Implementing Adaptive RLS for Payload Agnostic Input Shaping

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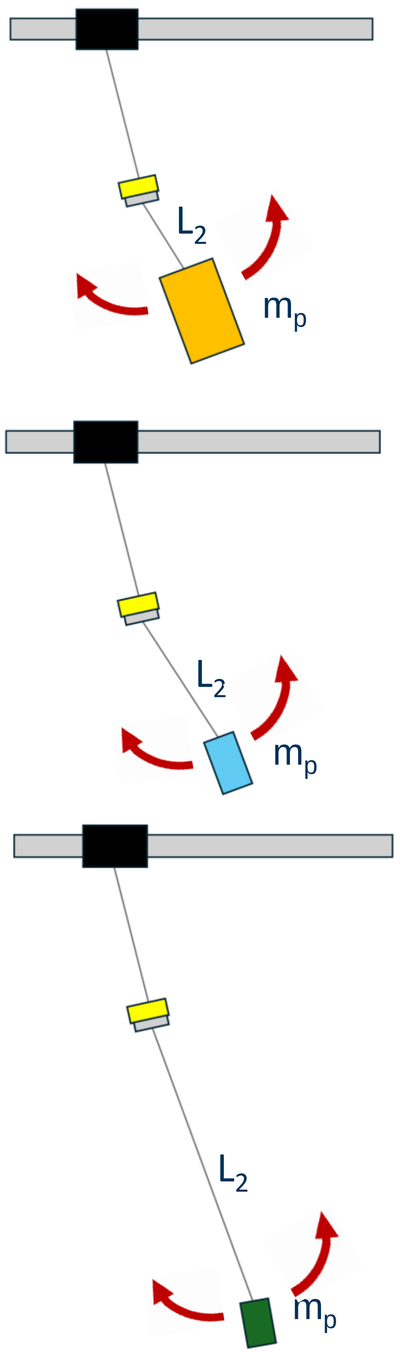
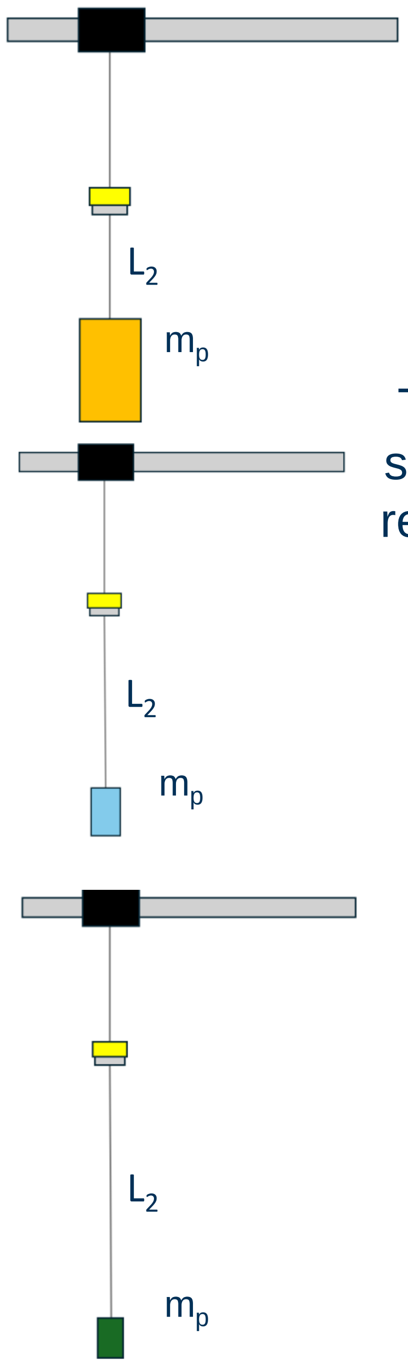
Objective

Initial State
Crane picks up new payload with unknown mass (m_p) and cable length (L_2)

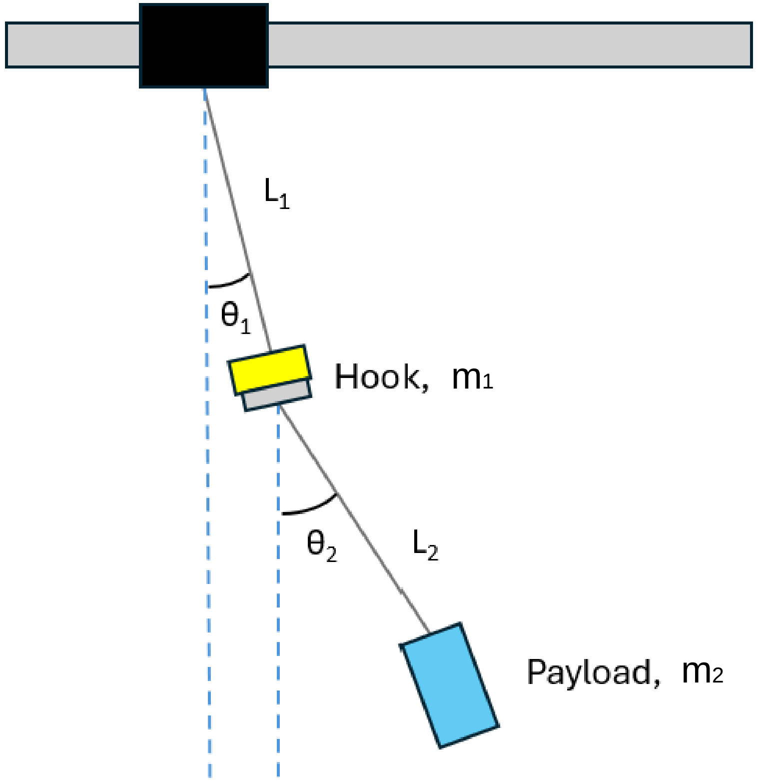


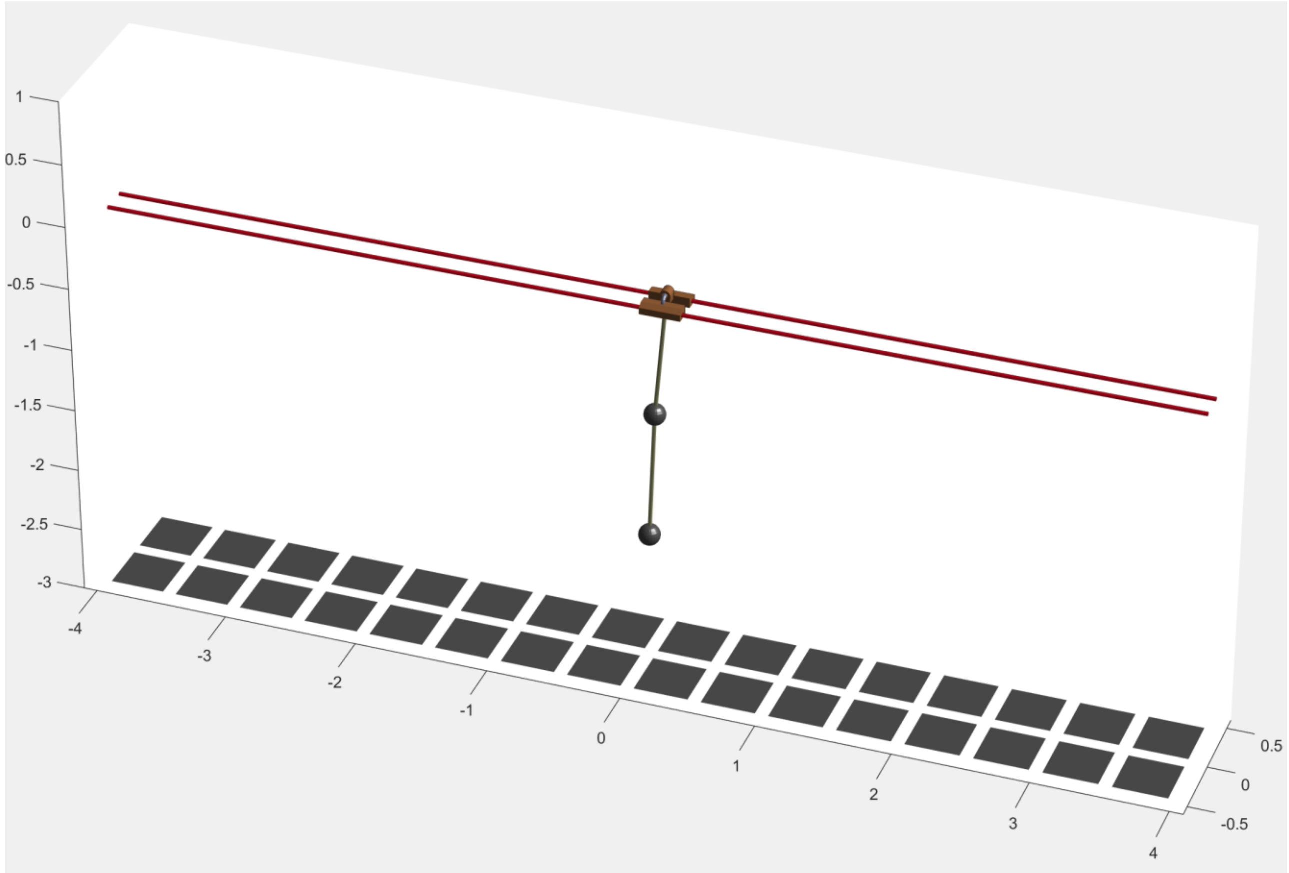
RLS + Adaptive Shaping
RLS continuously updates the model parameters as the crane moves, and modify the shaper in real-time



Final State
The oscillations in the system are attenuated, resulting in smooth and stable motion.

Equations of Motion





$$m_2\left(\ddot{x}C_2 + L_1\dot{\theta}_1^2 S_{2-1} + L_1\ddot{\theta}_1 C_{2-1} + L_2\ddot{\theta}_2\right) = -m_2 g S_2 - b_2\dot{x}C_2 - b_2 L_2\dot{\theta}_2 - b_2 L_1\dot{\theta}_1 C_{2-1}$$

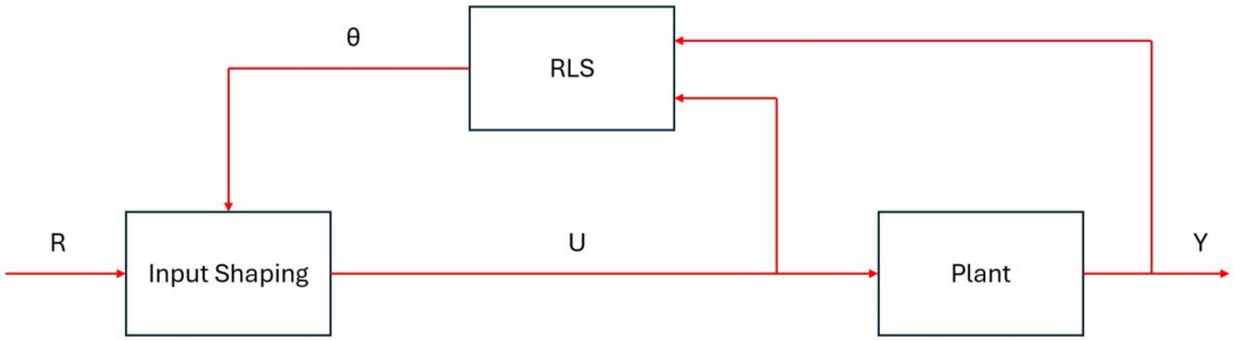
$$(m_1+m_2)\left(\ddot{x}C_1 + L_1\ddot{\theta}_1\right) + m_2\left(-L_2\dot{\theta}_2^2 S_{2-1} + L_2\ddot{\theta}_2 C_{2-1}\right) = -(m_1+m_2)gS_1 - (b_1+b_2)\left(\dot{x}C_1 + L_1\dot{\theta}_1\right) - b_2 L_2\dot{\theta}_2 C_{2-1}$$

RLS Method

- Simplified equations of motion
  - Small angle approximation
  - Neglect damping
  - Neglect centrifugal stiffness
  - Express θ_2 in terms of θ_1 and derivatives
- No forgetting factor
  - Found in simulation to be unstable with zero input

$$\frac{L_1 L_2(1-R)}{g}\theta_1^{(4)} + (L_1 + L_2)\ddot{\theta}_1 + g\theta_1 = -\frac{L_2(1-R)}{g}x^{(4)} - \ddot{x}$$

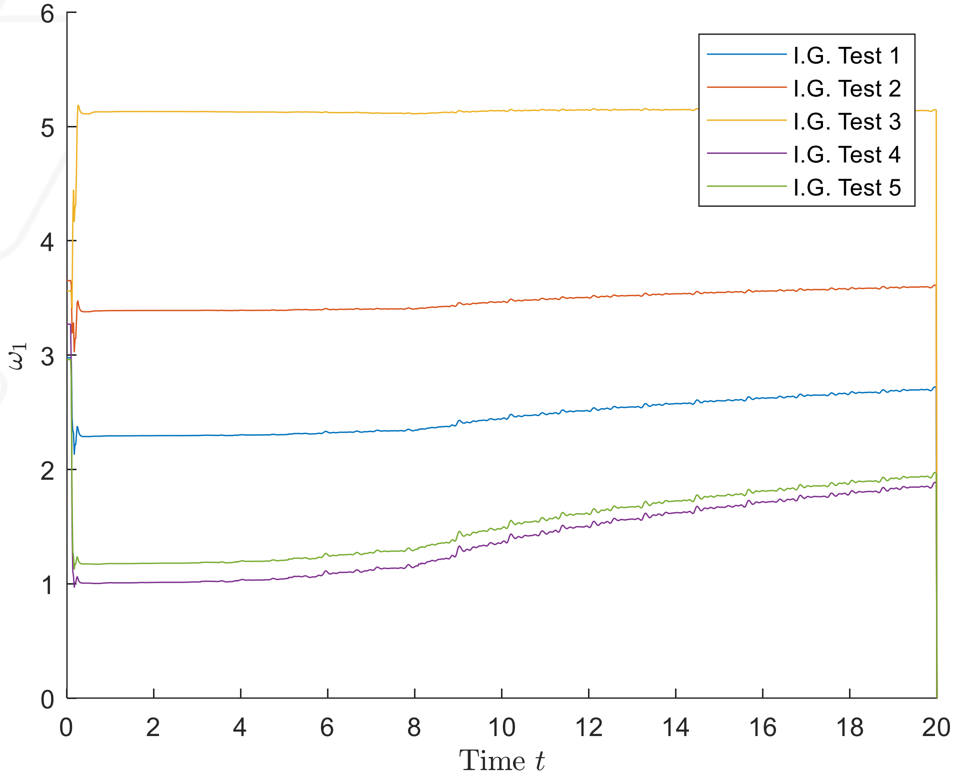
$$\theta_1^{(4)} + B_1\ddot{\theta}_1 + B_2\theta_1 = A_1 x^{(4)} + A_2\ddot{x}$$

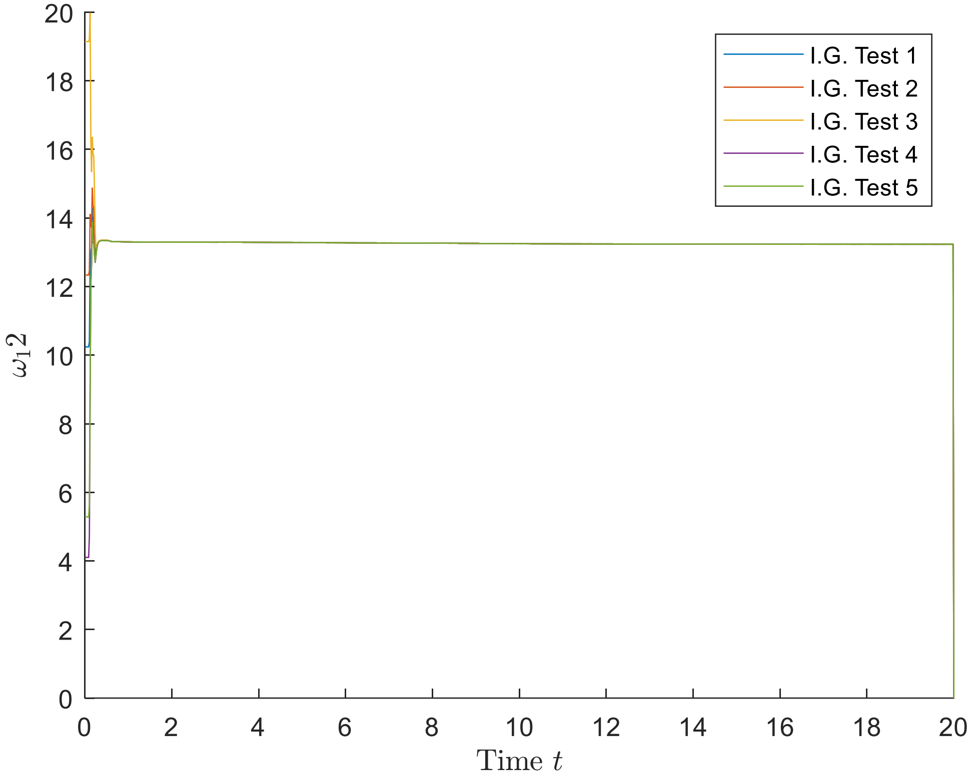


$$y = \theta_1^{(4)} \qquad \Theta = \begin{bmatrix} B_1 \\ B_2 \\ A_1 \\ A_2 \end{bmatrix} \qquad \Phi = \begin{bmatrix} -\ddot{\theta}_1 \\ -\theta_1 \\ x^{(4)} \\ \ddot{x} \end{bmatrix}$$

$$\omega_{n,1}^2, \omega_{n,2}^2 = \frac{-B_1 \pm \sqrt{B_1^2 - 4B_2}}{2}$$

Simulation Results – Initial Guess





Parameters	Theory	Test 1	Test 2	Test 3	Test 4	Test 5	Avg
L_2 (m)	0.7	0.5	0.1	0.1	0.8	0.77	--
m_2 (kg)	0.078	0.5	0.1	0.5	0.01	0.078	--
ω_1 (rad/s)	3.10	2.70	3.60	5.14	1.85	1.94	3.04
ω_2 (rad/s)	5.10	13.23	13.23	13.23	13.23	13.23	13.23

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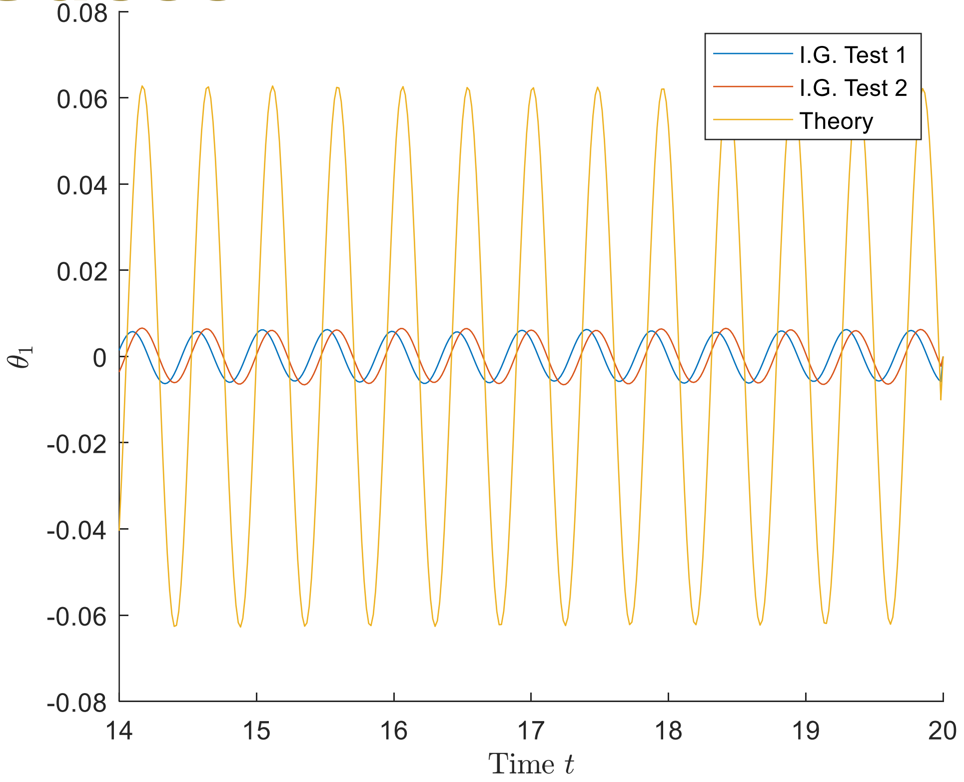
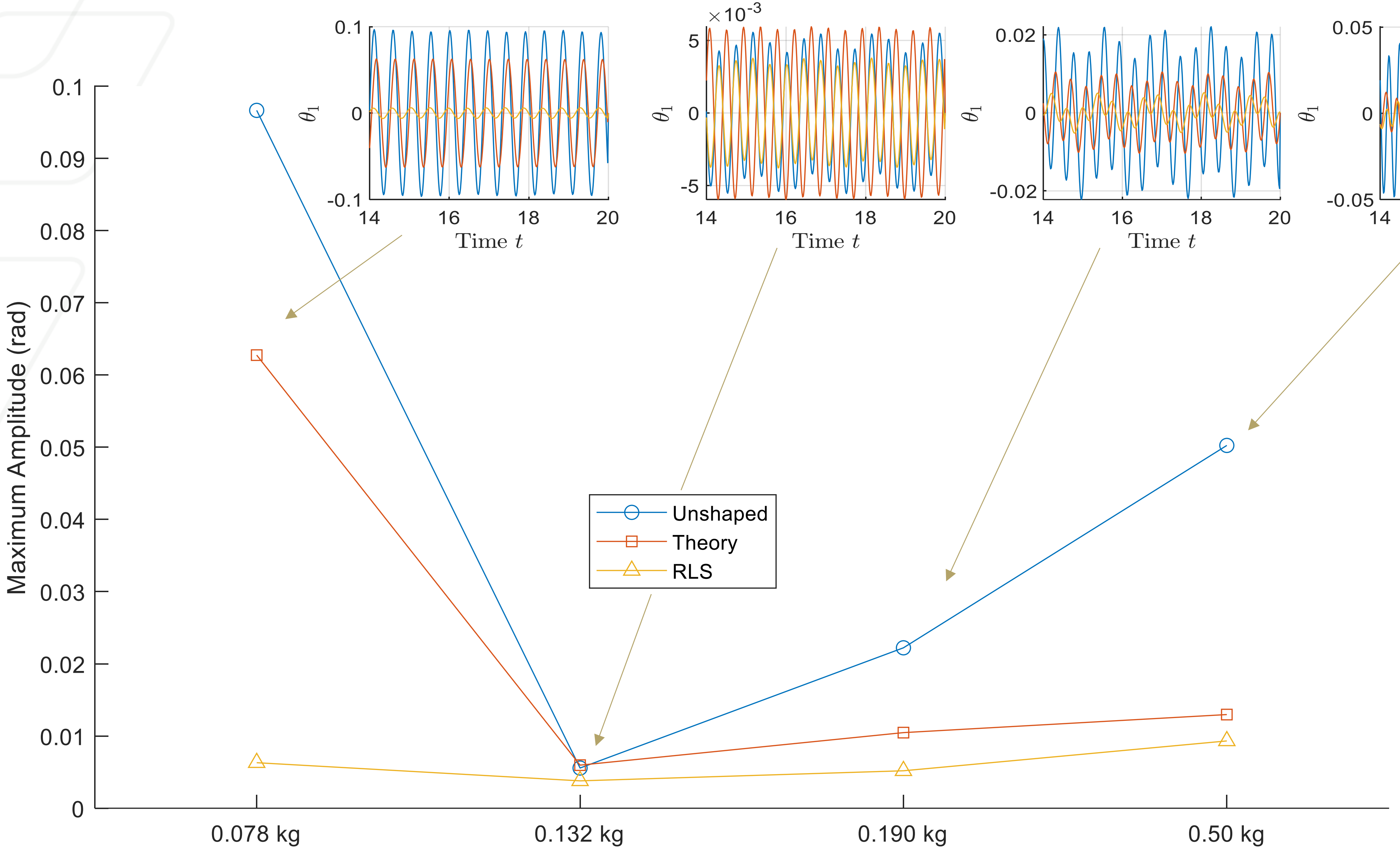
Simulation Results – Initial Guess

Using shapers from RLS and theory:



Parameters	Theory	Test 1	Test 2	Test 3	Test 4	Test 5	Avg
L_2 (m)	0.7	0.5	0.1	0.1	0.8	0.77	--
m_2 (kg)	0.078	0.5	0.1	0.5	0.01	0.078	--
ω_1 (rad/s)	3.10	2.70	3.60	5.14	1.85	1.94	3.04
ω_2 (rad/s)	5.10	13.23	13.23	13.23	13.23	13.23	13.23

Simulation Results – Effect of Payload Mass



Hardware Testing Procedure

Initialize RLS
Known values for hoist length, hook mass, and initial estimates for payload length and payload mass are used to initialize the RLS algorithm.

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Crane Operation
The crane is moved back and forth along the jib, allowing RLS to adapt and learn the payload parameters based on the crane's motion.

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Shaped Trajectory
The frequencies estimated by RLS are used to design a shaped trajectory with a two-mode ZV shaper, minimizing oscillations measured at the end of the move.

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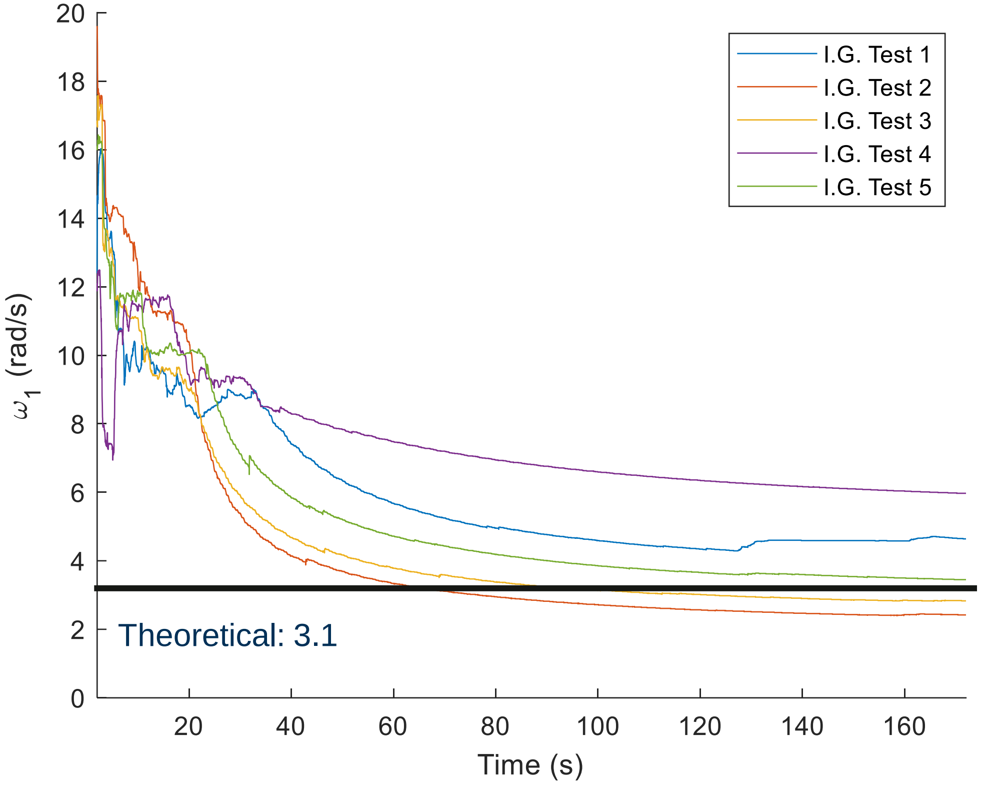
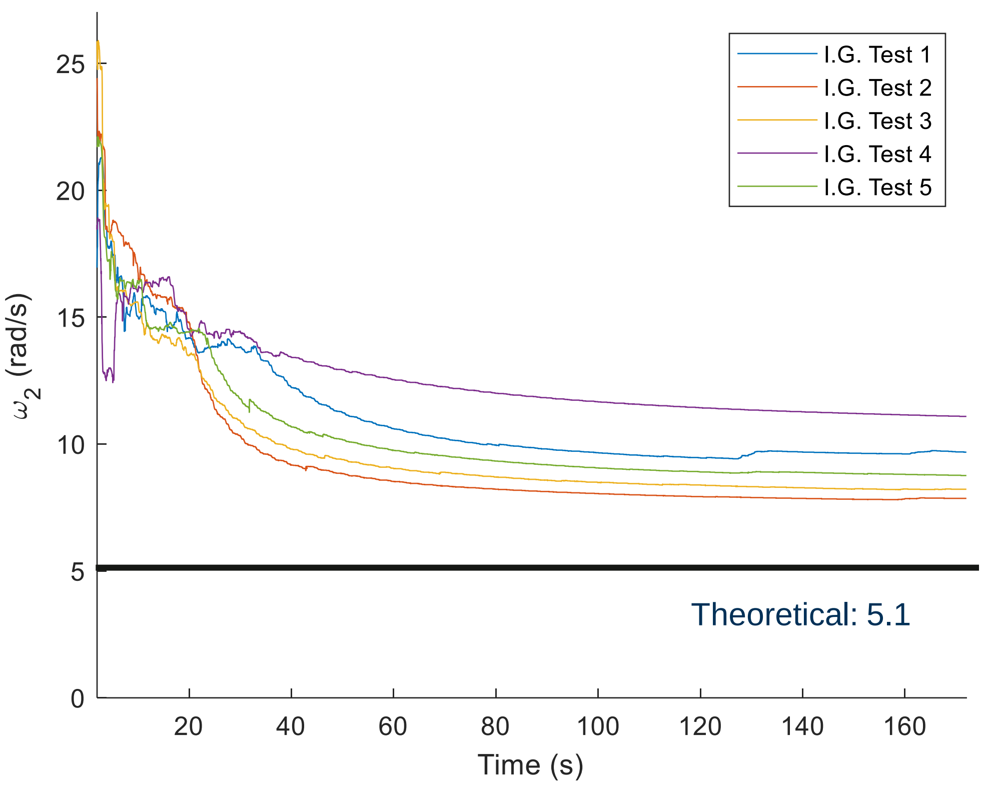
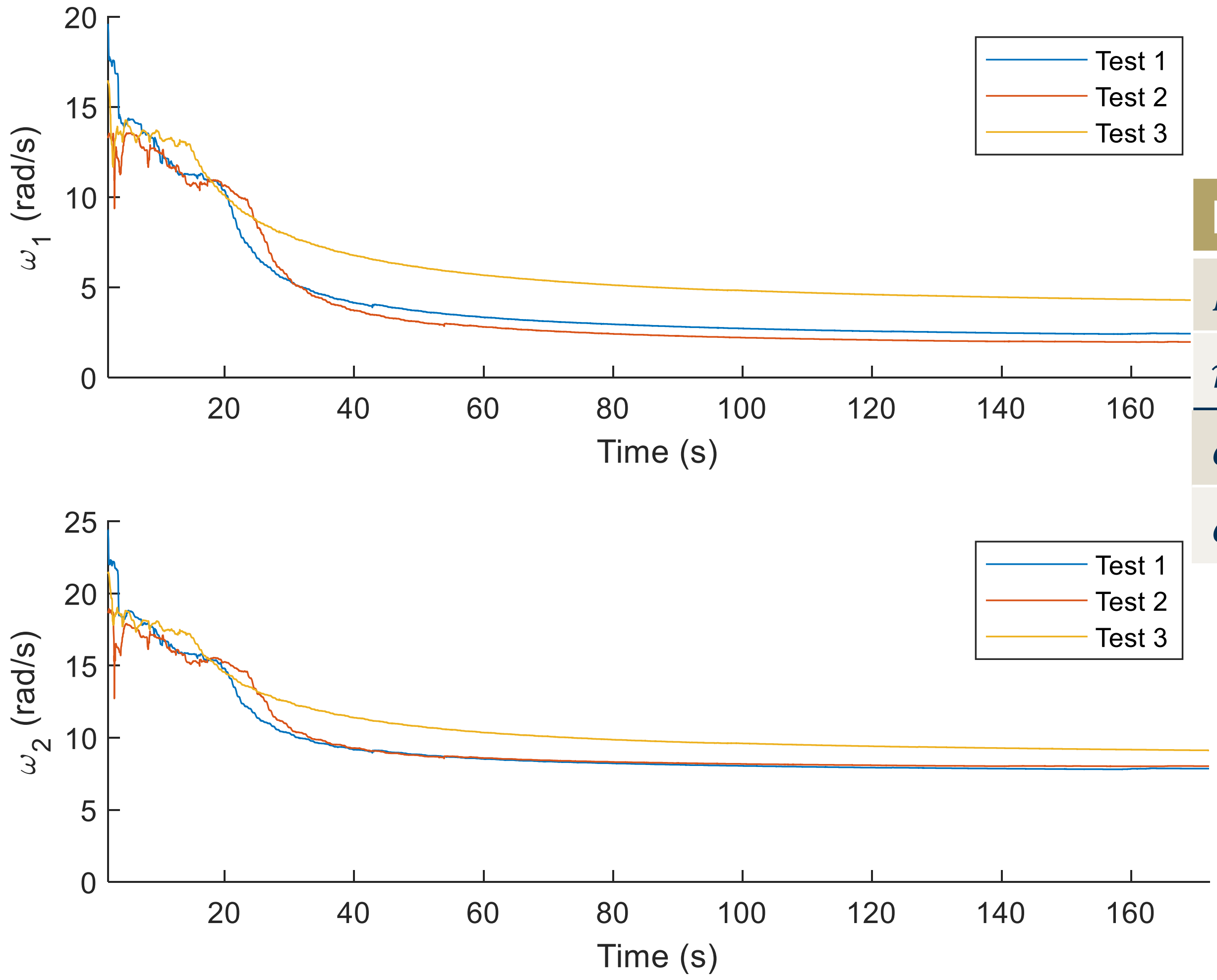
Initial Guess Testing





Parameters	Theory	Test 1	Test 2	Test 3	Test 4	Test 5	Avg
L_2 (m)	0.7	0.5	0.1	0.1	0.8	0.7	--
m_2 (kg)	0.078	0.5	0.1	0.5	0.01	0.078	--
ω_1 (rad/s)	3.10	3.95	2.42	2.68	5.77	3.18	3.6
ω_2 (rad/s)	5.10	9.11	7.86	8.04	10.91	8.51	8.89

Consistency Testing

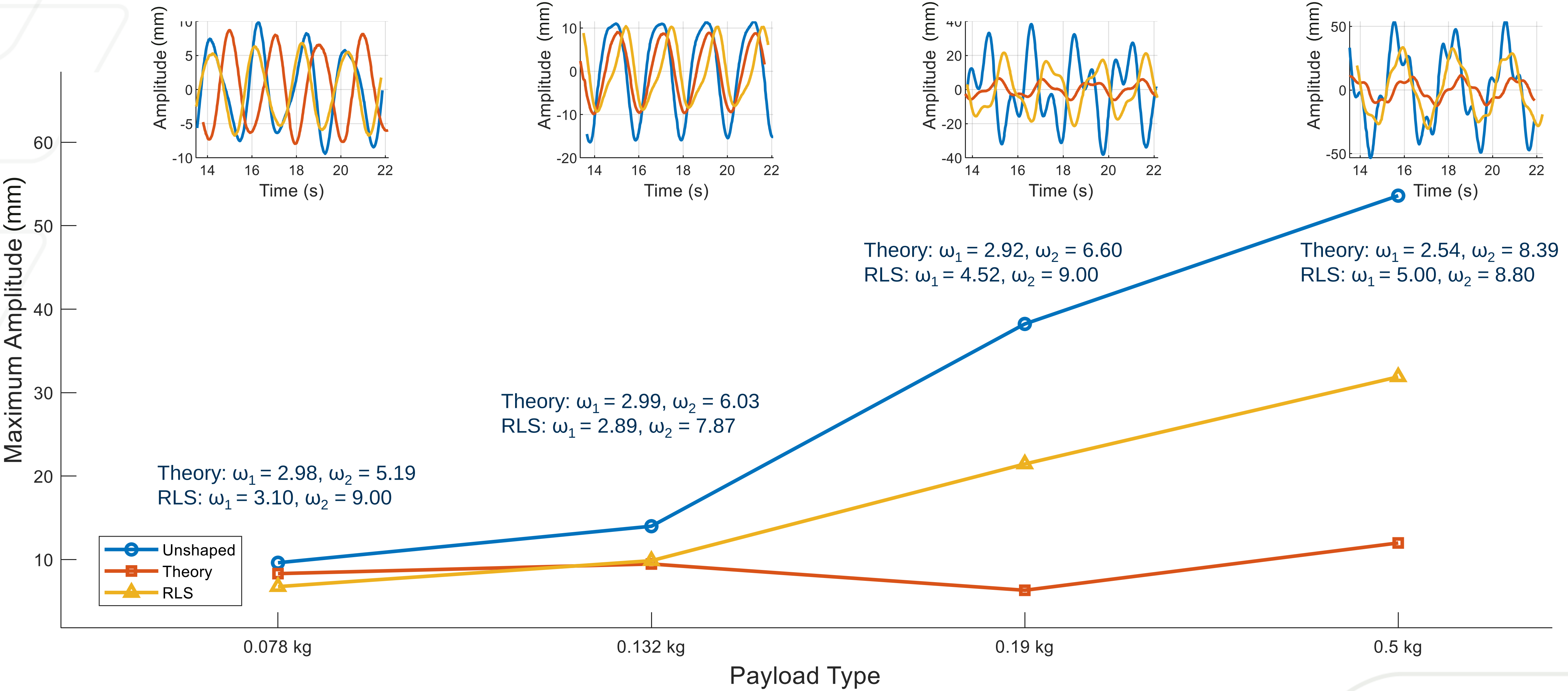


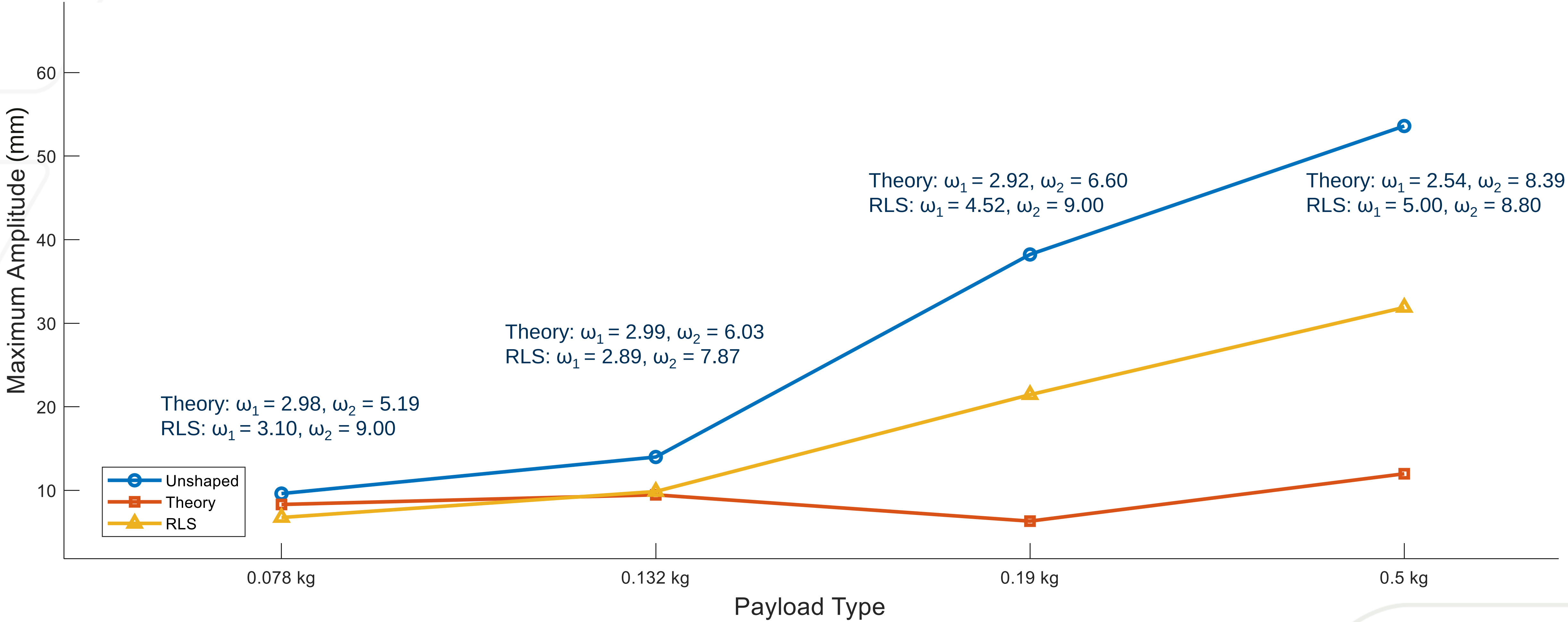
Parameter	Theory	Test 1	Test 2	Test 3	Avg
L_2 (m)	0.7	0.1	0.1	0.1	--
m_2 (kg)	0.078	0.1	0.1	0.1	--
ω_1 (rad/s)	3.10	2.42	2.26	4.08	2.92
ω_2 (rad/s)	5.10	7.86	8.37	8.94	8.39

Key Takeaways

- Frequency estimations vary greatly between different initial guesses
  - ω 1 varies with up to 86% error
  - ω 2 varies with up to 114% error
- Identical initial guesses converge to similar values but can be inconsistent
- Discrepancy between theory and average predicted frequencies suggests model inaccuracies
- Time to converge may be too high for practical implementation
  - Implementing forgetting factor < 1 may lead to faster convergence

Effect of Payload Mass on RLS Performance





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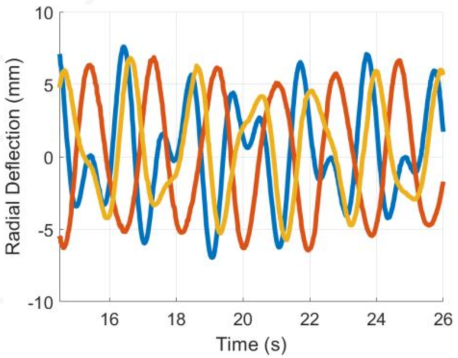
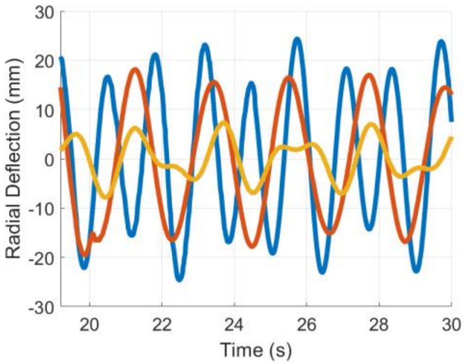
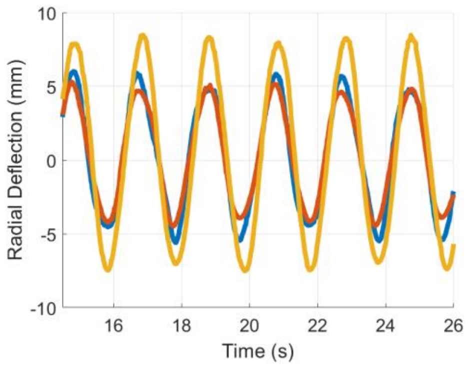
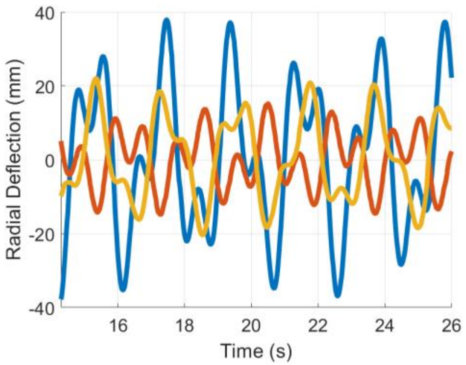
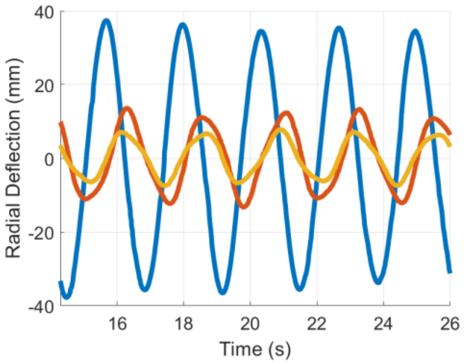
Effect of Payload Cable Length on RLS Performance

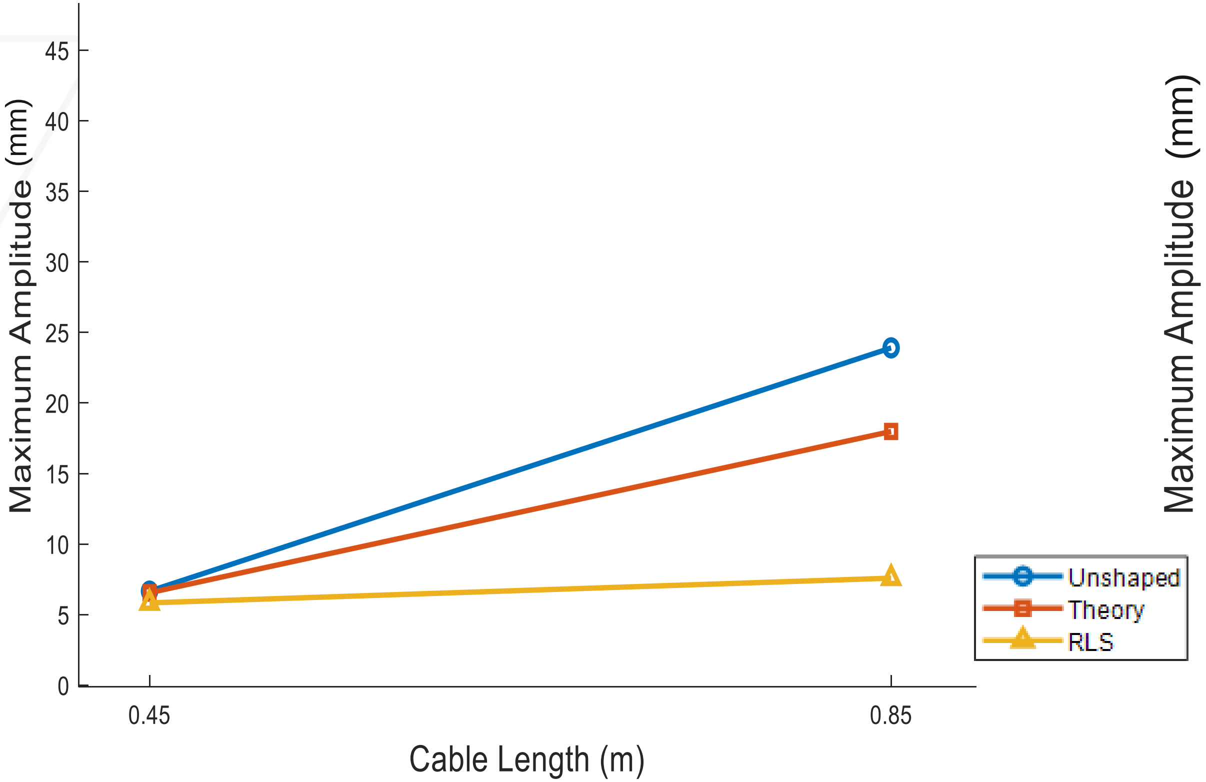




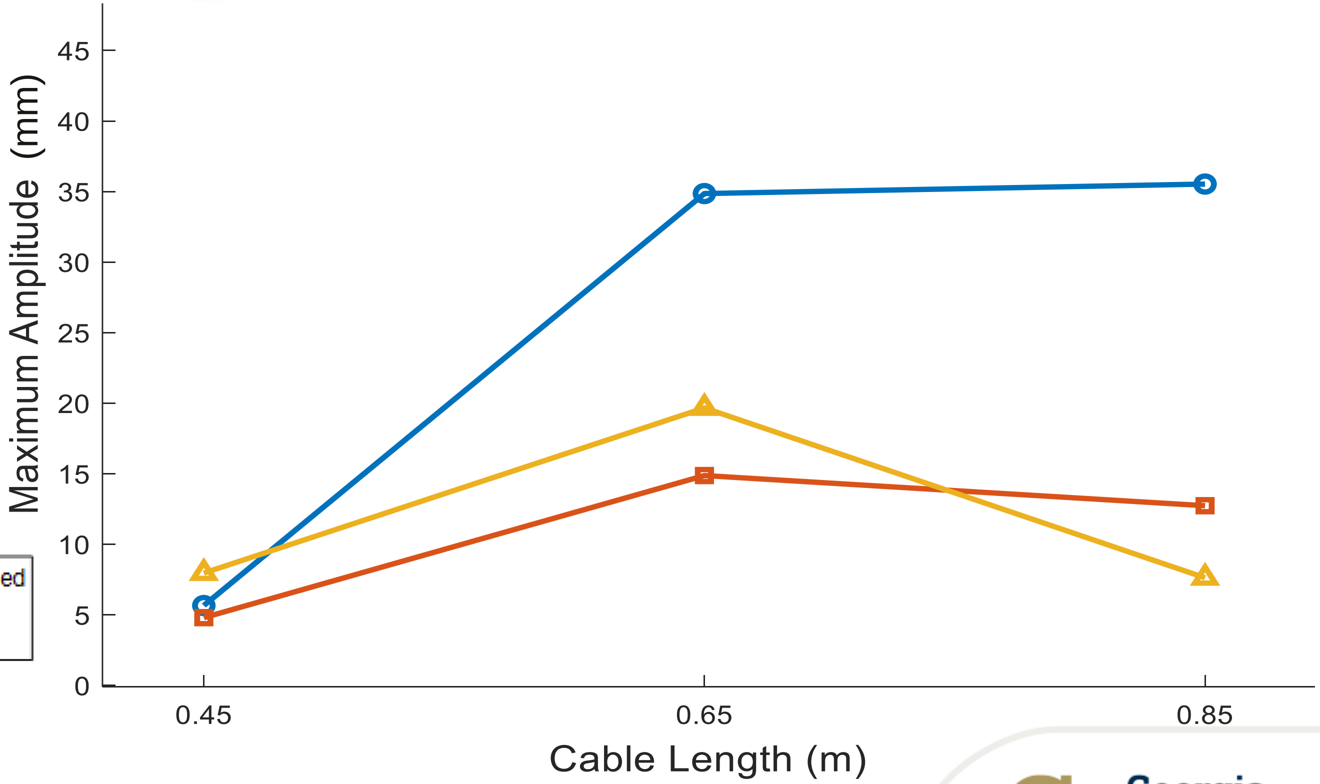








0.078 kg



0.19 kg

Limitations

- Modestly effective at reducing oscillation, for a given shaper
  - Improvements are small compared to effectiveness of more robust shaper
- Requires manually resetting RLS gain anytime system changes
  - Could be solved by a forgetting algorithm – simple forgetting factor doesn't work
- Physical System
  - Oscillation of the hook
  - Non-constant time step
- Modeling
  - Small angle approximation
  - Neglect of damping
  - Point mass simplification
  - State filtering for estimation

Future Work

- Minimize Parameter Learning Time
- Validate Frequencies with FFT
- Explore the Effects of Hook Mass Variations
- Optimize Trolley Movement Patterns
- Implement RLS During Slewing
- Evaluate Practicality with more robust Shaper

Questions?