2.151 Final Project

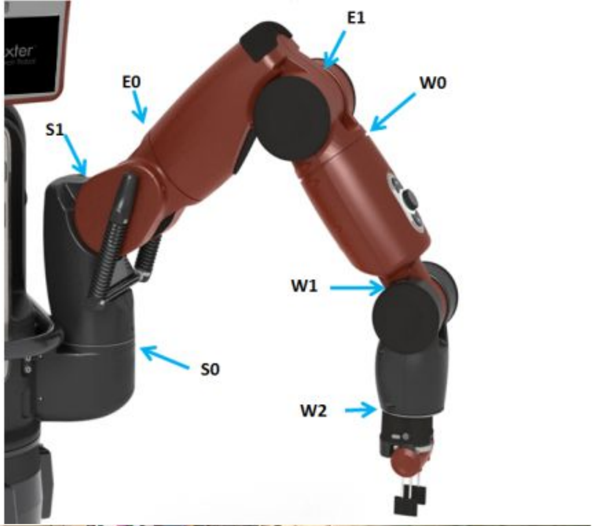
Lucille Hosford, Chris Welch, Brian Wilcox, Manjinder Singh

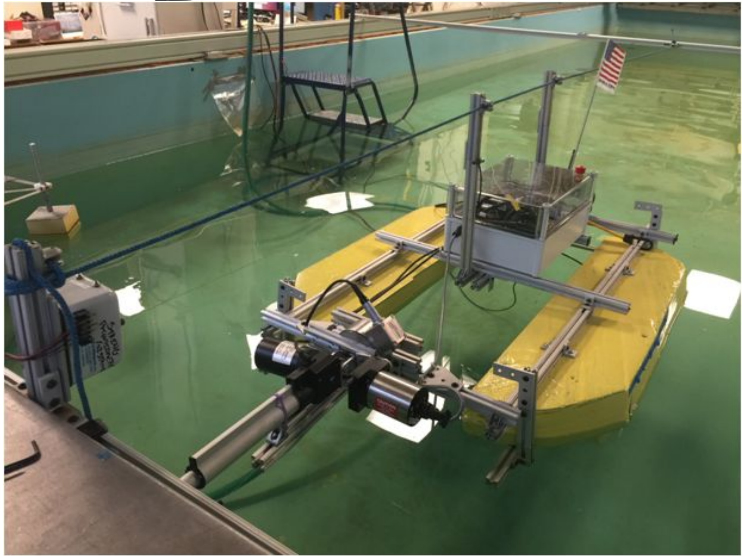
Impedance Control in the Oil and Gas Industry

- **Decommissioning** is the dismantling of offshore structures
- Current state of practices uses ROVs and divers
  - ROVs = Very expensive operational costs
  - Divers = Very significant safety risks
- **Replace with autonomy?**
  - Autonomous decommissioning vehicles must demonstrate comparable ability to **sense** and **manipulate**
- **Key tasks** include scrubbing biofouling and testing valve functionality
  - **Suggests impedance control!**

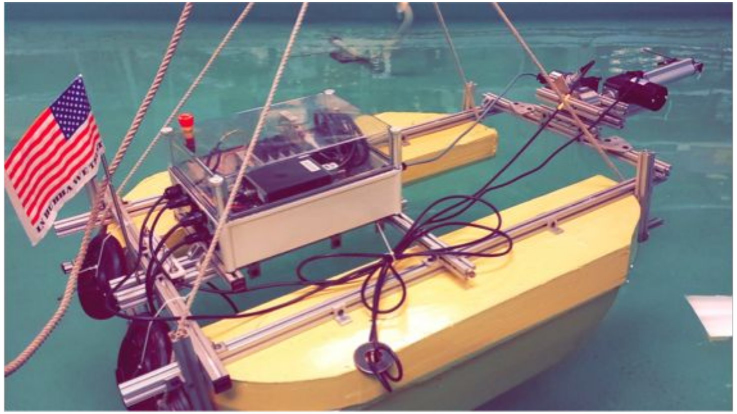
Baxter and Dexter

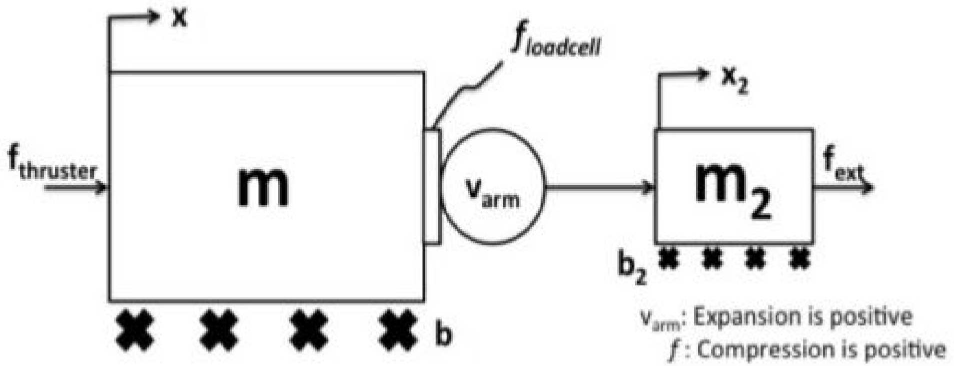
- **Long term goal:** Dexter affords ability to investigate free-flight collisions, but Baxter's manipulator more realistically exemplifies desired dexterity of a light intervention AUV
    - Use **Dexter**'s linear actuator to **find range of impedances** for acceptable collision characteristics
    - Demonstrate that **Baxter**'s multi dof arm can **reproduce those impedances**





Dexter State Space Representation: Open Loop Model

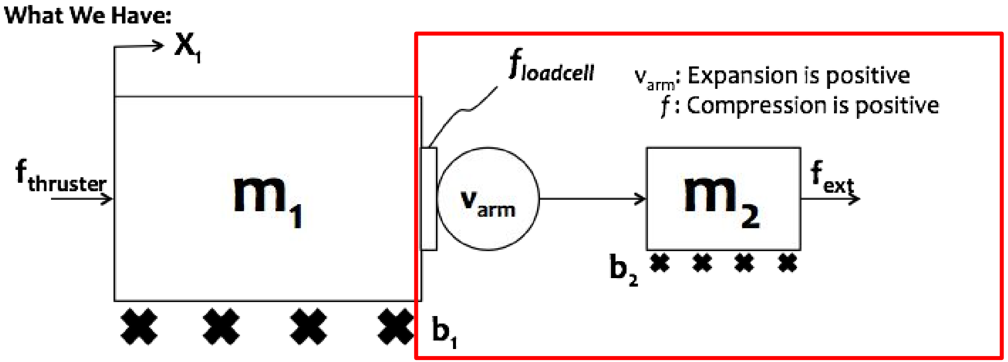


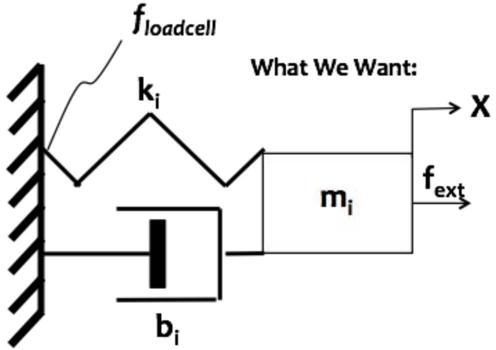


State Space Representation

$$\begin{bmatrix} \frac{\mathrm{d}(x1)}{\mathrm{d}t} \\ \frac{\mathrm{d}^2(x1)}{\mathrm{d}t^2} \\ \frac{\mathrm{d}(x2)}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-(b1+b2)}{m1+m2} & 0 \\ 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} x1 \\ \frac{\mathrm{d}(x1)}{\mathrm{d}t} \\ x2 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ \frac{-b2}{m1+m2} & \frac{-m2}{m1+m2} & \frac{1}{m1+m2} \\ 1 & 0 & 0 \end{bmatrix} * \begin{bmatrix} \frac{\mathrm{d}(x2)}{\mathrm{d}t} \\ \frac{\mathrm{d}^2(x2)}{\mathrm{d}t^2} \\ \mathrm{Ft} \end{bmatrix}$$

Dexter Equations of Motion: Closed Loop Model





$$m_1\ddot{x}_1 = f_t - f_l - b_1\dot{x}_1$$

$$m_2\ddot{x}_2 = f_l + f_e - b_2\dot{x}_2$$

$$x_2 = x_1 + x_{arm}$$

$$\ddot{x} = -\frac{b_i}{m_i}\dot{x} - \frac{k_i}{m_i}x + \frac{1}{m_i}f_l$$

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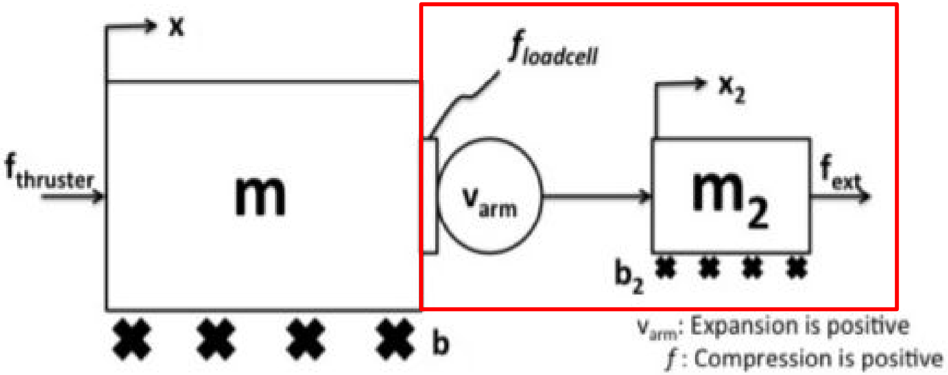
$$\begin{bmatrix} F_t \\ \dot{x_a} \end{bmatrix} = \begin{bmatrix} \frac{m_1 k_i}{m_2-m_i} & b_1 - \frac{m_1(b_2-b_i)}{m_2-m_i} & \frac{m_1(b_2-b_i)}{m_2-m_i} \\ \frac{k_i}{b_2-b_i} & \frac{m_2-m_i}{m_1(b_2-b_i)} - \frac{b_2}{b_2-b_i} + \frac{b_i}{b_2-b_i} & 0 \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \dot{x}_a \end{bmatrix} + \begin{bmatrix} \frac{m_1+m_2-m_i}{m_2-m_i} & \frac{m_1 k_i}{m_2-m_i} & -m_1 & \frac{-m_1 k_i}{m_2-m_i} & \frac{-m_1 b_i}{m_2-m_i} & 0 \\ \frac{m_1+m_2-m_i}{m_1(b_2-b_i)} & \frac{k_i}{b_2-b_i} & \frac{-(m_2-m_i)}{b_2-b_i} & \frac{k_i}{b_2-b_i} & \frac{b_i}{b_2-b_i} & \frac{-(m_2-m_i)}{m_1(b_2-b_i)} \end{bmatrix}\begin{bmatrix} F \\ \ddot{x}_a \end{bmatrix}$$

- The above state space model describes necessary actuation with respect to sensor inputs in order to achieve a desirable, user-defined endpoint impedance
- However, **focus for Baxter** is on the **actuator's impedance characteristics**



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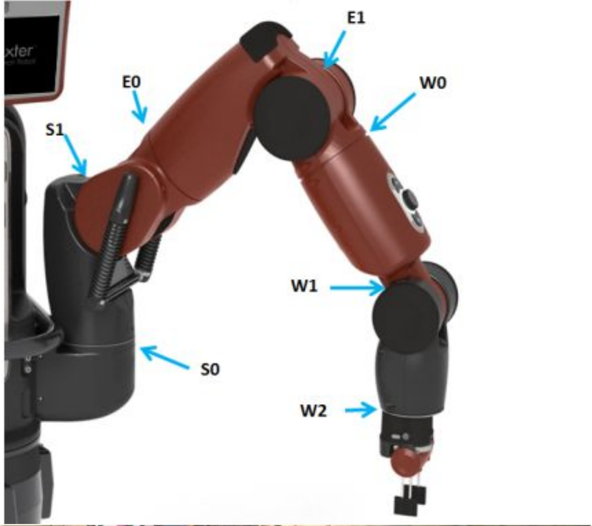
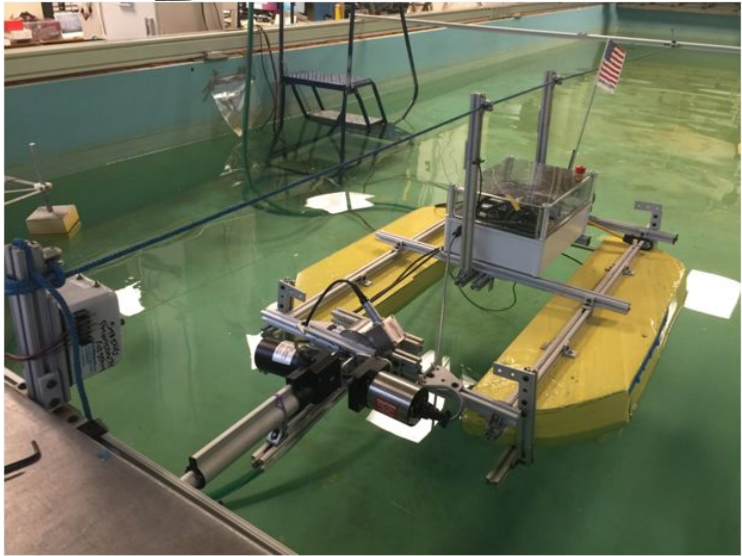
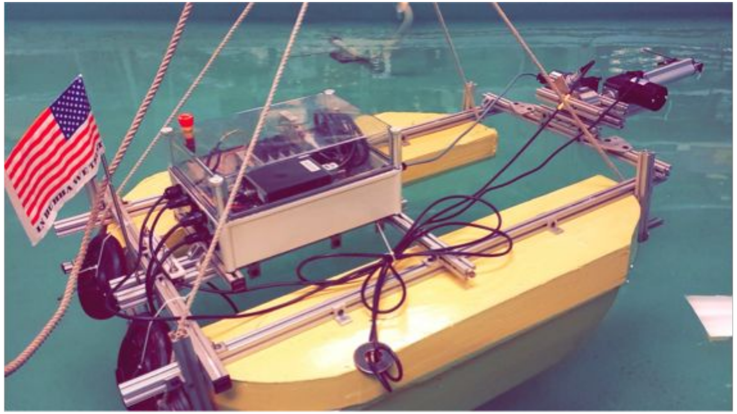
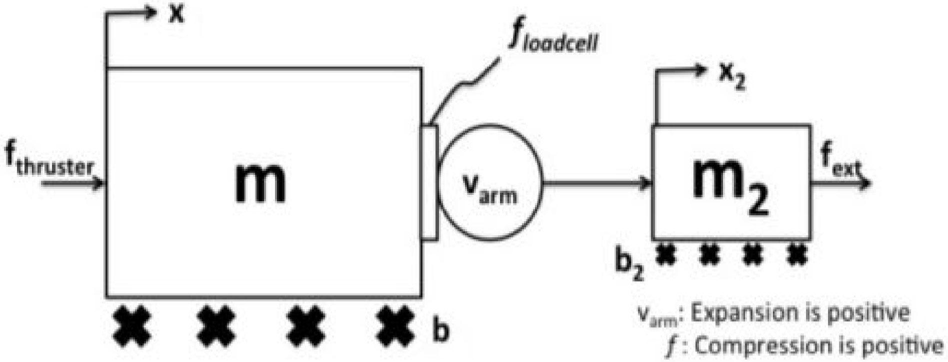




Dexter State Space Representation: Open Loop Model





State Space Representation

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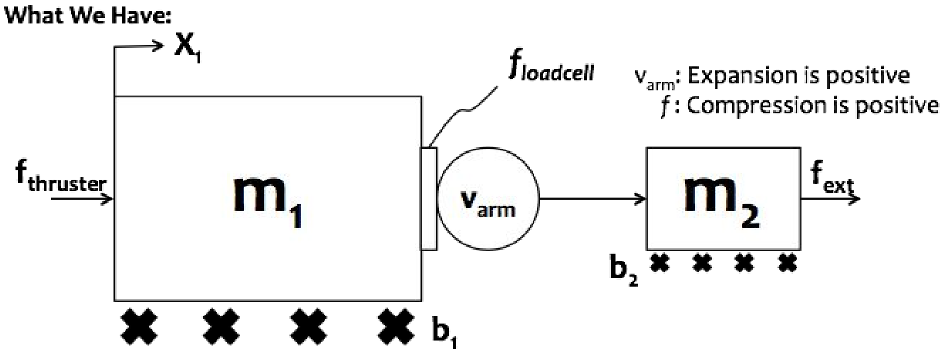

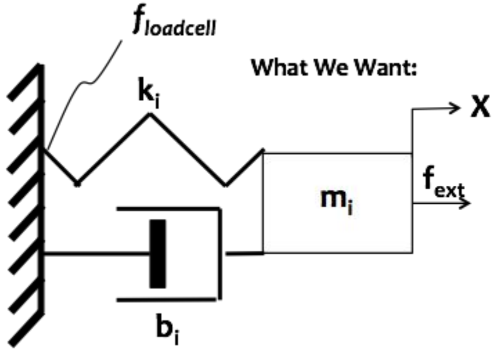

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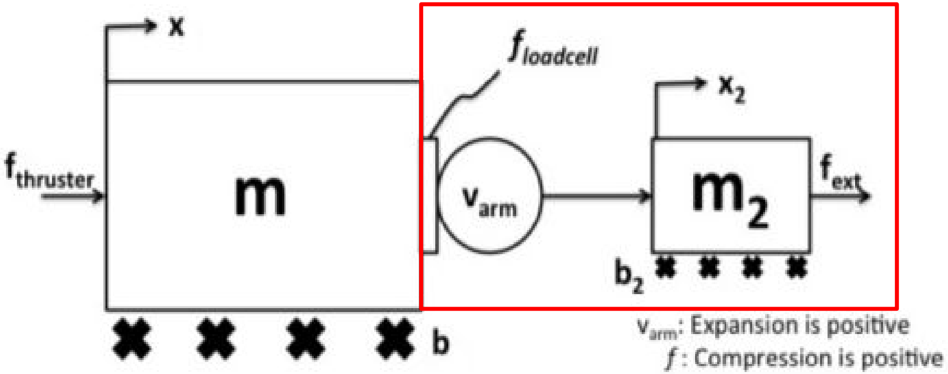
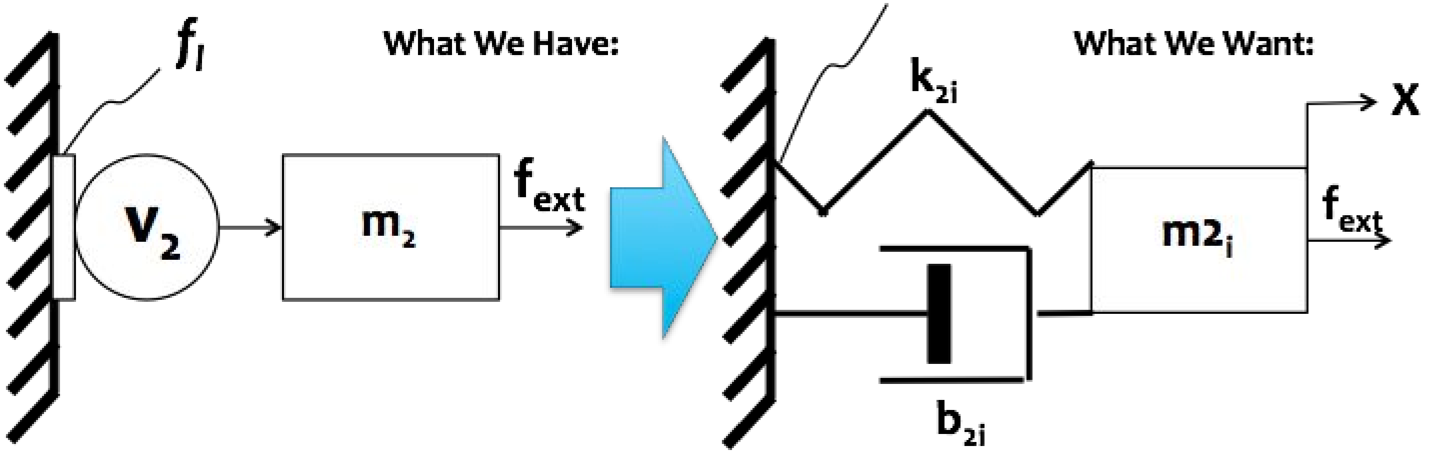


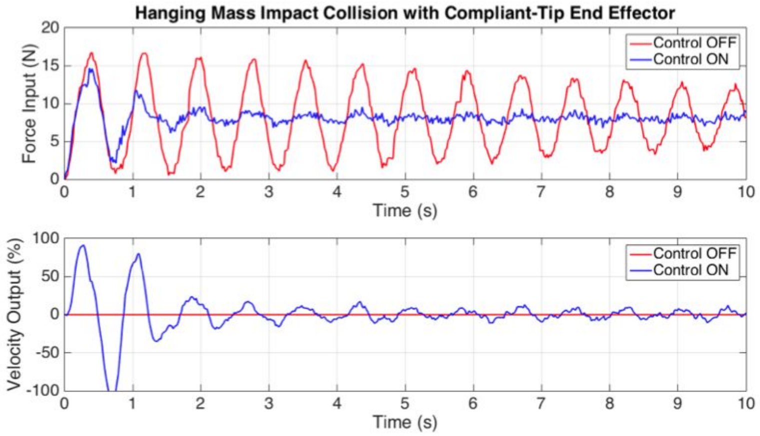
Turning a Non-Backdrivable Linear Actuator Into a Passive System

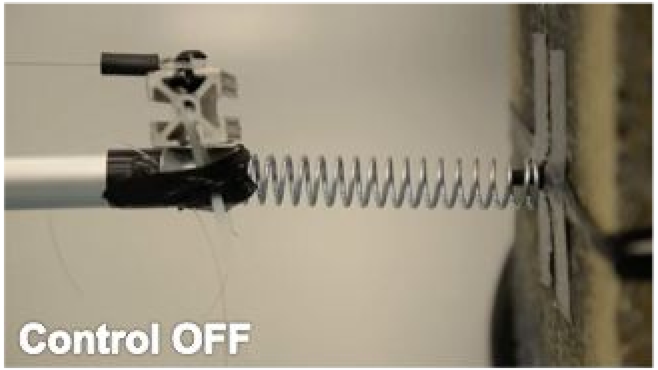
- Creating a controller for the linear actuator based desired impedance parameters allows for:
  - A closed-loop system that promotes robust and stable interactions due to passivity
  - Achievable design constraints (e.g., Peak impact force, Settling time)
  - Definitive impedance values for Baxter to reproduce

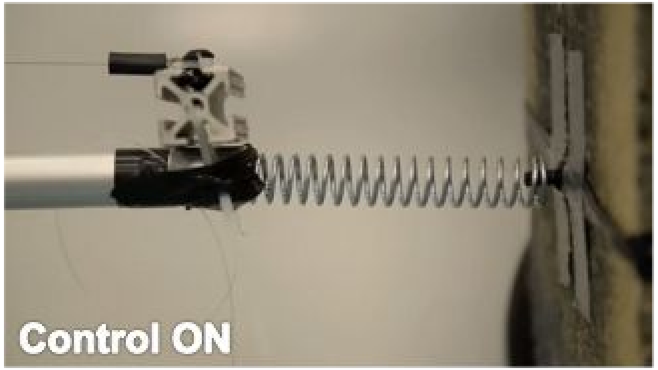


Determining Desirable Impedance Characteristics

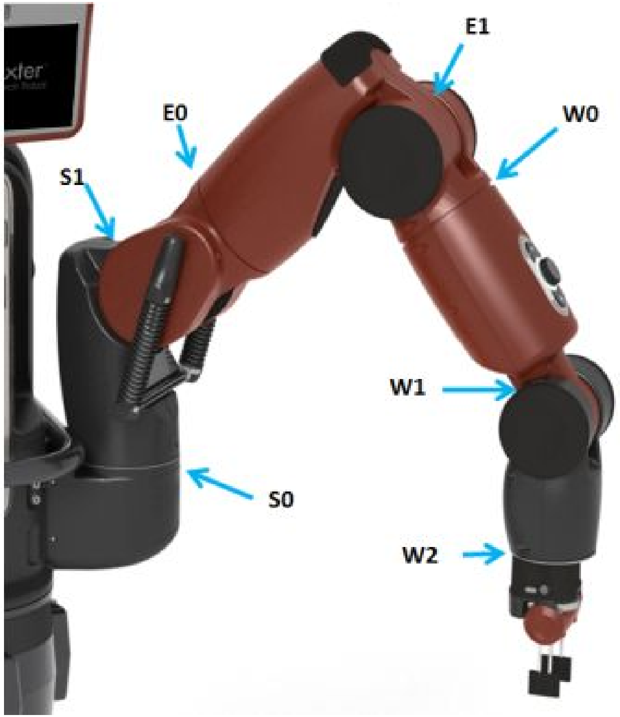
- A **reduction in peak force** provides a buffer for a controller to react to any unforeseen collisions
  - Alleviates significant risks for valuable equipment on hard-to-reach AUVs
- A **sharp reduction in settling time** suggests a smaller influence by external disturbances, such as underwater currents
  - Minimizes unpredictable disturbances during any on going contact tasks
- **Feed impedance values to Baxter!**







Baxter Research Robot



For the purposes of the experiment, Baxter was constrained to planar motion by only allowing joints S1, E1, and W1 to move.

Baxter Research Robot: Open loop model

Neglecting SEA dynamics, Equations of Motion

$$(M(q) + I_r)\ddot{q} + C(\dot{q}, q) + D\dot{q} + g(q) = \tau_{motors}$$

Simplifies to

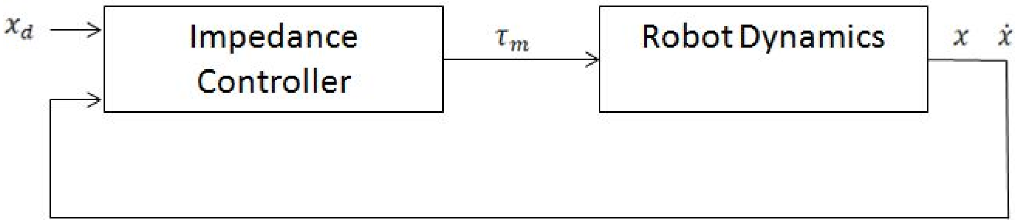
$$(M(q) + I_r)\ddot{q} + D\dot{q} = \tau_{motors}$$

State space representation

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & -(M(q) + I_r)^{-1}D \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ (M(q) + I_r)^{-1} \end{bmatrix}\tau_{motors}$$

$$\dot{x} = [0\ J]\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + [0]\tau_{motors}$$

Baxter Research Robot: Closed loop model

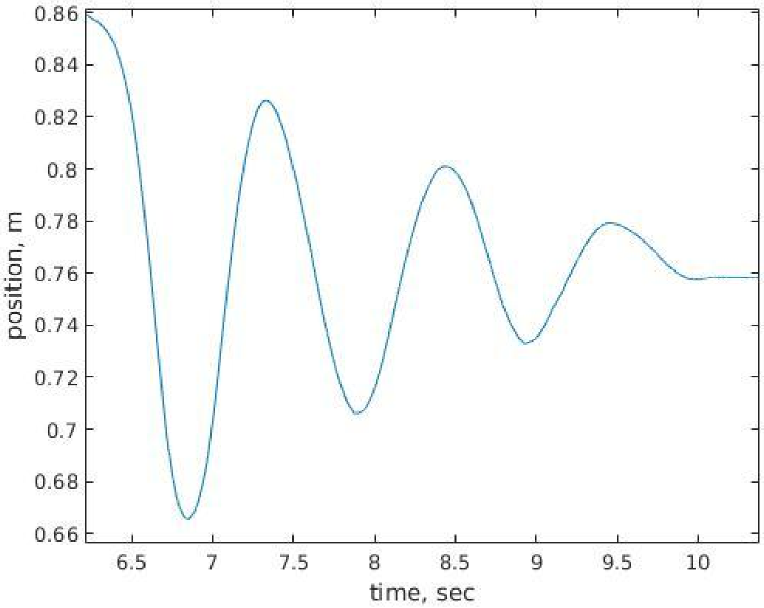


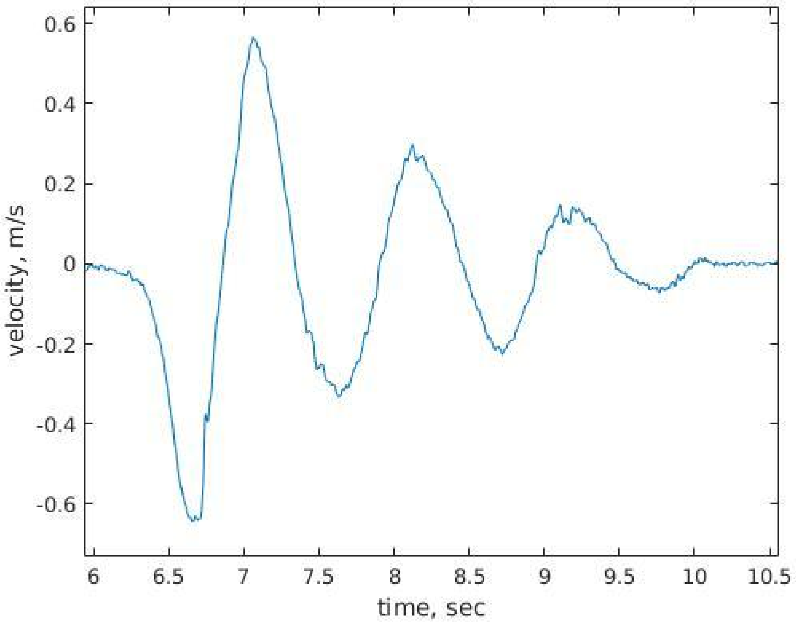
$$F_{motor} = K(x_d - x) - B\dot{x} \quad \tau_{motor} = J^T(F_{motor})$$

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -(M(q)+I_r)^{-1}J^TKJ & -(M(q)+I_r)^{-1}(D+J^TBJ) \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ (M(q)+I_r)^{-1}J^TKJ \end{bmatrix} q_d$$

$$\dot{x} = \begin{bmatrix} 0 & J \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + [0]q_d$$

Baxter Research Robot: Real Data





Baxter Research Robot: LQR Design

- What if we want to specify performance criteria for the states?
  - Max actuator force
  - Stroke Length
- Use LQR to optimize performance and control effort

$$\min_{\mathbf{u}(t)} V = \int_{\tau=t}^{\tau=T} \left(\mathbf{x}^t \mathbf{Q} \mathbf{x} + \mathbf{u}^t \mathbf{R} \mathbf{u} \right) d\tau$$

Baxter Research Robot: LQR Design

- Bryson's Rule

$$Q = \begin{bmatrix} \frac{\alpha_1^2}{(x_1)^2_{\max}} & & & \\ & \frac{\alpha_2^2}{(x_2)^2_{\max}} & & \\ & & \ddots & \\ & & & \frac{\alpha_n^2}{(x_n)^2_{\max}} \end{bmatrix}$$

$$R = \rho \begin{bmatrix} \frac{\beta_1^2}{(u_1)^2_{\max}} & & & \\ & \frac{\beta_2^2}{(u_2)^2_{\max}} & & \\ & & \ddots & \\ & & & \frac{\beta_m^2}{(u_m)^2_{\max}} \end{bmatrix}$$

- Baxter system criteria:
  - x1max (x position) = 0.5214 m
  - u1max (shoulder torque) = 50 Nm
  - u2max(elbow torque) = 15 Nm
  - u3max(wrist torque) = 15 Nm

Baxter Research Robot: LQR Design

Q =

3.6787	0	0	0	0	0
0	0.0100	0	0	0	0
0	0	0.0100	0	0	0
0	0	0	0.0100	0	0
0	0	0	0	0.0100	0
0	0	0	0	0	0.0100

R =

0.0004	0	0
0	0.0044	0
0	0	0.0044

Expensive vs Cheap Control

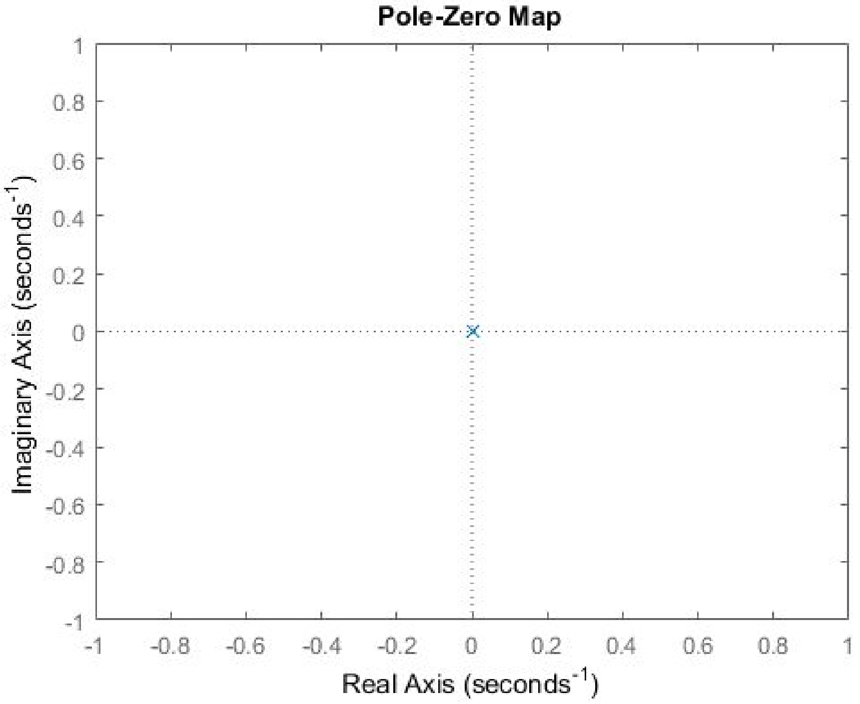
p = 1 (equal weighting)

p = 1e6 (expensive control)

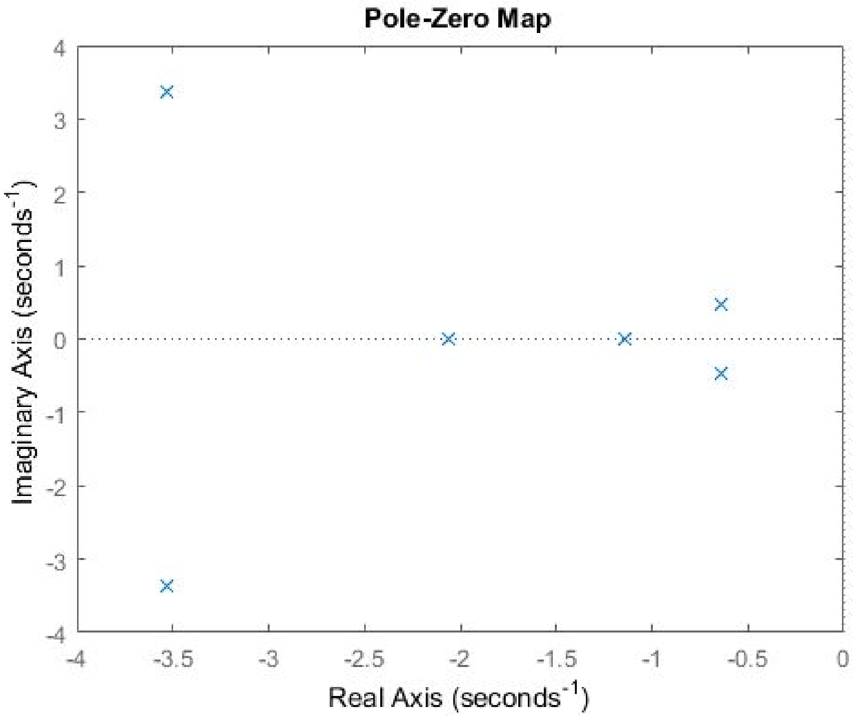
p = 1e-6 (cheap control)

Baxter Research Robot: LQR Design

Open-Loop

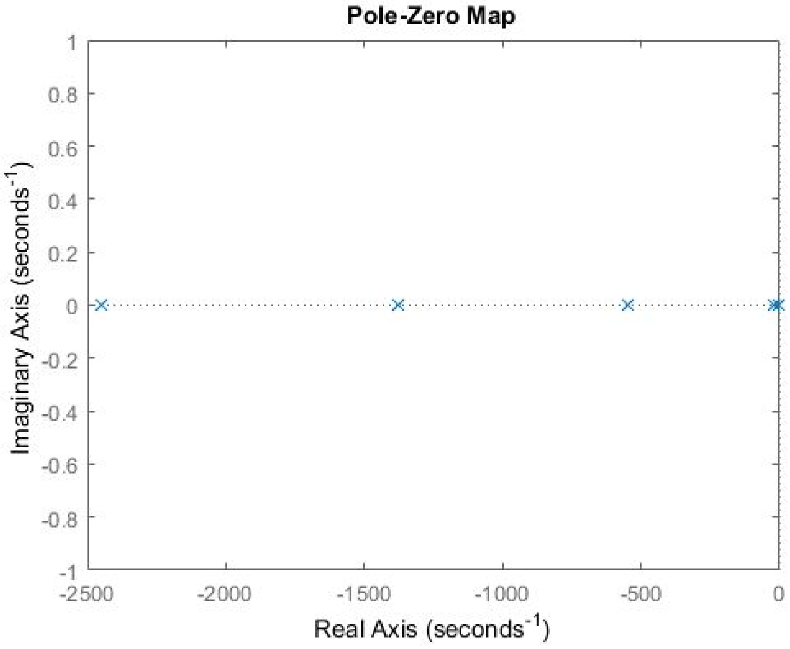


Closed Loop: Equal Weighting

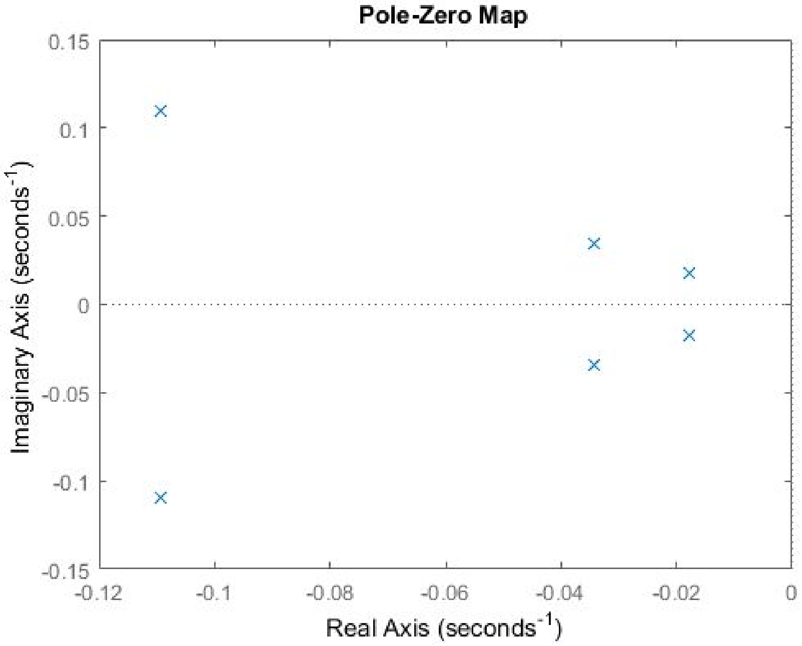


Baxter Research Robot: LQR Design

Closed Loop: Cheap



Closed Loop: Expensive

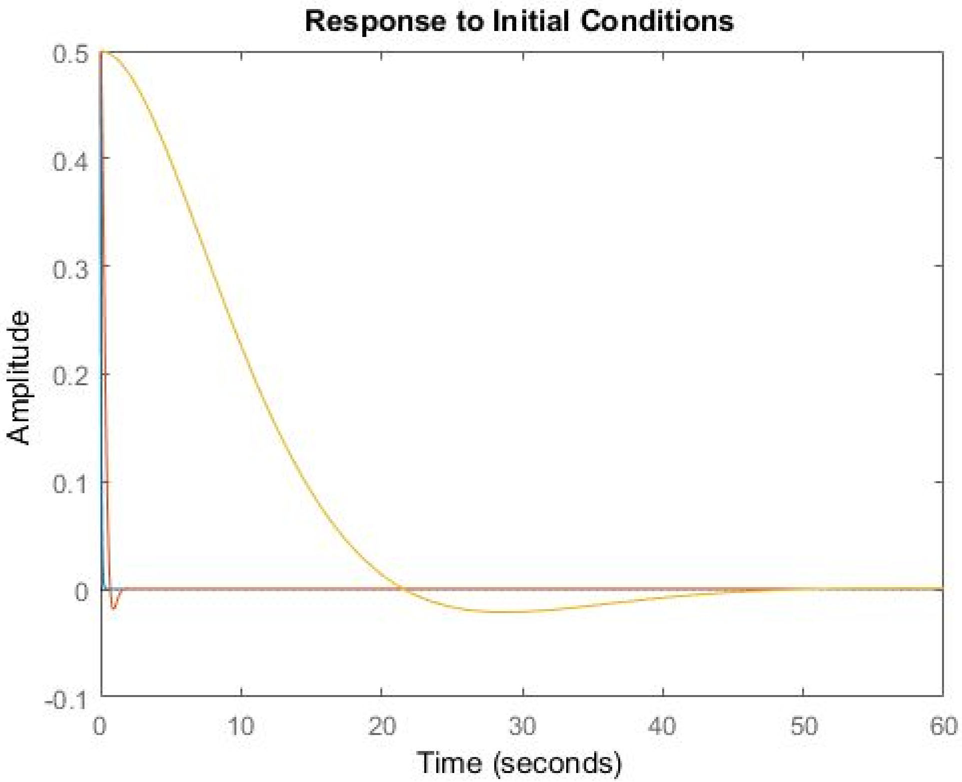


Baxter Research Robot: LQR Design

blue - cheap

orange - expensive

yellow - equal



Baxter Research Robot: LQR Discussion

- Expensive control is realistic given good performance results and less control (actuator effort)
- Choosing relative weighting of states/inputs may be significant
- Can we design performance criteria around impact collision response?
- Can we combine impedance into cost function for LQR design?

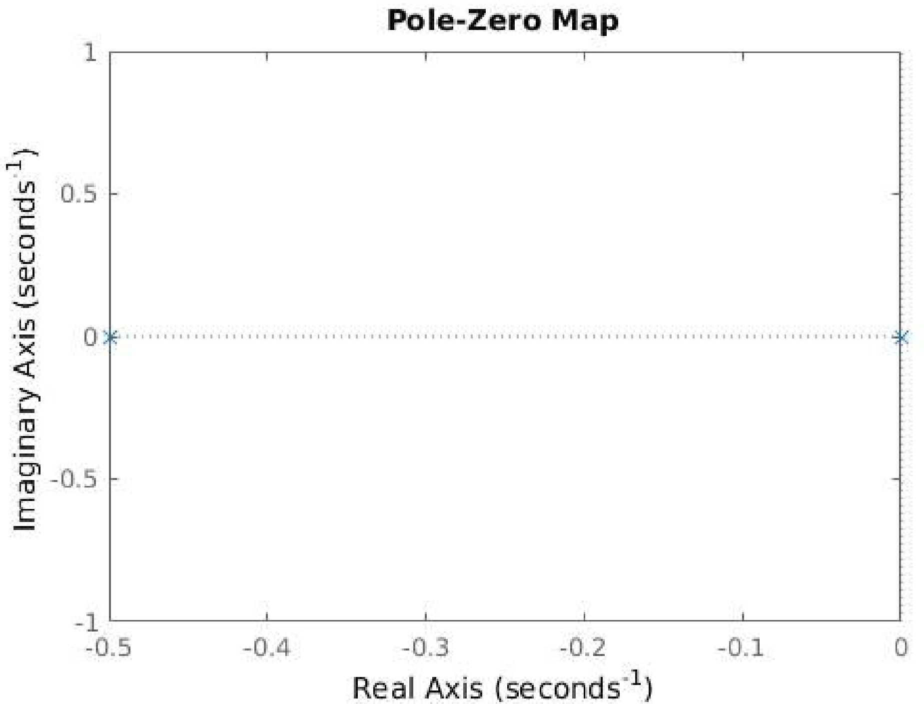
Dexter LQR Design

Criteria:
Max Thrust=10 Nm
Max Stroke length=10 in
Different Designs:

- Cheap
- Expensive
- Equal
- Weighting xa vs x1

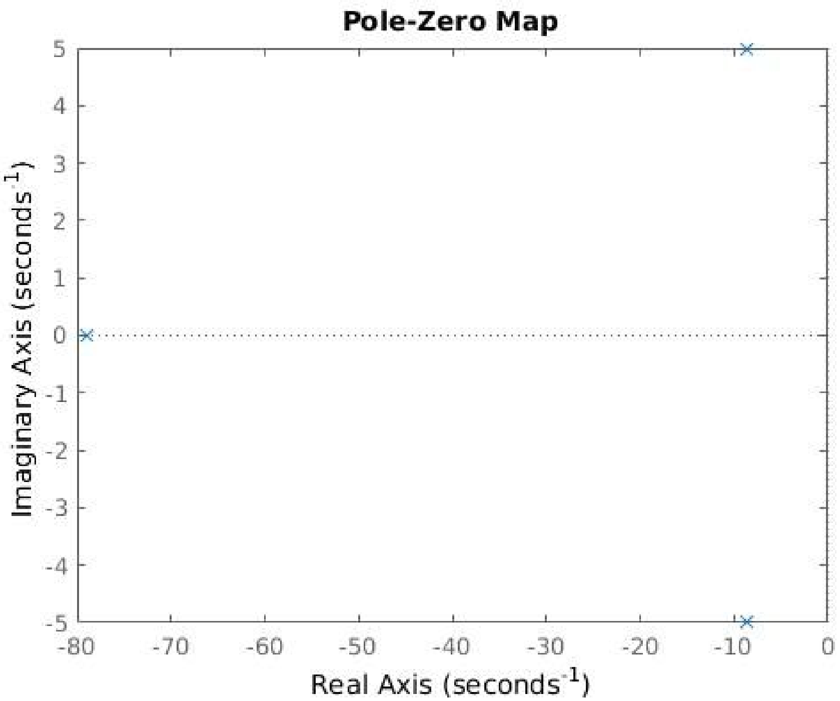
Dexter LQR Design

Open-Loop

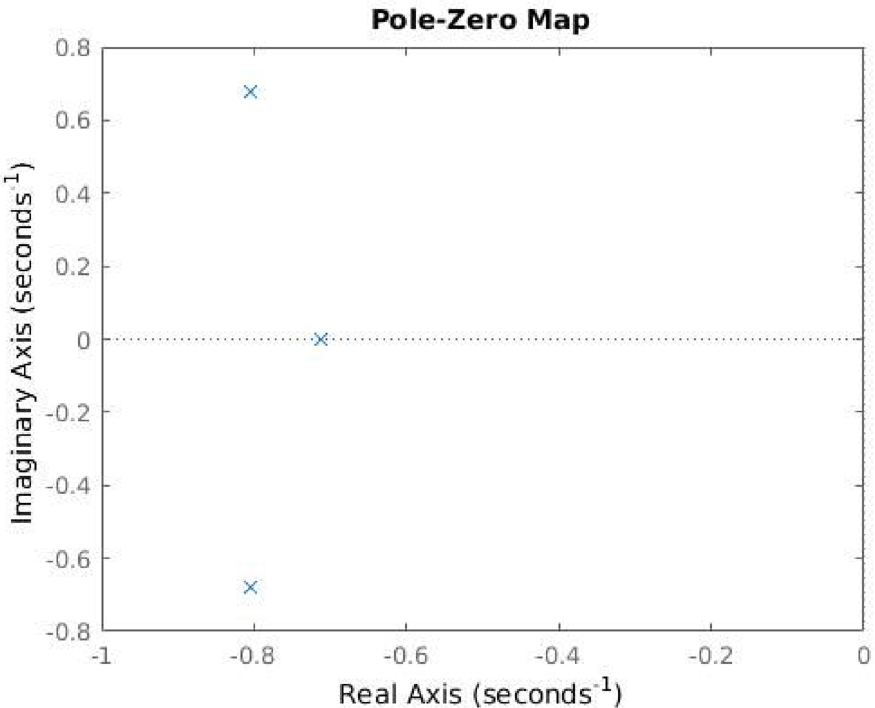


Dexter LQR Design

Cheap

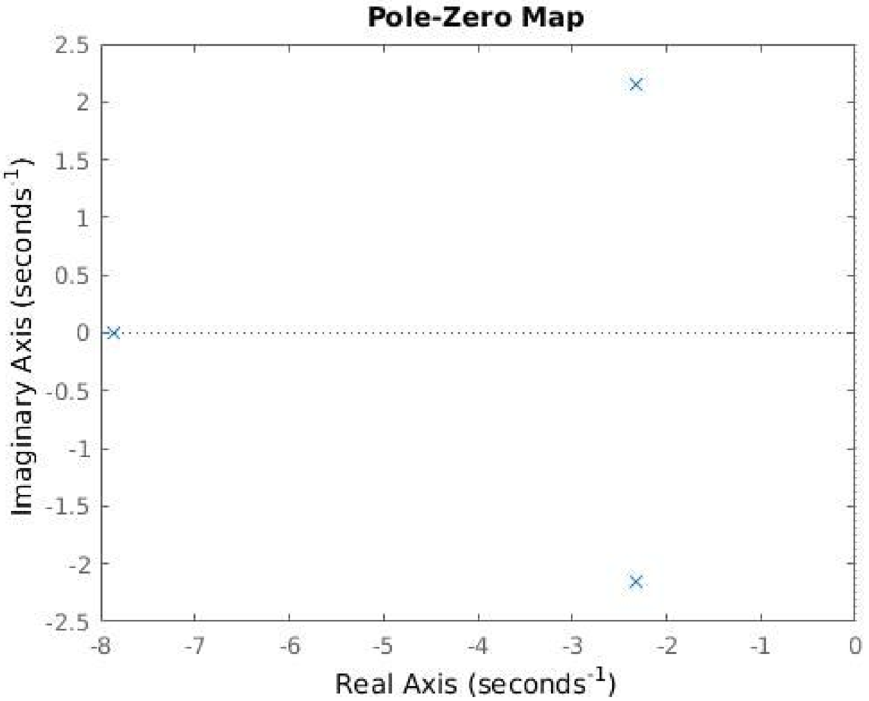


Expensive

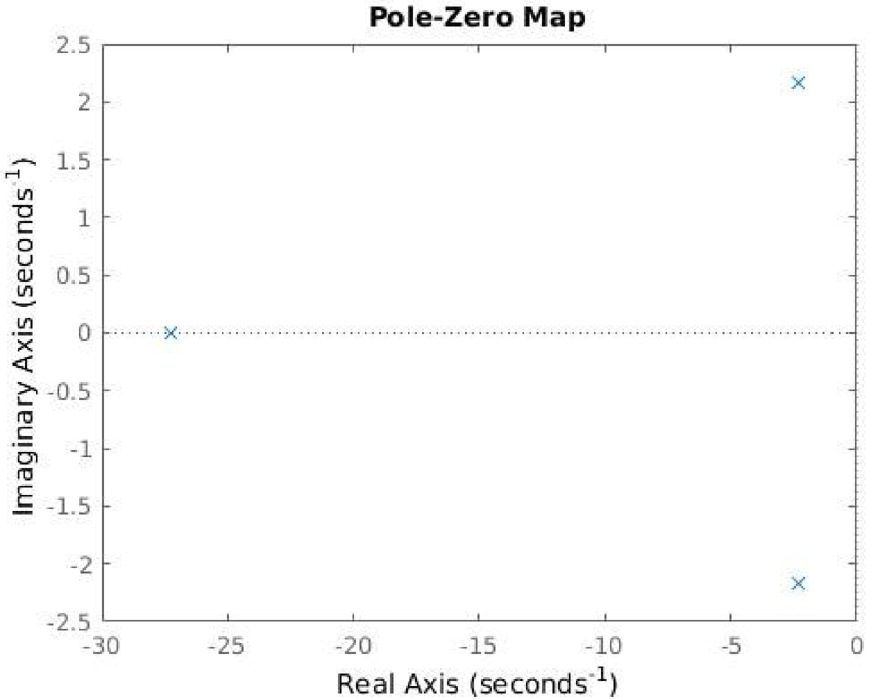


Dexter LQR Design

Equal



Diff Weights



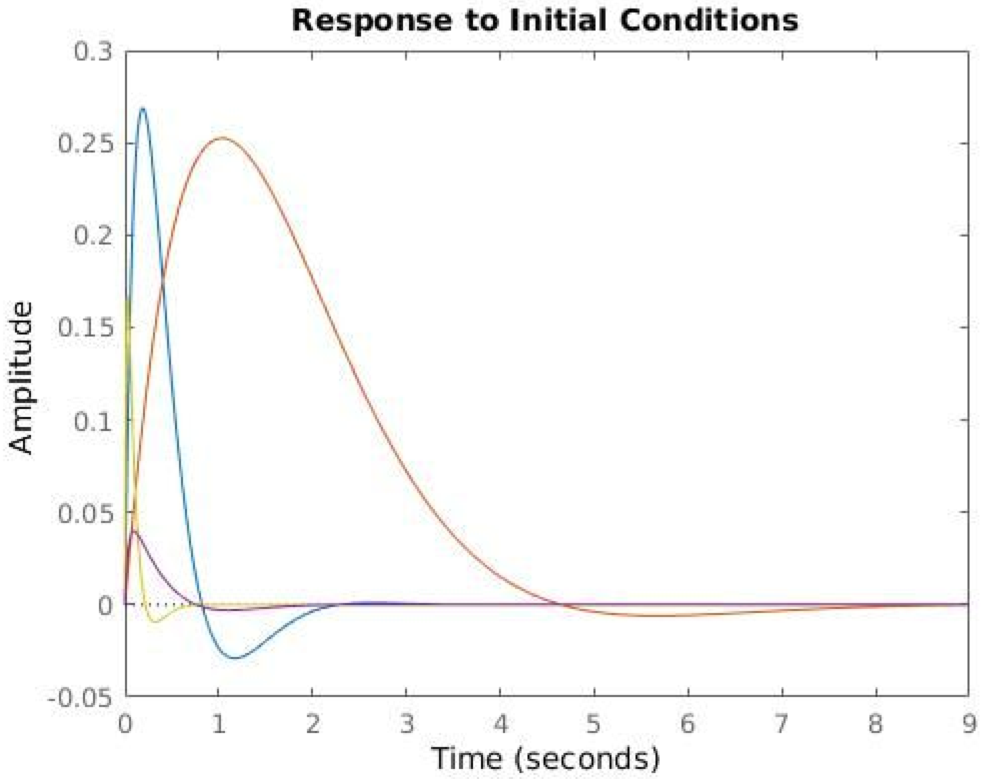
Dexter LQR Design

yellow - cheap

red - expensive

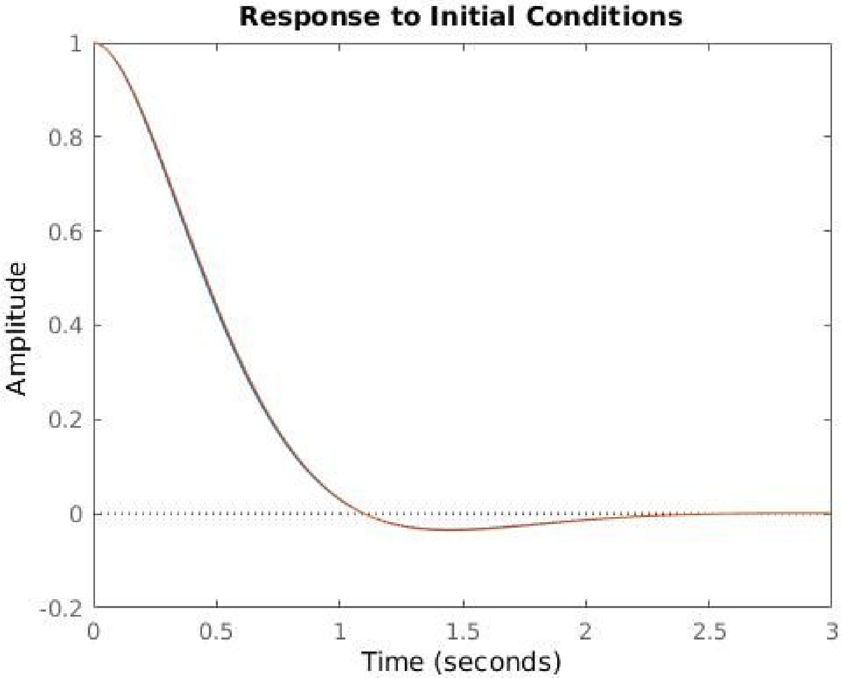
blue - equal

blue- different weighting for state_variables

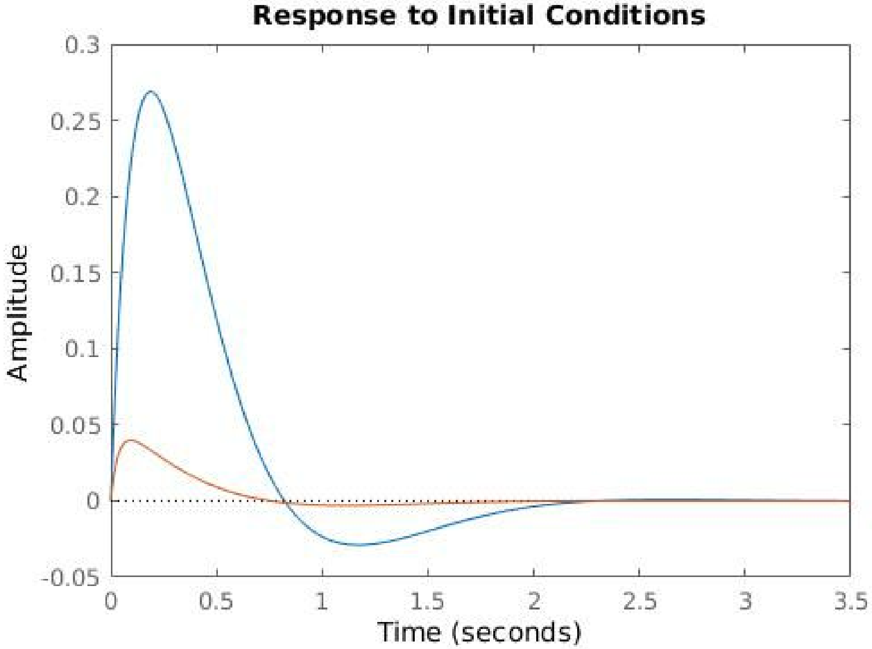


Dexter LQR Design

x1



xa



Future Work

Dexter

- Implement the MIMO system on the raft. Determine how robust it is to the nonlinear damping of the surrounding fluid

Baxter

- Determine how delays in system affect achievable range of impedances.

Appendix: Series Elastic Actuators: Open loop model

Equations of motion

$$M(q)\ddot{q} + C\dot{q} = \tau_{measured} + \tau_{ext}$$

$$I_r\ddot{\theta} + D\dot{\theta} = \tau_{motor} - \tau_{measured}$$

$$\tau_{measured} = K_{SEA}(\theta - q)$$

State space representation

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ -M^{-1}K_{SEA} & -M^{-1}C & M^{-1}K_{SEA} & 0 \\ 0 & 0 & 0 & I \\ {I_r}^{-1}K_{SEA} & 0 & -{I_r}^{-1}K_{SEA} & -{I_r}^{-1}D \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ {I_r}^{-1} \end{bmatrix}\tau_{motor}$$

$$\dot{x} = [0\ J\ 0\ 0]\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + [0]\tau_{motor}$$

Appendix: Baxter Research Robot: Real System

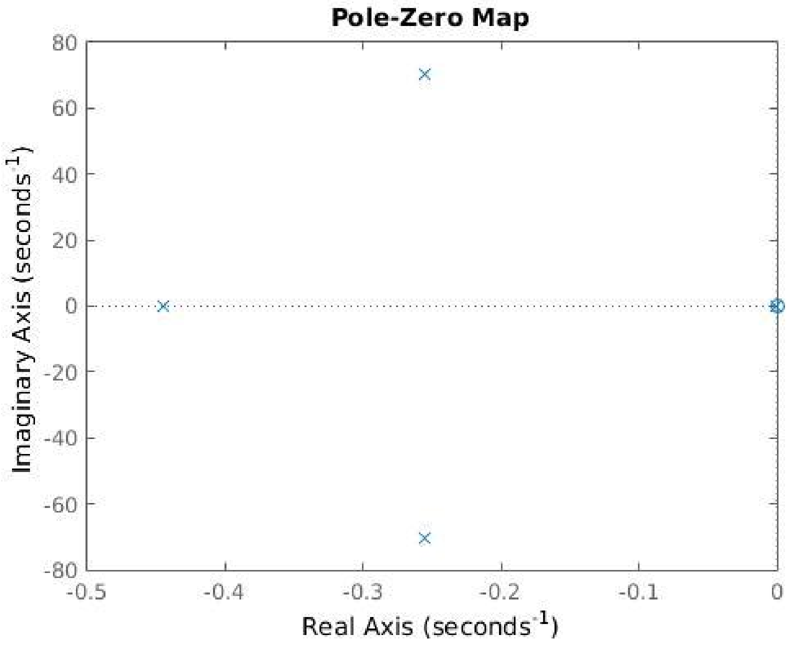
Can achieve a fairly broad range of impedances using this approach.

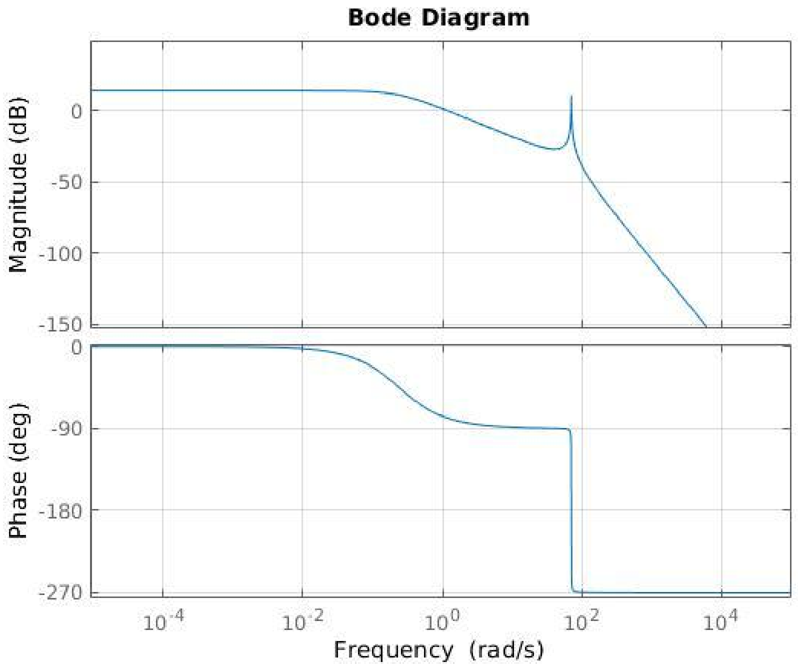
There is a limit to how high the gains can be turned up that is not accounted for in this “simplified” model.

two likely reasons:

1. Delay in the system→ not a “state space” problem
2. The model does not account for all the dynamics of the system

Appendix: Single SEA





- Acts like a second order model until about 100 rad/s (far above Baxter's operating frequency)
- The second pair of poles not accounted for in the simplified model can still be driven into the RHP at high gains

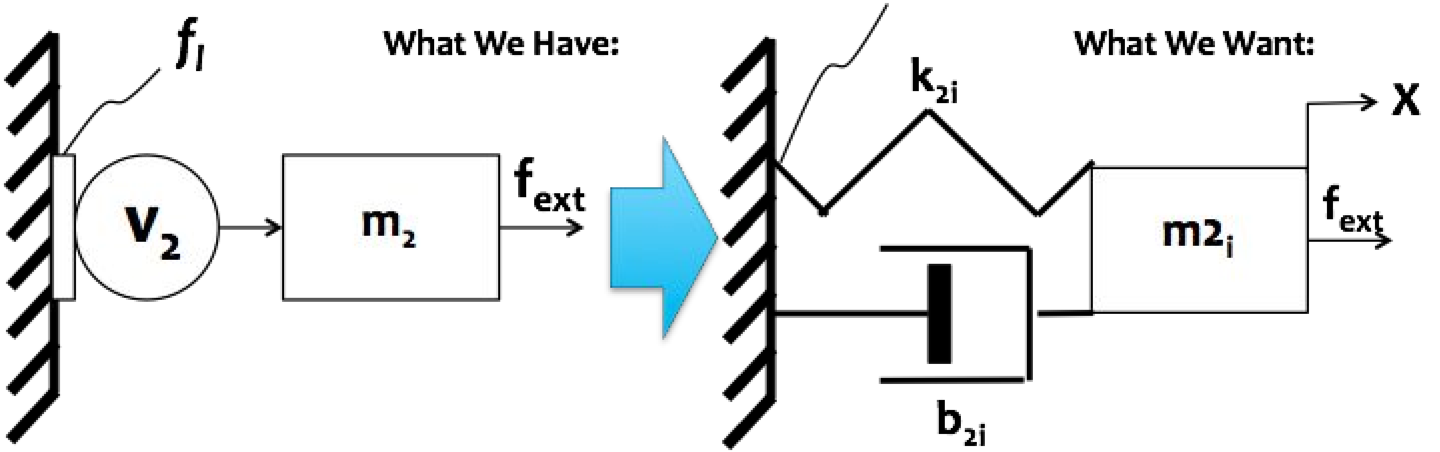
Appendix: Series Elastic Actuators: Closed loop model

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ -M^{-1}K_{SEA} & -M^{-1}C & M^{-1}K_{SEA} & 0 \\ 0 & 0 & 0 & I \\ I_r{}^{-1}K_{SEA} - I_r{}^{-1}J^T KJ & -I_r{}^{-1}J^T BJ & -I_r{}^{-1}K_{SEA} & -I_r{}^{-1}D \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ I_r{}^{-1}J^T KJ \end{bmatrix} q_d$$

$$\dot{x} = \begin{bmatrix} 0 & J & 0 & 0 \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + [0]q_d$$

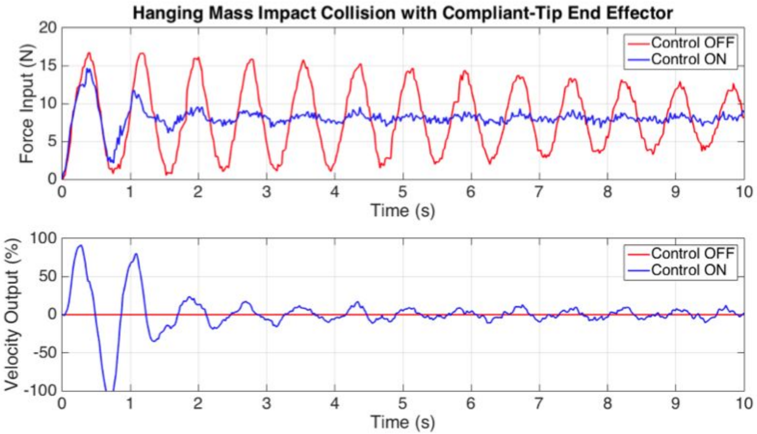
Turning a Non-Backdrivable Linear Actuator Into a Passive System

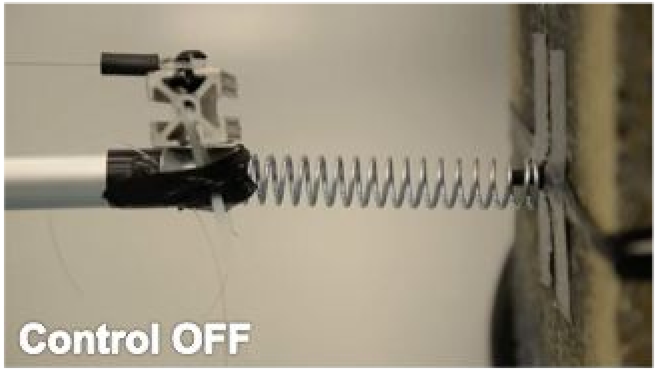
- Creating a controller for the linear actuator based desired impedance parameters allows for:
  - A closed-loop system that promotes robust and stable interactions due to passivity
  - Achievable design constraints (e.g., Peak impact force, Settling time)
  - Definitive impedance values for Baxter to reproduce

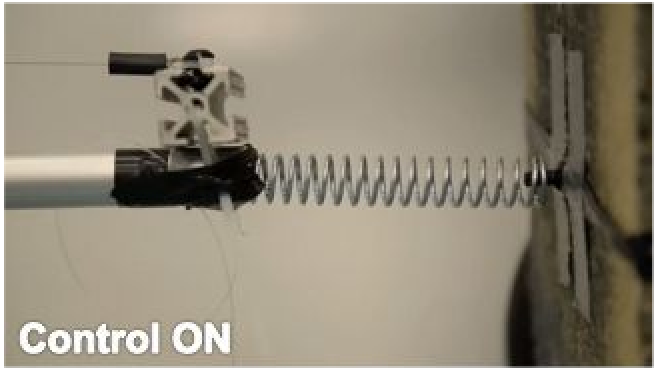


Determining Desirable Impedance Characteristics

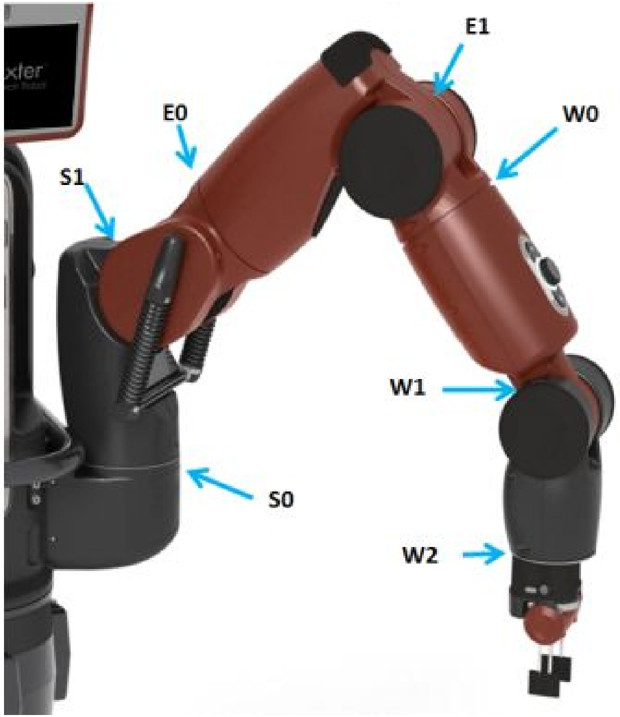
- A **reduction in peak force** provides a buffer for a controller to react to any unforeseen collisions
  - Alleviates significant risks for valuable equipment on hard-to-reach AUVs
- A **sharp reduction in settling time** suggests a smaller influence by external disturbances, such as underwater currents
  - Minimizes unpredictable disturbances during any on going contact tasks
- **Feed impedance values to Baxter!**







Baxter Research Robot



For the purposes of the experiment, Baxter was constrained to planar motion by only allowing joints S1, E1, and W1 to move.

Baxter Research Robot: Open loop model

Neglecting SEA dynamics, Equations of Motion

$$(M(q) + I_r)\ddot{q} + C(\dot{q}, q) + D\dot{q} + g(q) = \tau_{motors}$$

Simplifies to

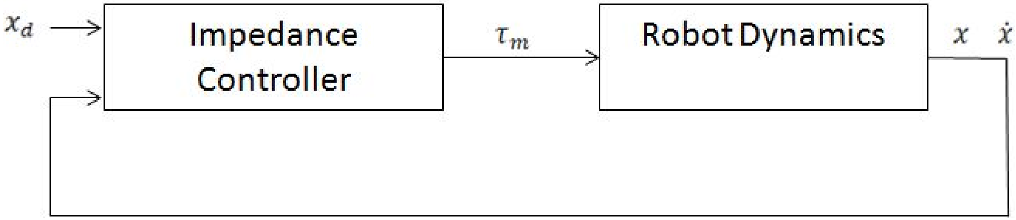
$$(M(q) + I_r)\ddot{q} + D\dot{q} = \tau_{motors}$$

State space representation

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & -(M(q)+I_r)^{-1}D \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ (M(q)+I_r)^{-1} \end{bmatrix}\tau_{motors}$$

$$\dot{x} = [0 \; I]\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + [0]\tau_{motors}$$

Baxter Research Robot: Closed loop model

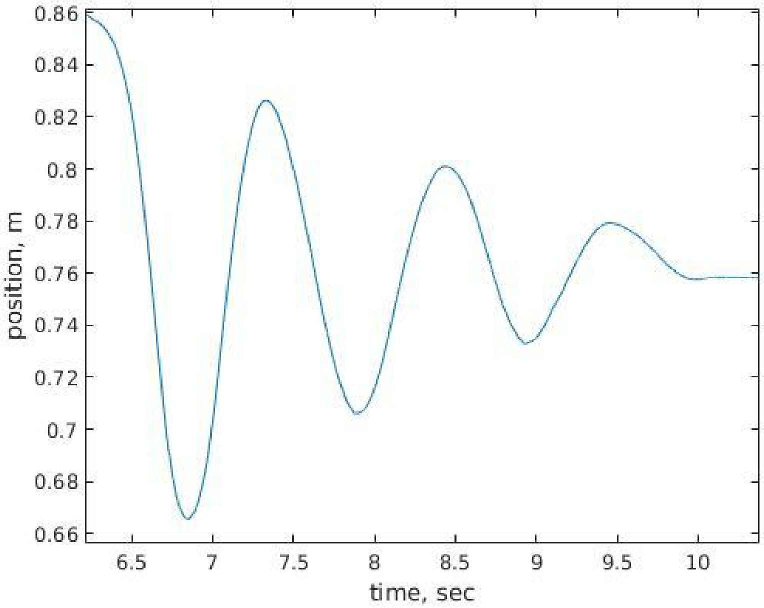


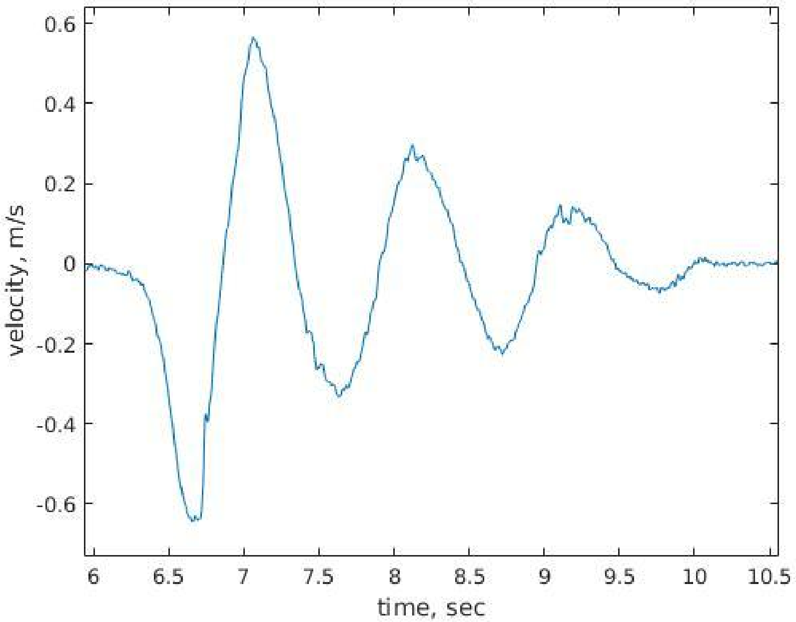
$$F_{motor} = K(x_d - x) - B\dot{x} \quad \tau_{motor} = J^T(F_{motor})$$

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -(M(q)+I_r)^{-1}J^TKJ & -(M(q)+I_r)^{-1}(D+J^TBJ) \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ (M(q)+I_r)^{-1}J^TKJ \end{bmatrix} q_d$$

$$\dot{x} = \begin{bmatrix} 0 & J \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \end{bmatrix} + [0]q_d$$

Baxter Research Robot: Real Data





Baxter Research Robot: LQR Design

- What if we want to specify performance criteria for the states?
  - Max actuator force
  - Stroke Length
- Use LQR to optimize performance and control effort

$$\min_{\mathbf{u}(t)} V = \int_{\tau=t}^{\tau=T} \left(\mathbf{x}^t \mathbf{Q} \mathbf{x} + \mathbf{u}^t \mathbf{R} \mathbf{u} \right) d\tau$$

Baxter Research Robot: LQR Design

- Bryson's Rule

$$Q = \begin{bmatrix} \frac{\alpha_1^2}{(x_1)^2_{\max}} & & & \\ & \frac{\alpha_2^2}{(x_2)^2_{\max}} & & \\ & & \ddots & \\ & & & \frac{\alpha_n^2}{(x_n)^2_{\max}} \end{bmatrix} \qquad R = \rho \begin{bmatrix} \frac{\beta_1^2}{(u_1)^2_{\max}} & & & \\ & \frac{\beta_2^2}{(u_2)^2_{\max}} & & \\ & & \ddots & \\ & & & \frac{\beta_m^2}{(u_m)^2_{\max}} \end{bmatrix}$$

- Baxter system criteria:
  - x1max (x position) = 0.5214 m
  - u1max (shoulder torque) = 50 Nm
  - u2max(elbow torque) = 15 Nm
  - u3max(wrist torque) = 15 Nm

Baxter Research Robot: LQR Design

Q =

$$\begin{matrix} 3.6787 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0100 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0100 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0100 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0100 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0100 \end{matrix}$$

R =

$$\begin{matrix} 0.0004 & 0 & 0 \\ 0 & 0.0044 & 0 \\ 0 & 0 & 0.0044 \end{matrix}$$

Expensive vs Cheap Control

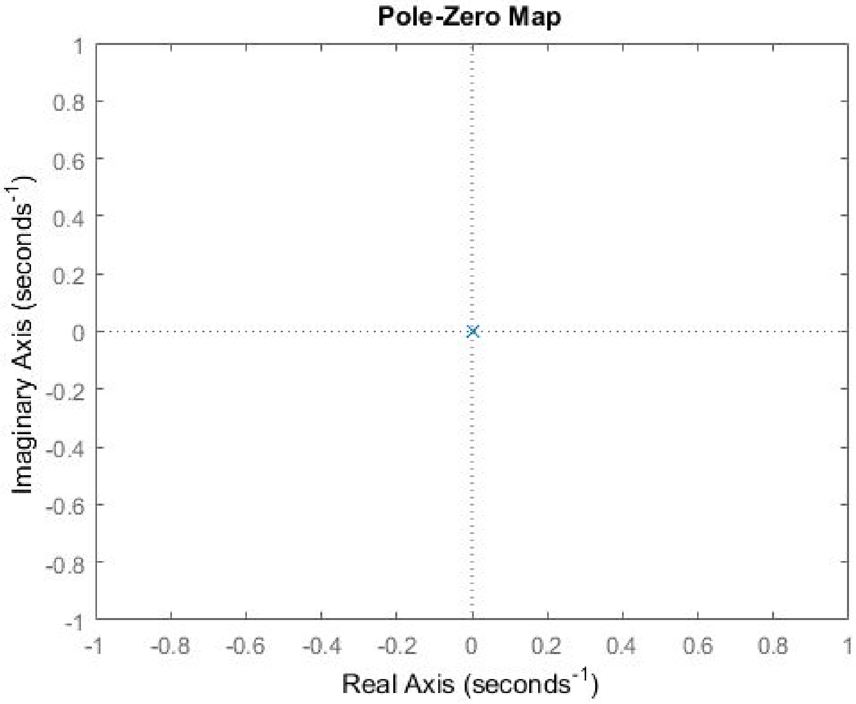
p = 1 (equal weighting)

p = 1e6 (expensive control)

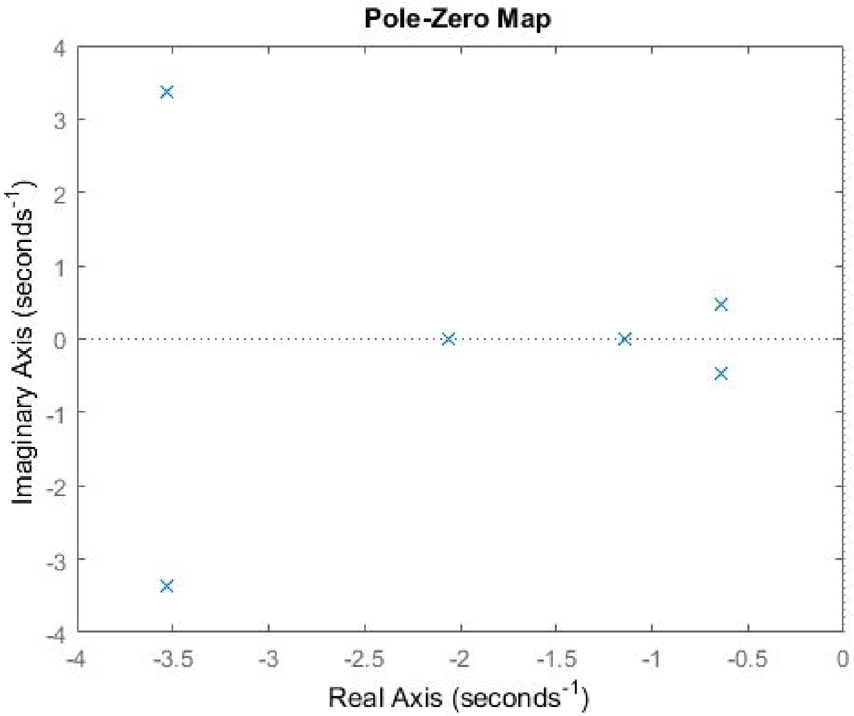
p = 1e-6 (cheap control)

Baxter Research Robot: LQR Design

Open-Loop

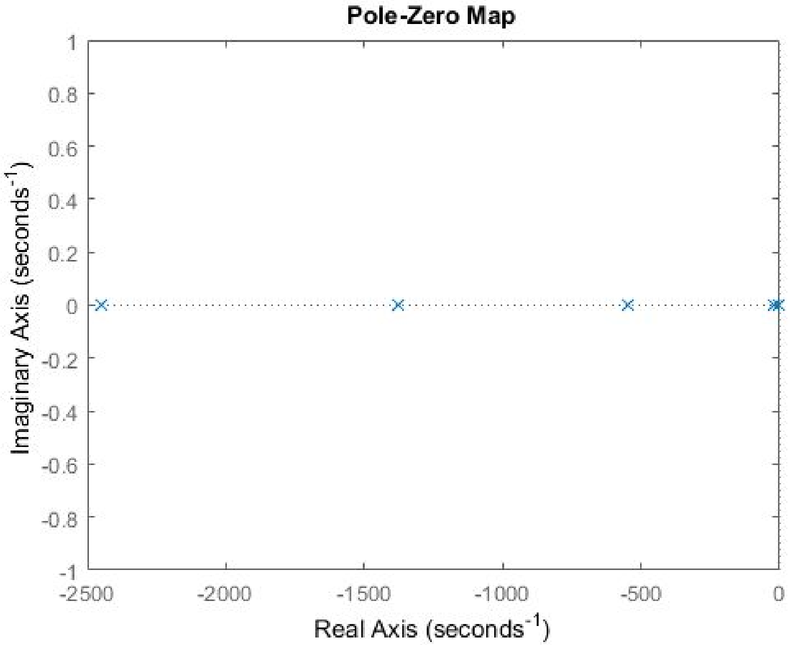


Closed Loop: Equal Weighting

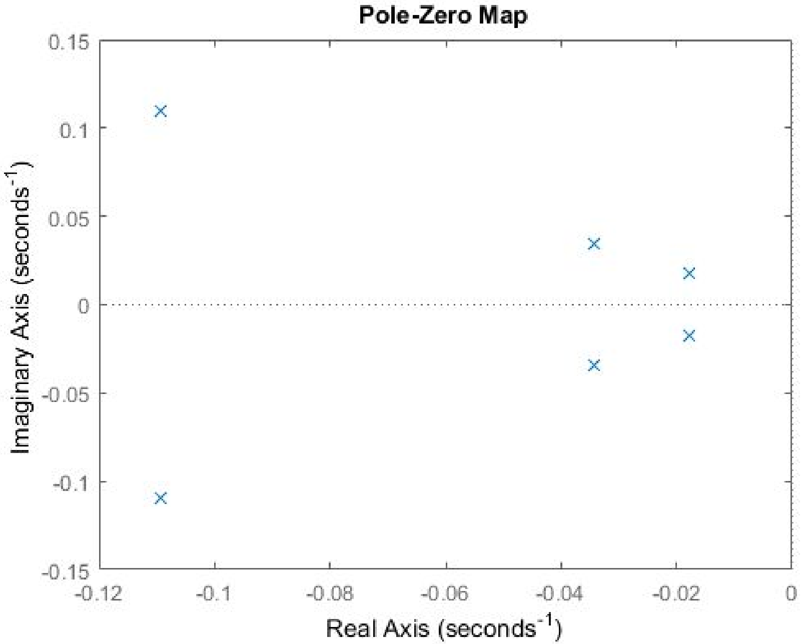


Baxter Research Robot: LQR Design

Closed Loop: Cheap



Closed Loop: Expensive

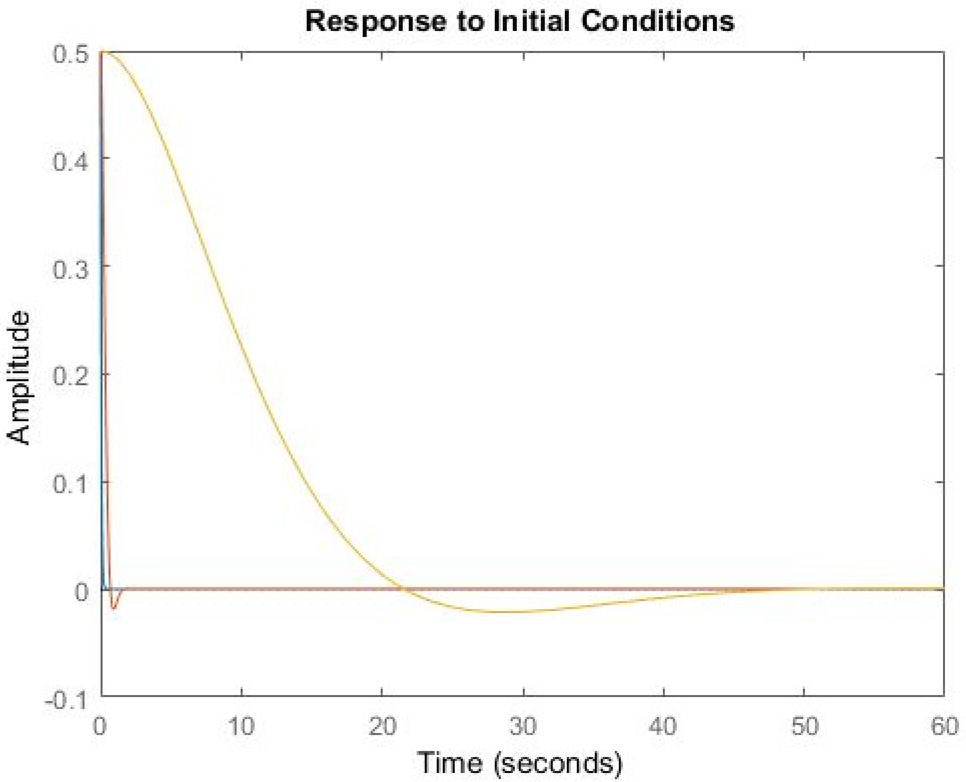


Baxter Research Robot: LQR Design

blue - cheap

orange - expensive

yellow - equal



Baxter Research Robot: LQR Discussion

- Expensive control is realistic given good performance results and less control (actuator effort)
- Choosing relative weighting of states/inputs may be significant
- Can we design performance criteria around impact collision response?
- Can we combine impedance into cost function for LQR design?

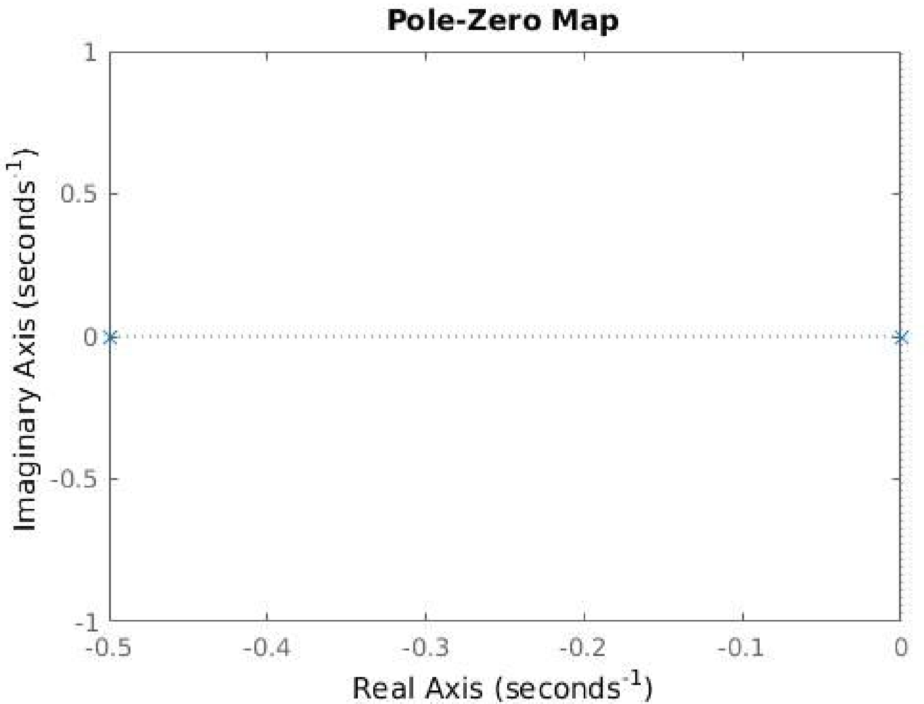
Dexter LQR Design

Criteria:
Max Thrust=10 Nm
Max Stroke length=10 in
Different Designs:

- Cheap
- Expensive
- Equal
- Weighting xa vs x1

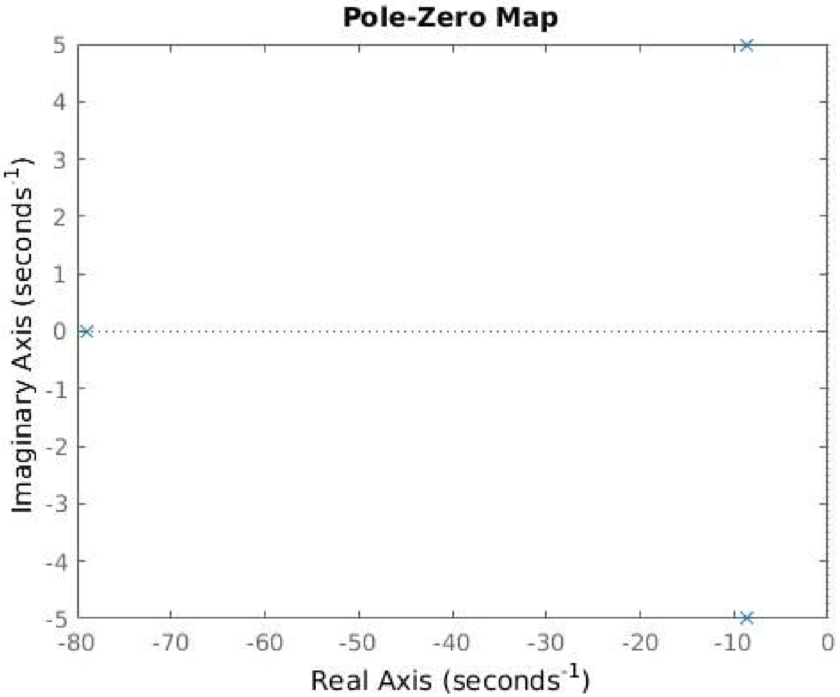
Dexter LQR Design

Open-Loop

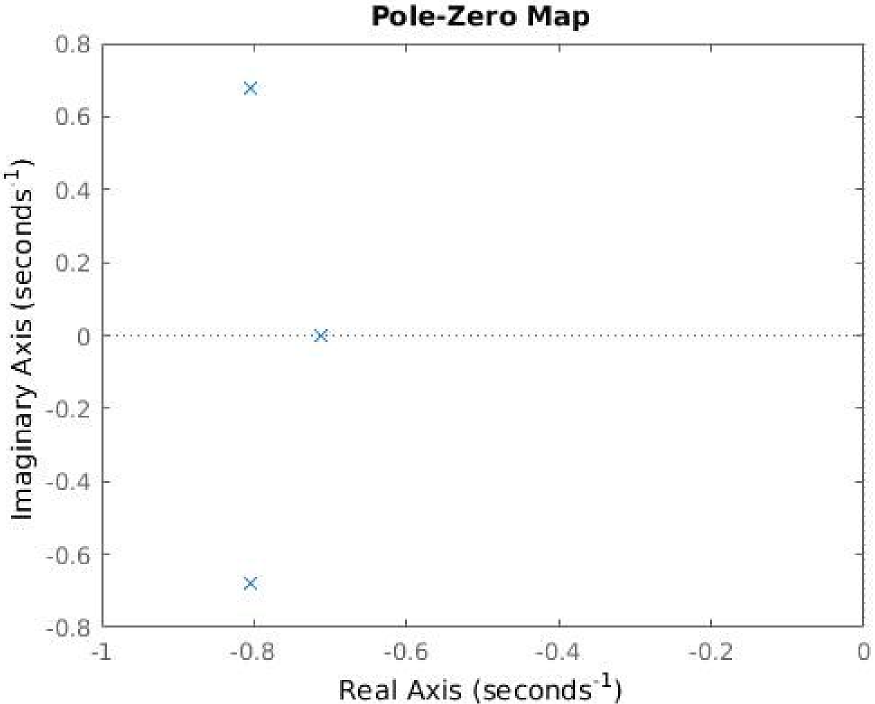


Dexter LQR Design

Cheap

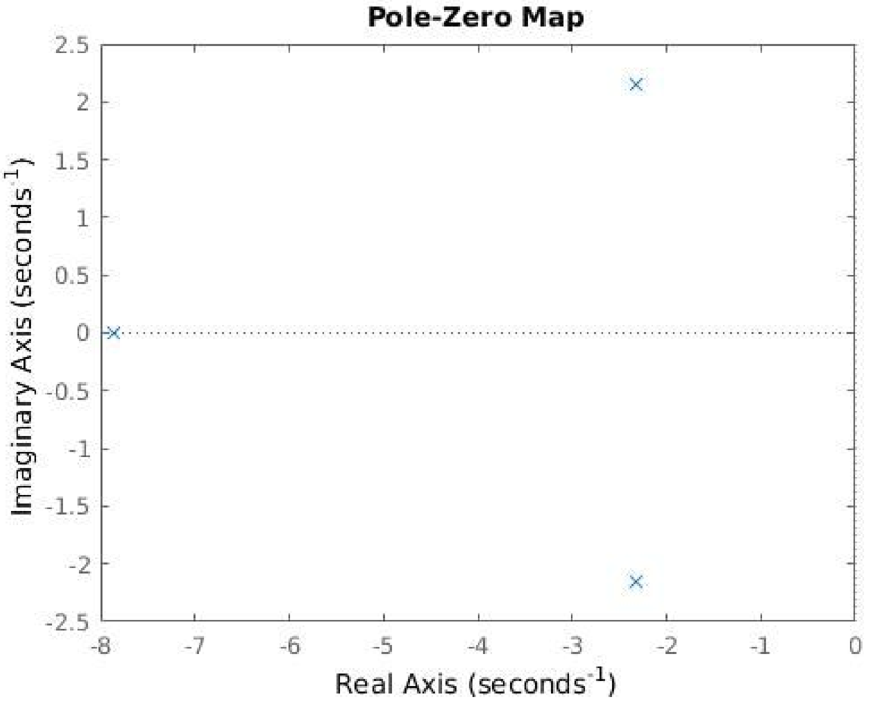


Expensive

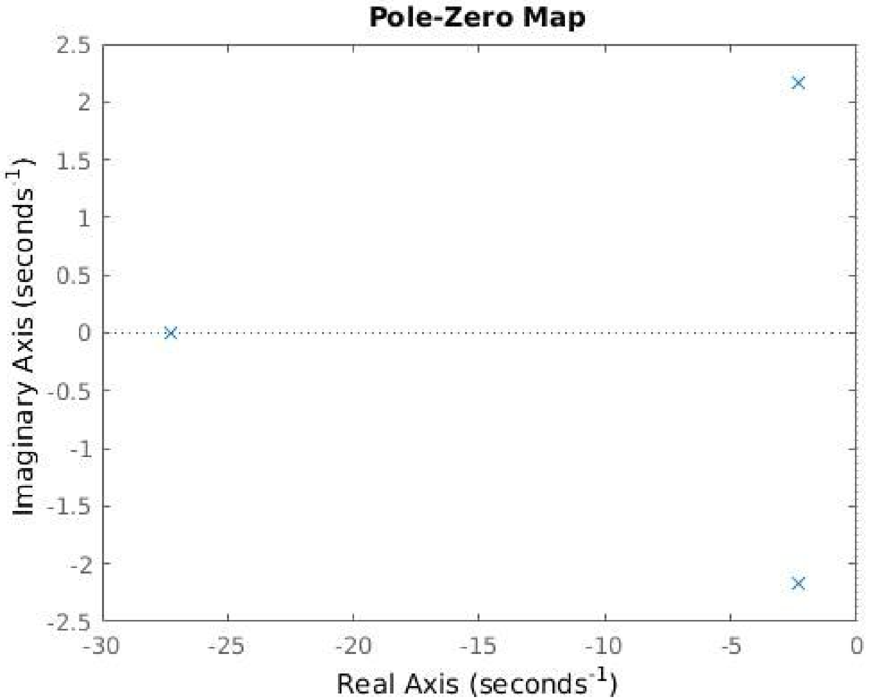


Dexter LQR Design

Equal



Diff Weights



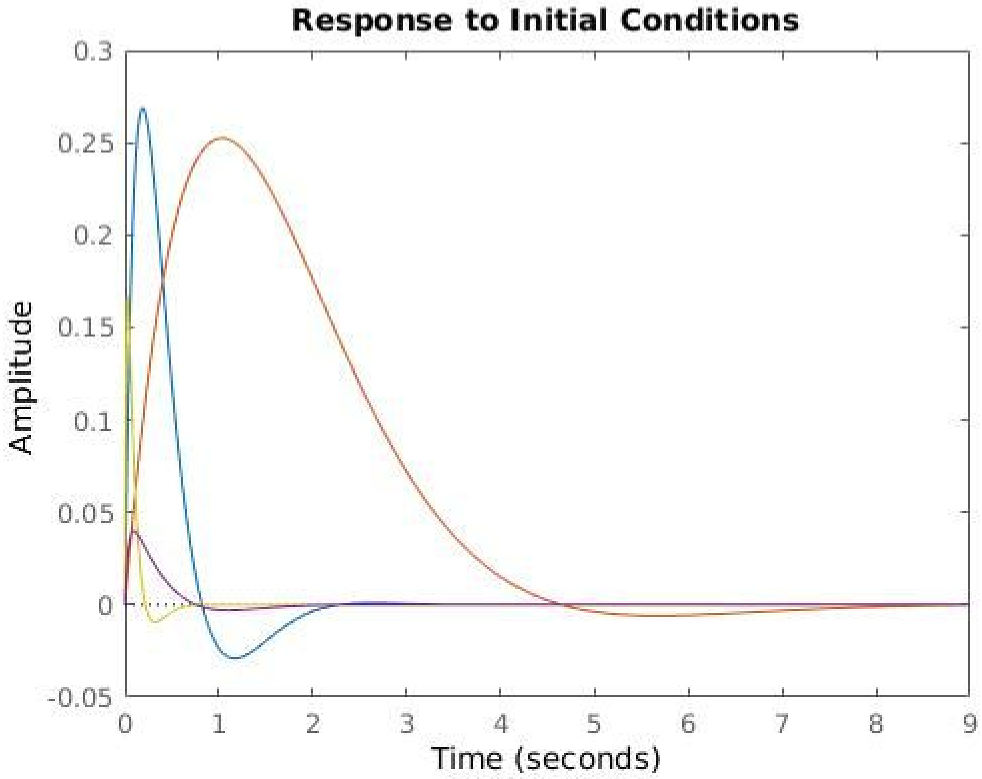
Dexter LQR Design

yellow - cheap

red - expensive

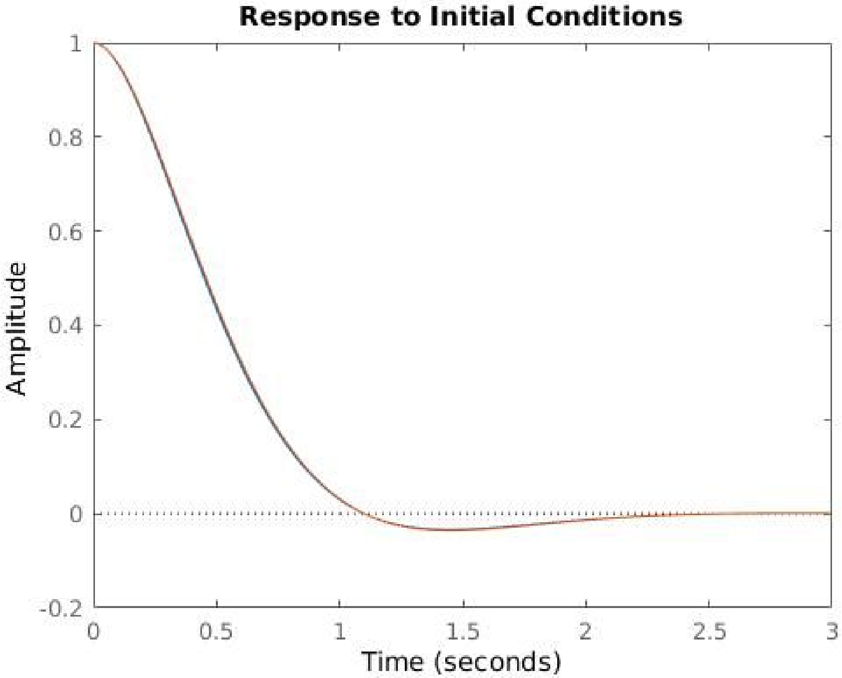
blue - equal

blue- different weighting for state_variables

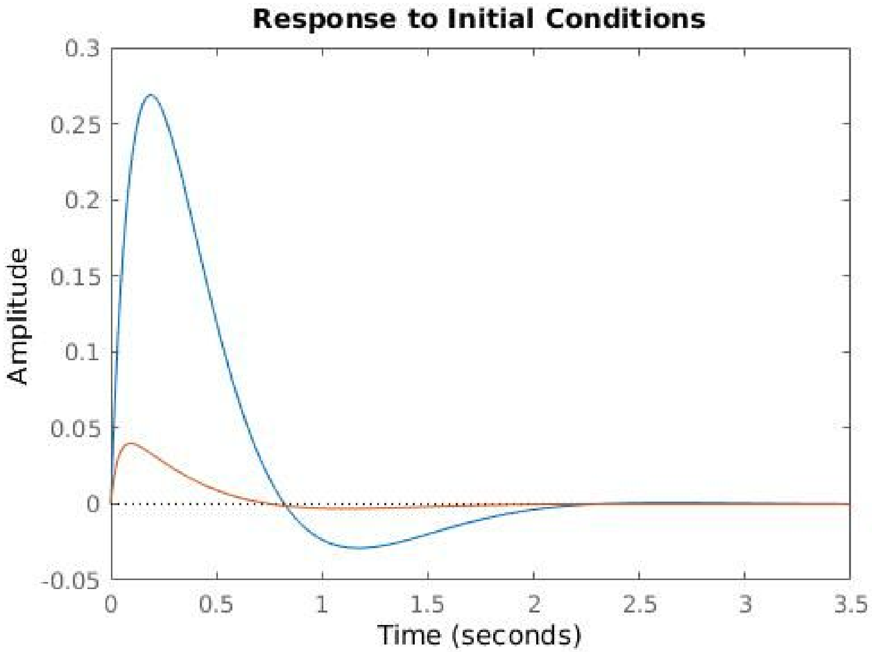


Dexter LQR Design

x1



xa



Future Work

Dexter

- Implement the MIMO system on the raft. Determine how robust it is to the nonlinear damping of the surrounding fluid

Baxter

- Determine how delays in system affect achievable range of impedances.

Appendix: Series Elastic Actuators: Open loop model

Equations of motion

$$M(q)\ddot{q} + C\dot{q} = \tau_{measured} + \tau_{ext}$$

$$I_r\ddot{\theta} + D\dot{\theta} = \tau_{motor} - \tau_{measured}$$

$$\tau_{measured} = K_{SEA}(\theta - q)$$

State space representation

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ -M^{-1}K_{SEA} & -M^{-1}C & M^{-1}K_{SEA} & 0 \\ 0 & 0 & 0 & I \\ I_r{}^{-1}K_{SEA} & 0 & -I_r{}^{-1}K_{SEA} & -I_r{}^{-1}D \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ I_r{}^{-1} \end{bmatrix}\tau_{motor}$$

$$\dot{x} = [0\ J\ 0\ 0]\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + [0]\tau_{motor}$$

Appendix: Baxter Research Robot: Real System

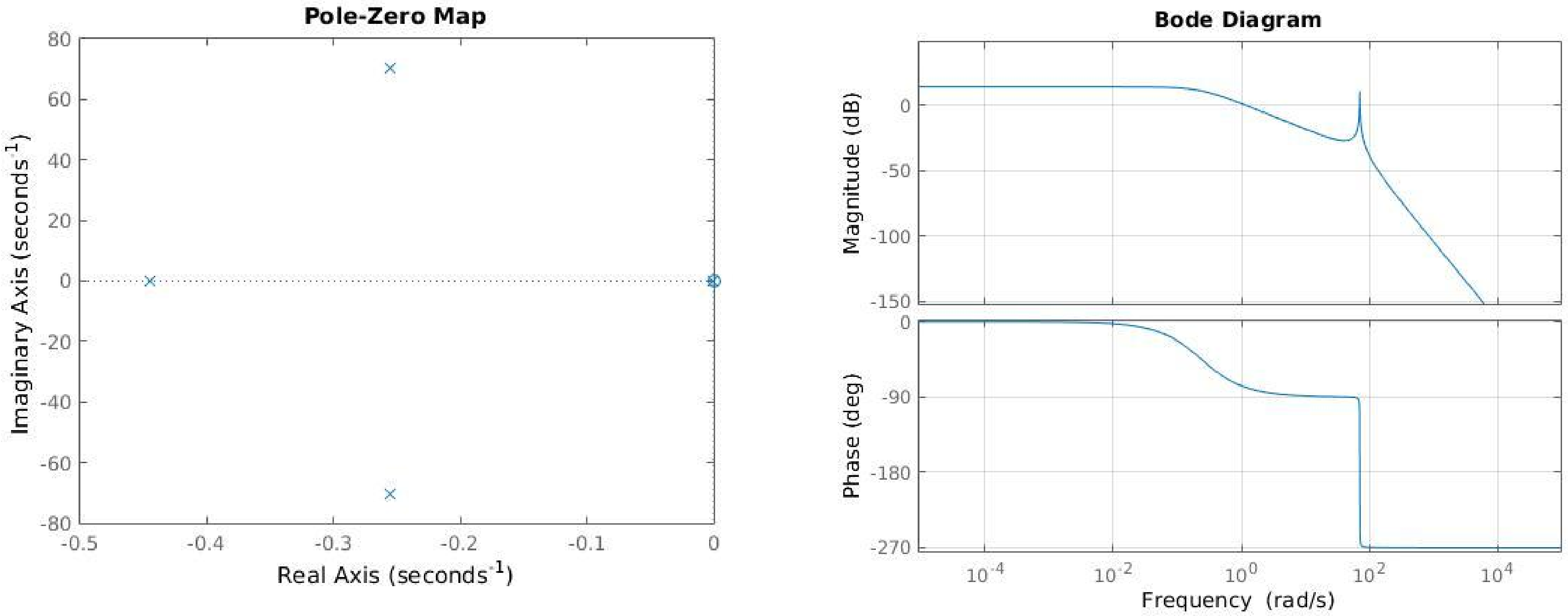
Can achieve a fairly broad range of impedances using this approach.

There is a limit to how high the gains can be turned up that is not accounted for in this “simplified” model.

two likely reasons:

1. Delay in the system→ not a “state space” problem
2. The model does not account for all the dynamics of the system

Appendix: Single SEA



- Acts like a second order model until about 100 rad/s (far above Baxter's operating frequency)
- The second pair of poles not accounted for in the simplified model can still be driven into the RHP at high gains

Appendix: Series Elastic Actuators: Closed loop model

$$\frac{d}{dt}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & I & 0 & 0 \\ -M^{-1}K_{SEA} & -M^{-1}C & M^{-1}K_{SEA} & 0 \\ 0 & 0 & 0 & I \\ I_r{}^{-1}K_{SEA} - I_r{}^{-1}J^T KJ & -I_r{}^{-1}J^T BJ & -I_r{}^{-1}K_{SEA} & -I_r{}^{-1}D \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ I_r{}^{-1}J^T KJ \end{bmatrix} q_d$$

$$\dot{x} = \begin{bmatrix} 0 & J & 0 & 0 \end{bmatrix}\begin{bmatrix} q \\ \dot{q} \\ \theta \\ \dot{\theta} \end{bmatrix} + [0] q_d$$