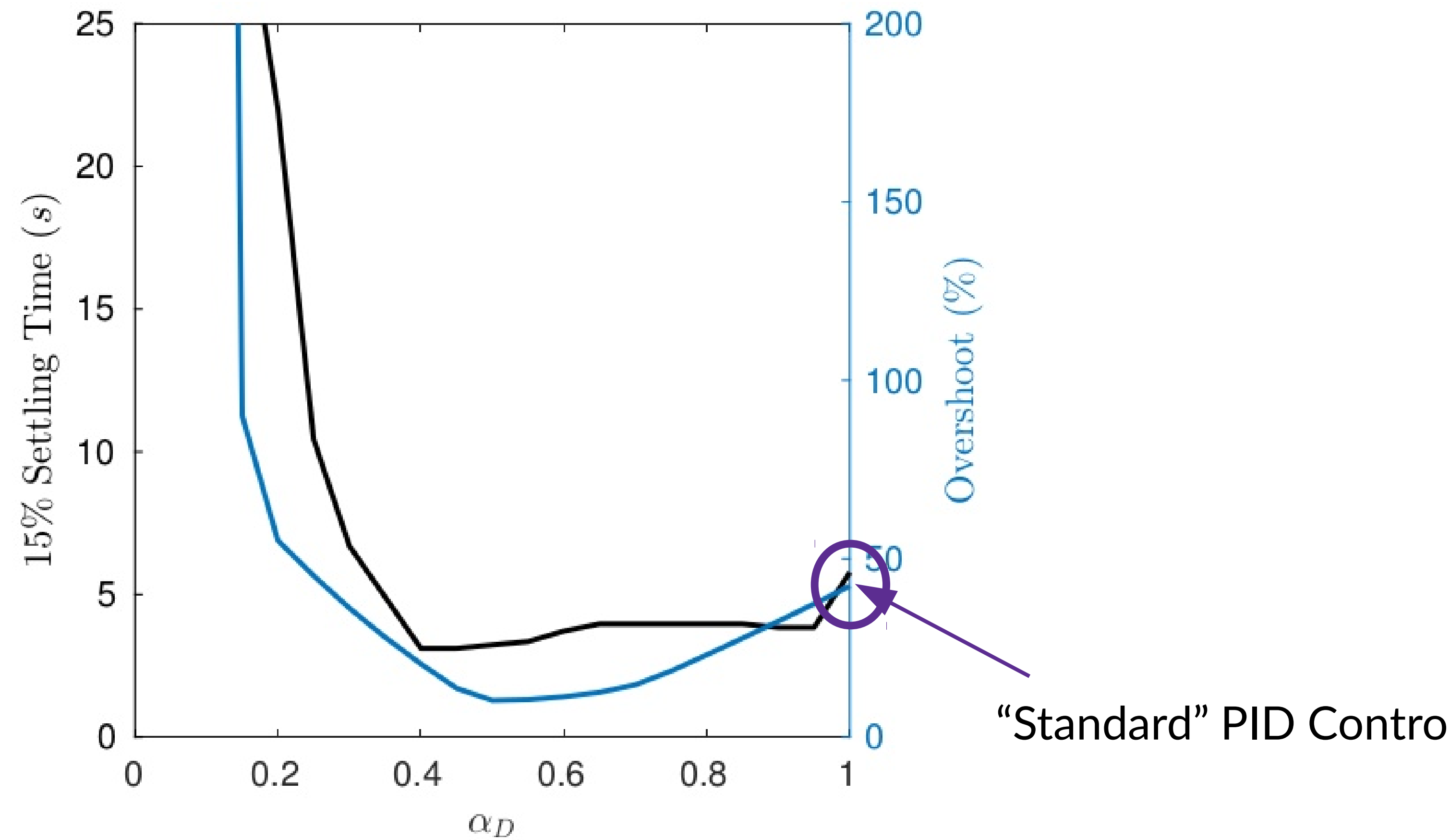


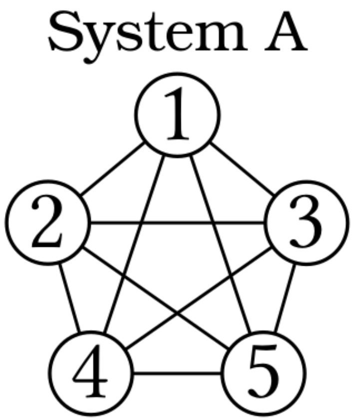
Lets now test some specific cases, and observe how these performance measures vary with fractional order of controller



Pick a specific choice of gains and ***vary the fractional derivative order.***

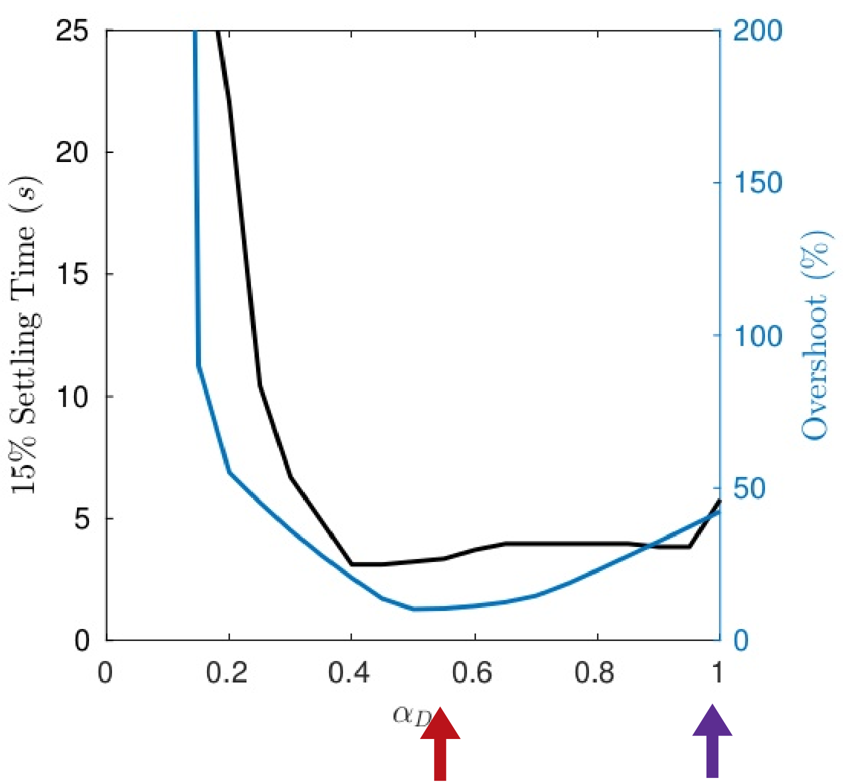
$$u_i = -\sum_{j=1}^{N} a_{ij} \left(k_I \int (x_i - x_j)dt + k_P(x_i - x_j) + k_D \underline{D^{\alpha_D}} (x_i - x_j) \right)$$

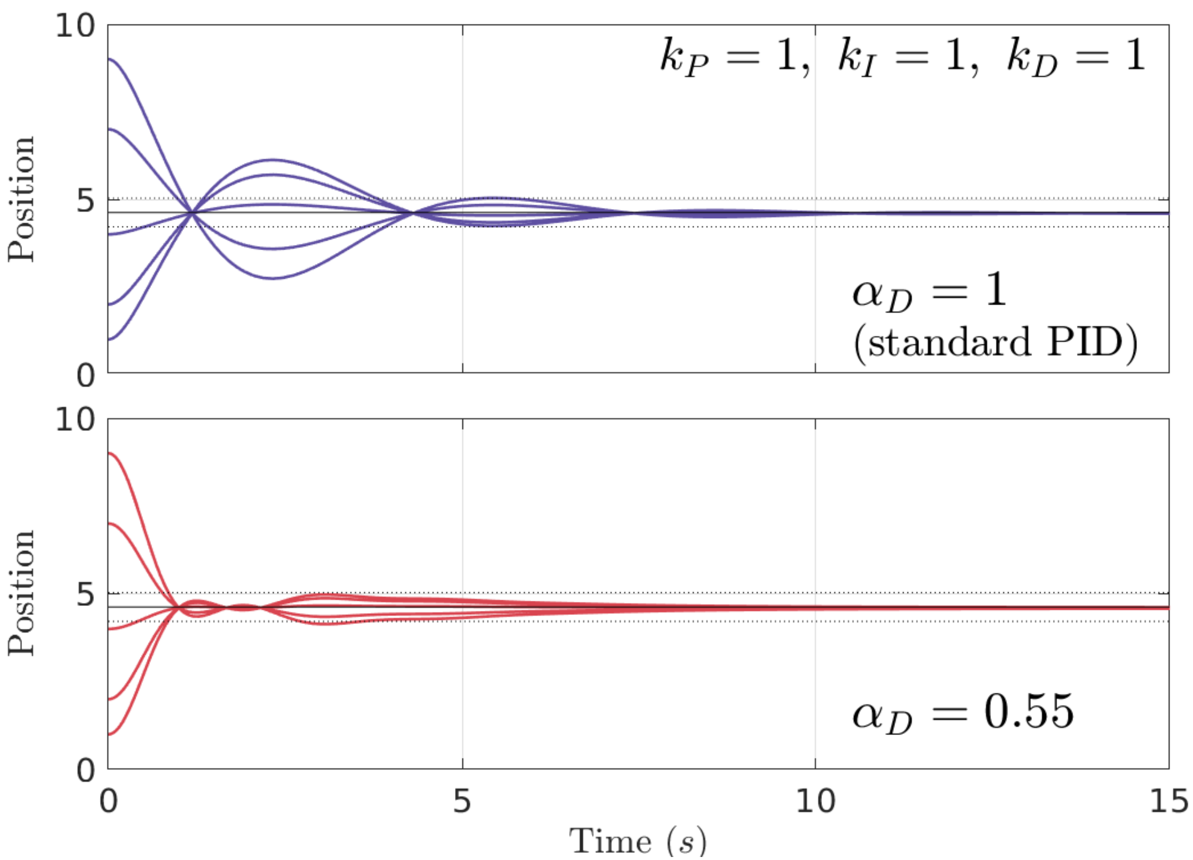


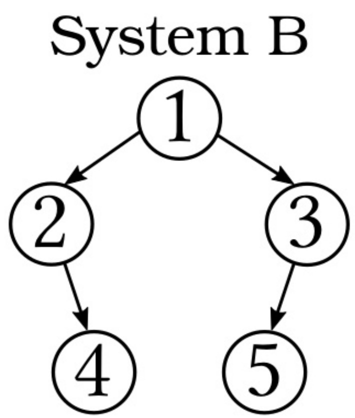


Pick a specific choice of gains and ***vary the fractional derivative order.***

$$u_i = -\sum_{j=1}^{N} a_{ij} \left(k_I \int (x_i - x_j)dt + k_P(x_i - x_j) + k_D D^{\alpha_D}(x_i - x_j) \right)$$

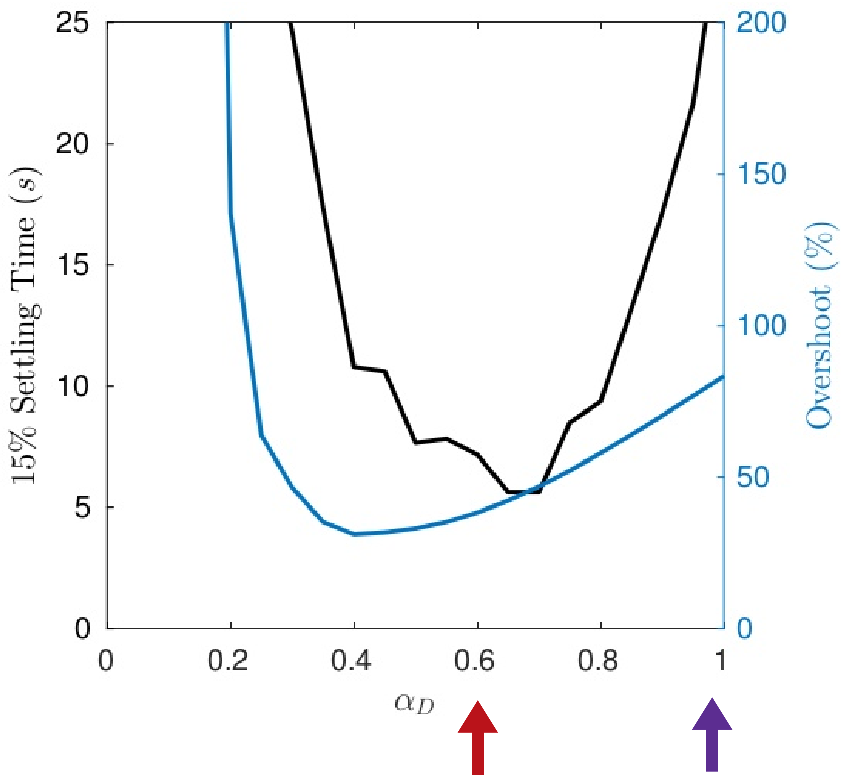


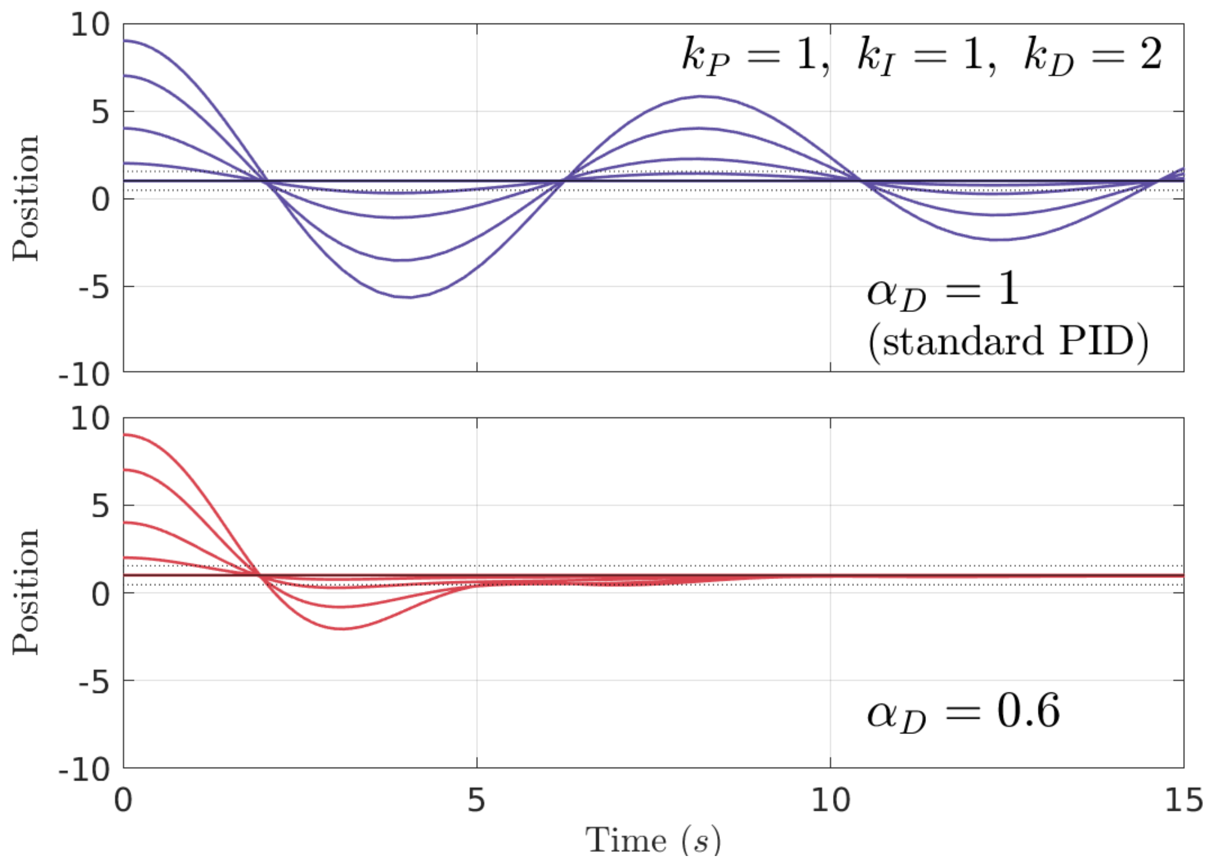




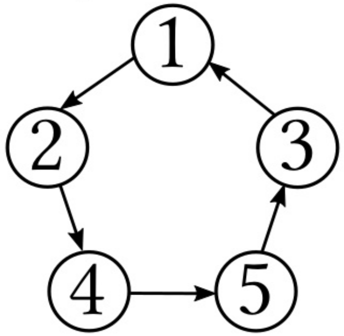
Pick a specific choice of gains and ***vary the fractional derivative order.***

$$u_i = -\sum_{j=1}^{N} a_{ij}\left(k_I \int (x_i - x_j)dt + k_P(x_i - x_j) + k_D D^{\alpha_D}(x_i - x_j)\right)$$

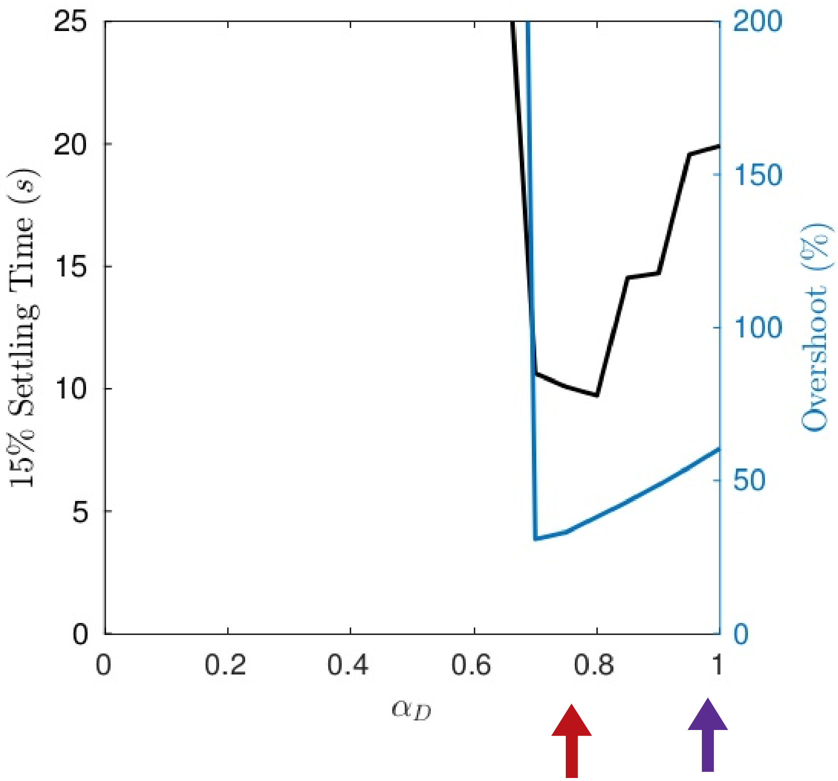


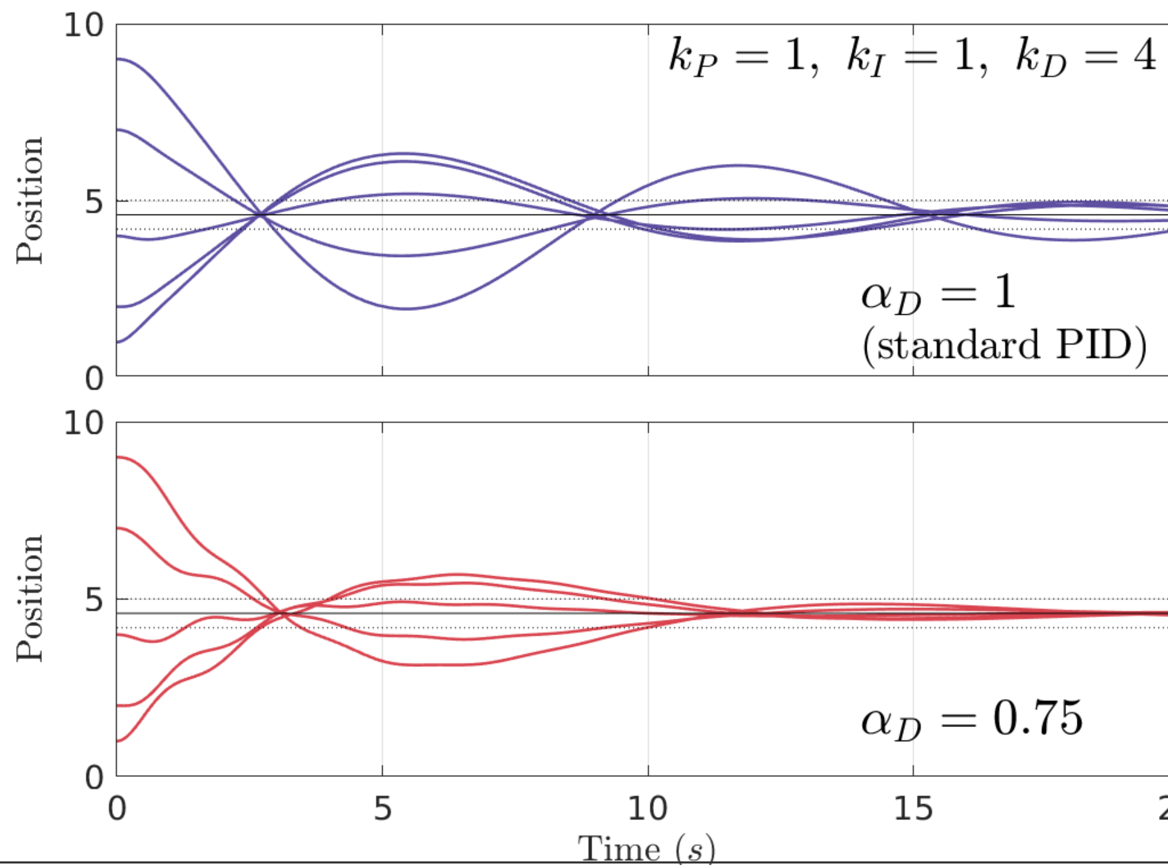


System C



In all cases, varying the derivative order away from unity gives better performance

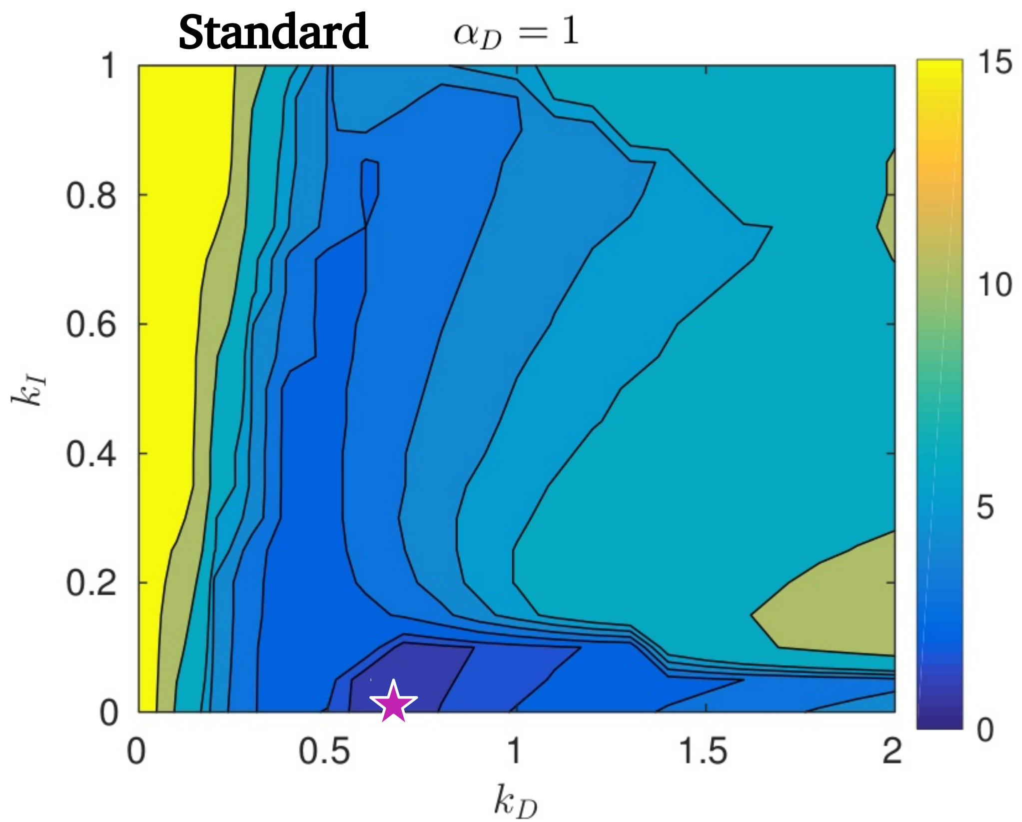




Concrete demonstration that fractional control can outperform standard control:

Survey over the parameter space

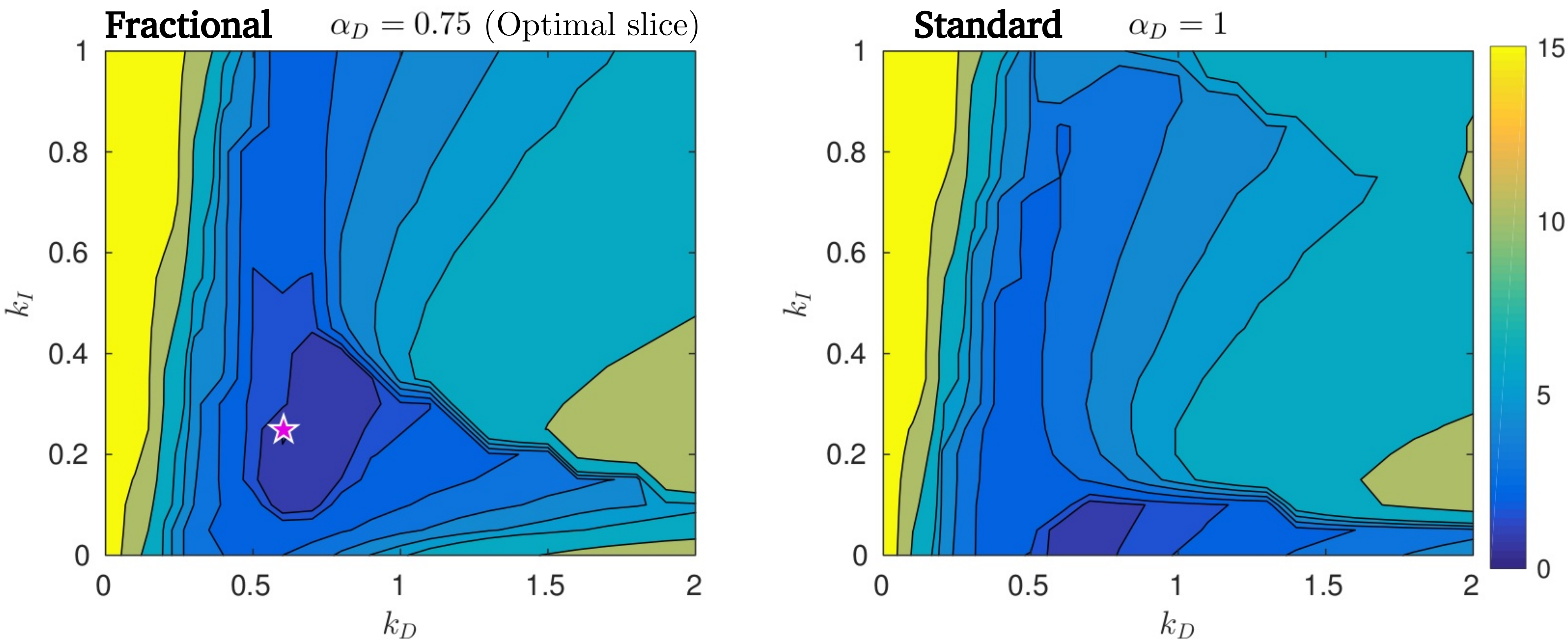
Choose $k_P = 1,$ survey over $\{k_I,\ k_D, \alpha_D\}$ to find optimal settling time



Optimal settling time: $t_s = 1.067$ s

Concrete demonstration that fractional control can outperform standard control:
Survey over the parameter space

Choose $k_P = 1,$ survey over $\{k_I,\ k_D, \alpha_D\}$ to find optimal settling time



Optimal settling time: $t_s = 0.862$ s

Optimal settling time: $t_s = 1.067$ s

Approximately 20% Improvement using fractional control.

Concrete demonstration that fractional control can outperform standard control:

Survey over the parameter space

- Optimize both settling time ***and*** control effort (fuel cost)

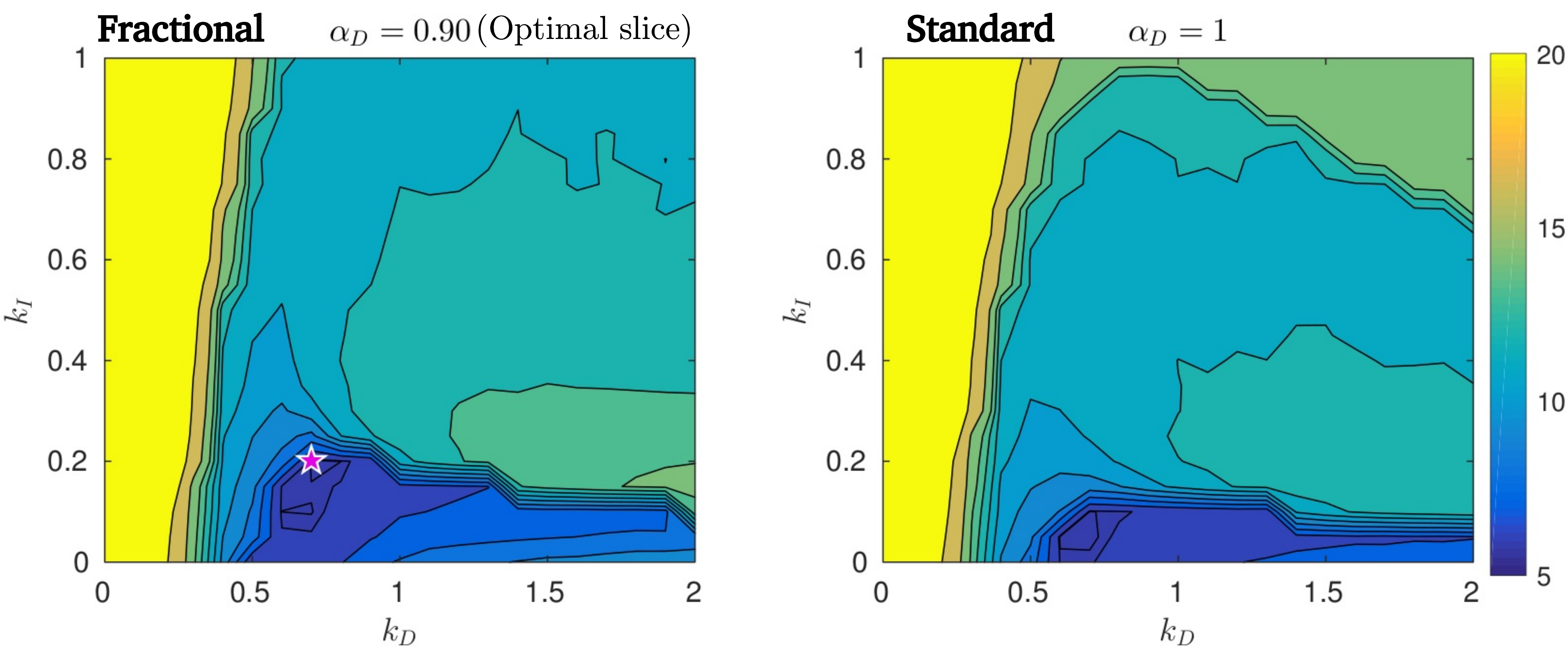
Survey over parameter space and compute *geometric mean* of settling time and control effort.

$$J = \sqrt{U \cdot \tau_s}$$

Using geometric mean avoids complications arising from differences in scale... i.e., Newtons vs seconds

Concrete demonstration that fractional control can outperform standard control:

Survey over the parameter space



Optimal point: $J = 5.78$

Optimal point: $J = 5.83$

Can achieve faster settling time with less fuel cost

Summary

- We have **generalized consensus controllers** for multivehicle systems by including both ***integral*** and ***fractional derivative*** control.

- For double-integrator dyanamics, these generalizations were proven to be **asymptotically stable**

- Stability conditions on controller gains were derived

  This is relevant for ***controller design***

- We've shown that fractional control can outperform standard (integer-order) control.

  This is a result of the ***increased tunability*** of the controller…

$$\{k_P, k_I, k_D\} \longrightarrow \{k_P, k_I, k_D, \alpha\}$$

  …which gives more freedom in shaping the trajectory

Thank you!