



SLS

Space Launch System

Demonstration of the Space Launch System Augmenting Adaptive Control Algorithm on a Quad-Rotor

**AIAA Sci-Tech Conference, Orlando FL
January 9, 2018**

***Luke Miller, Jing Pei, and Paul Rothhaar
NASA Langley Research Center***

- ◆ **Background**
- ◆ **Experimental Setup**
- ◆ **Baseline Linear Control**
- ◆ **Adaptive Augmenting Control (AAC)**
- ◆ **Demonstrating the three key objectives of the augmenting adaptive control (AAC) algorithm on the Quad-Rotor platform**
- ◆ **Conclusions and Ongoing work**

- ◆ **SLS EM-1 marks the first time an adaptive controller is to be implemented on a human-rated launch vehicle**
 - The adaptive controller is intended to augment the performance of the already well-tuned baseline linear controller.
 - Done by extending the envelope of failures and flight anomalies.
- ◆ **In a launch vehicle, the controlled error dynamics are lower in frequency than the internal dynamics (flex, slosh) and parasitic (engine) dynamics**
 - As we approach instability due to *insufficient forward loop gain* (aerodynamics, thrust uncertainty), the error dynamics *diverge exponentially or at a frequency at or below the design control frequency*.
 - As we approach instability due to *excessive forward loop gain*, we observe the introduction of high-frequency spectrum in the control loop.
 - These are general characteristics of the control of damped complex roots with servo lag, delay, and complex engine poles.

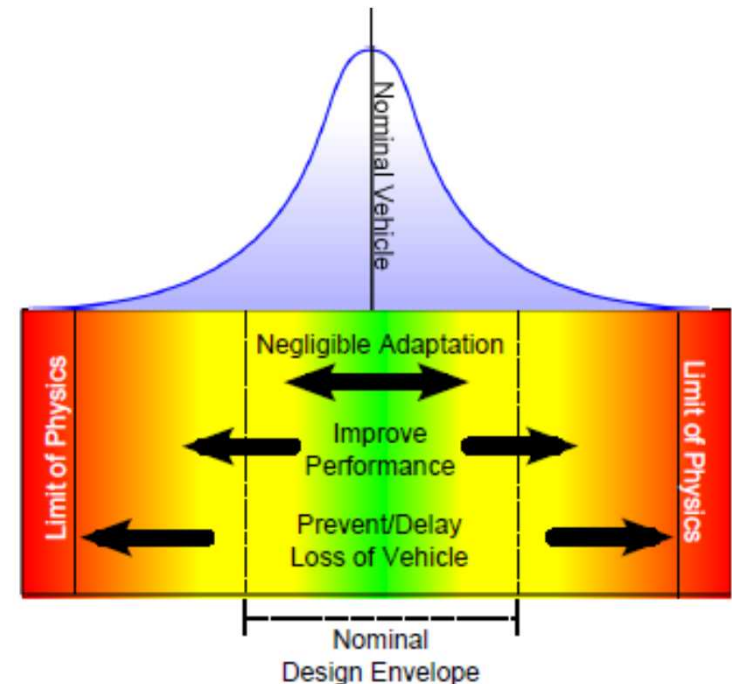


- ◆ **Three key functionalities of the SLS Augmenting Adaptive Control (AAC) algorithm**
 - Objective 1: Minimum adaptation when the baseline control system is performing within the nominal envelope.
 - Objective 2: Increase performance when tracking error becomes too large.
 - Objective 3: Decrease system overall gain to suppress undesirable high frequency dynamics in the control path.

- ◆ **Demonstrate the key functionalities the AAC algorithm on the Quad-Rotor hardware at the LaRC Autonomy Incubator (AI)**
 - Dynamics of controlling a conditionally stable quad-rotor is analogous to controlling an aerodynamically unstable launch vehicle.
 - In theory, the AAC algorithm should be applicable for a wide range of conditionally stable dynamical systems

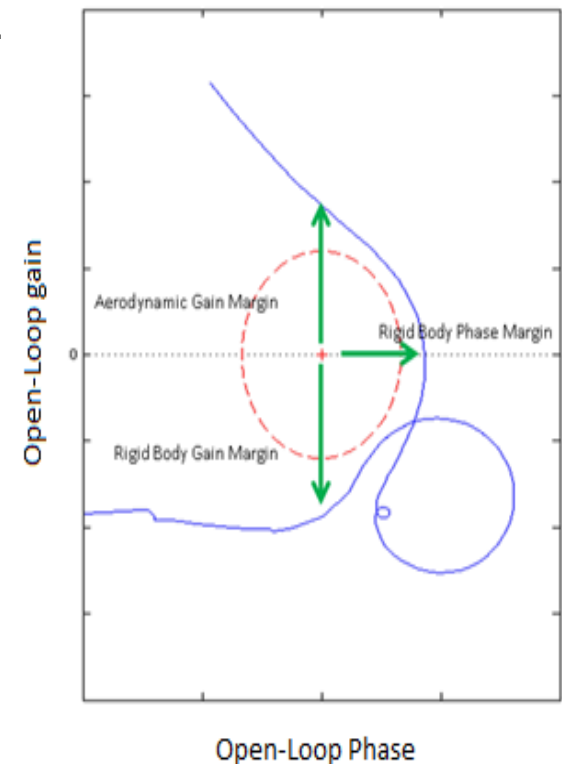
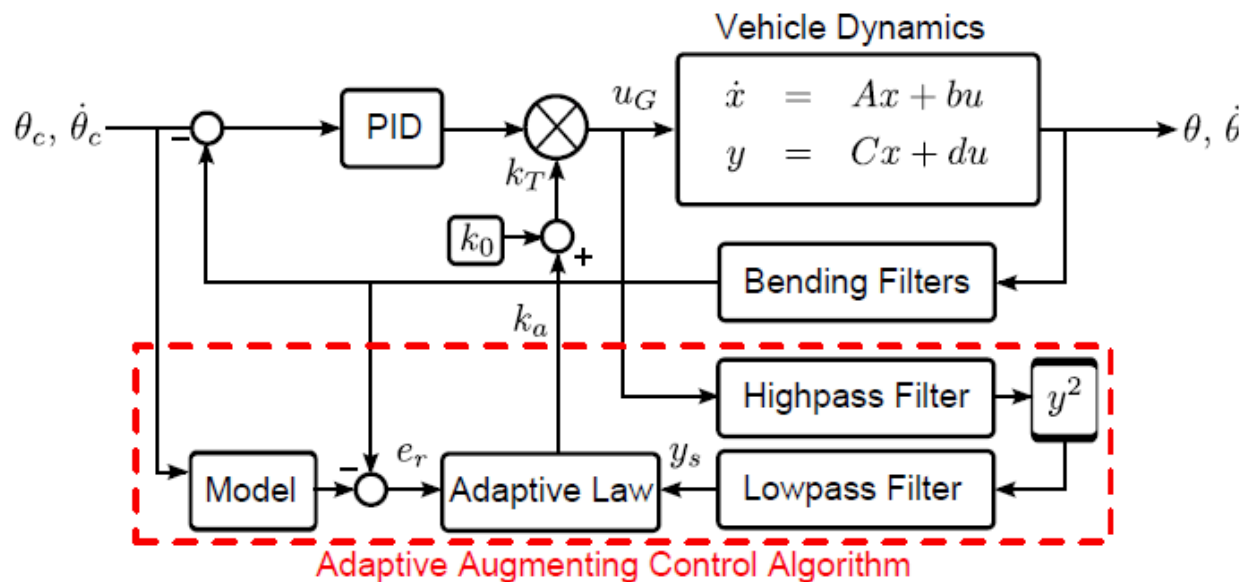
◆ **Part of a SLS-NASA Engineering Safety Center (NESC) joint risk mitigation effort in providing additional confidence into AAC design, operation, and robustness**

- Simple, “Classroom” type of setup
- Simple dynamics and intuitive for non-controls engineers
- Provides insight into the complex SLS



◆ **AAC is a form of model reference adaptive control**

- The forward loop gain K_T is augmented by a signal K_a which comprises of low frequency content in the reference model error signal, and high frequency content that's in the control signal.
- Multiplicative augmentation is easy to assess in terms of gain margin.
- Limits of adaptation (K_T) are based on the stability margin requirements (+/- 6 dB) for the baseline linear controller.
- AAC is there to “extend” the nominal stability margins.



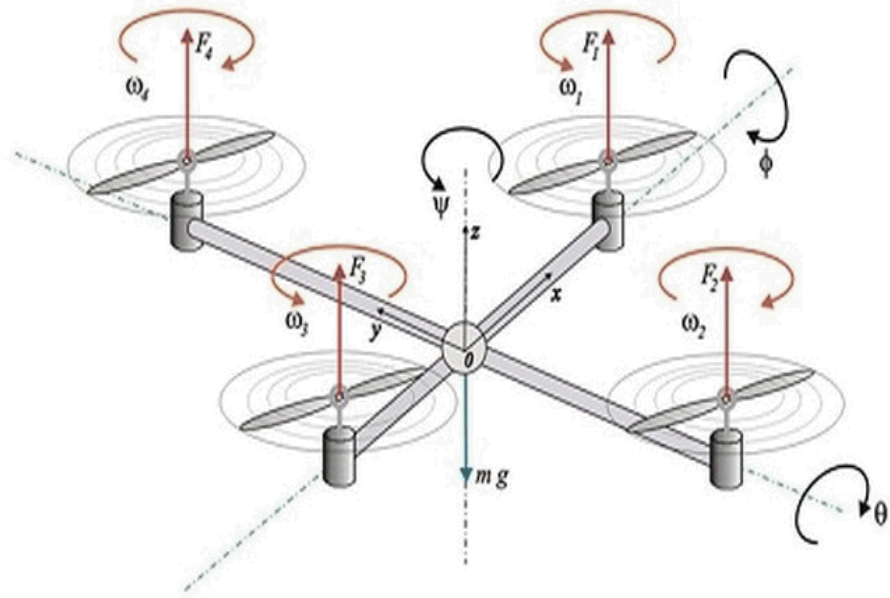
- ◆ Orr, J. and VanZwieten, T. "Robust, Practical, Adaptive Control for Launch Vehicles". AIAA 2012-4549
- ◆ Wall, J., Orr, J., VanZwieten, T. "Space Launch System Implementation of Adaptive Augmenting Control". AAS 14-051
- ◆ VanZwieten, T., Gilligan E. and et al. "Adaptive Augmenting Control Flight Characterization Experiment on an F/A-18". AAS 14-052
- ◆ Wall, J., VanZwieten, T. and et al. "In-Flight Suppression of a Destabilized F/A-18 Structural Mode Using the Space Launch System Adaptive Augmenting Control System". AIAA 2015-1775
- ◆ VanZwieten, T., Hannan, M. "Evaluating the Stability of NASA's Space Launch System with Adaptive Augmenting Control". ESA GNC 2017
- ◆ Pei, J. and Rothhaar, P. "Demonstration of the Space Launch System Augmenting Adaptive Control Algorithm on a Pole-Cart Platform". AIAA SciTech 2018.

◆ Control Problem

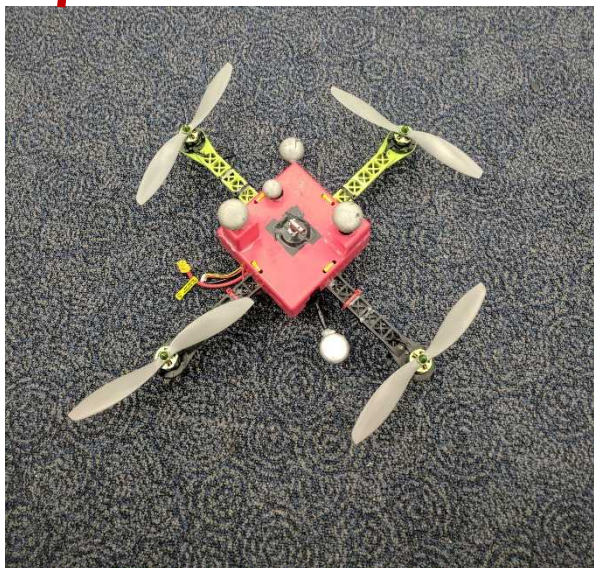
- Quad-Rotor actively stabilizes itself by adjusting the speed of the four rotors.
- Similarly, a launch vehicle adjusts gimbaled nozzles to actively stabilize itself.

◆ Simple and inexpensive

- Intuitive to understand
- Help gain insight into the more complex system SLS



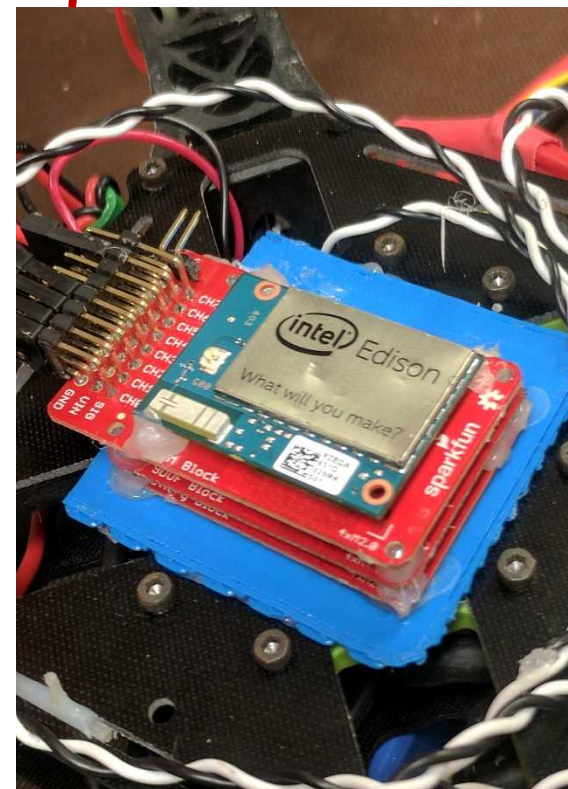
Quad-rotor
Hardware



Control Station



On-board Intel
Edison and IMU

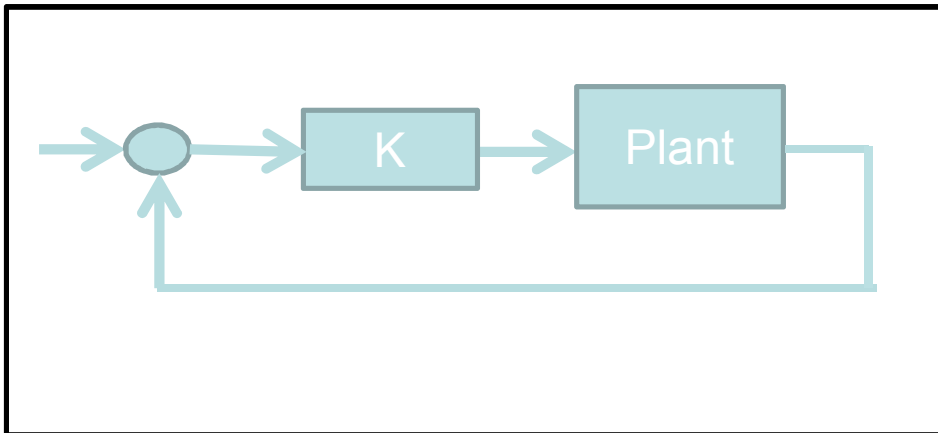


Off-Board:

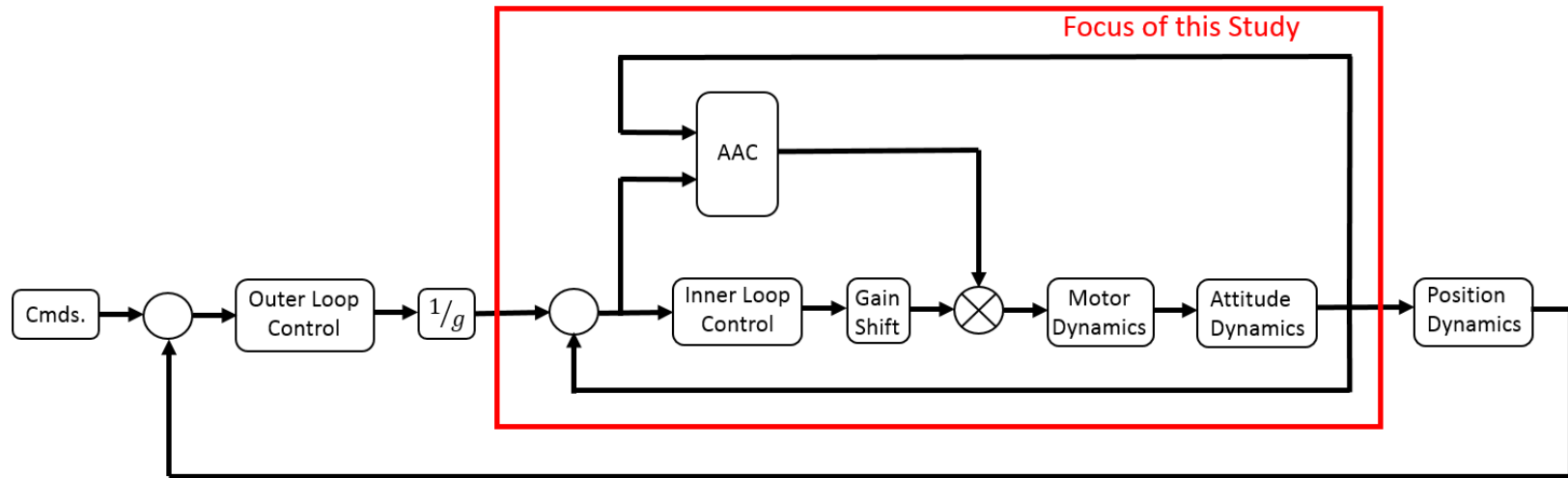
- ◆ Vicon motion capture system outputs position and attitude measurements.
- ◆ Fed directly into the controller.
- ◆ The position measurement is smoothed with a LPF.
- ◆ The derivative is taken to obtain velocity.

On-Board:

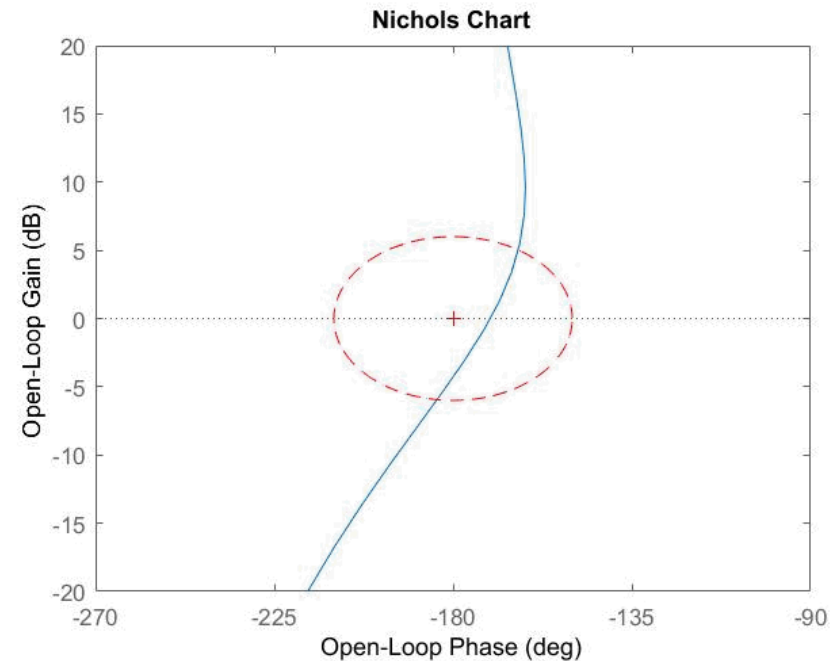
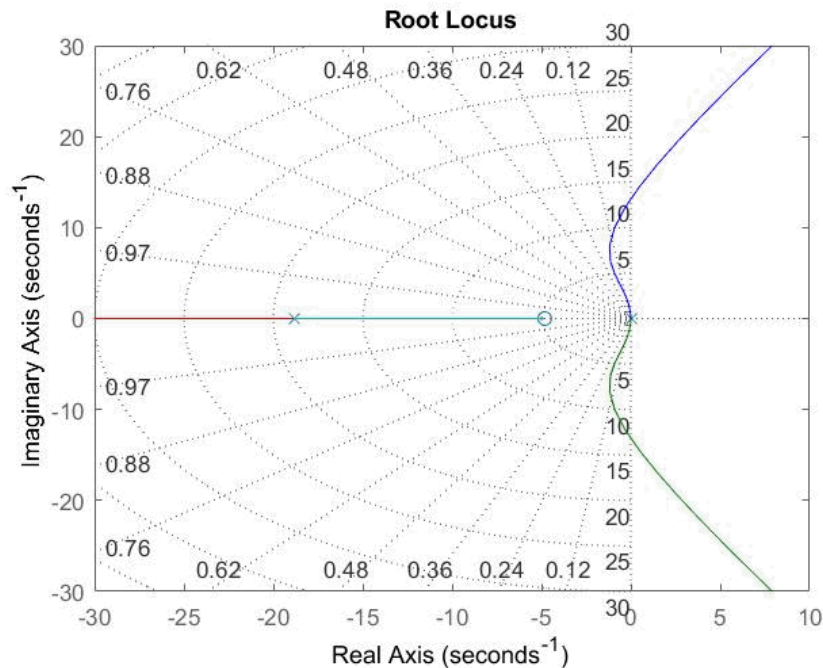
- ◆ Inertial Measurement unit (IMU) outputs body rate measurements.
- ◆ Fed directly into the controller.



- Design a PD control system to actively stabilize the quadrotor at hover.



Current work focuses on intentionally making the inner loop unstable and show that the AAC can help the quad regain stability

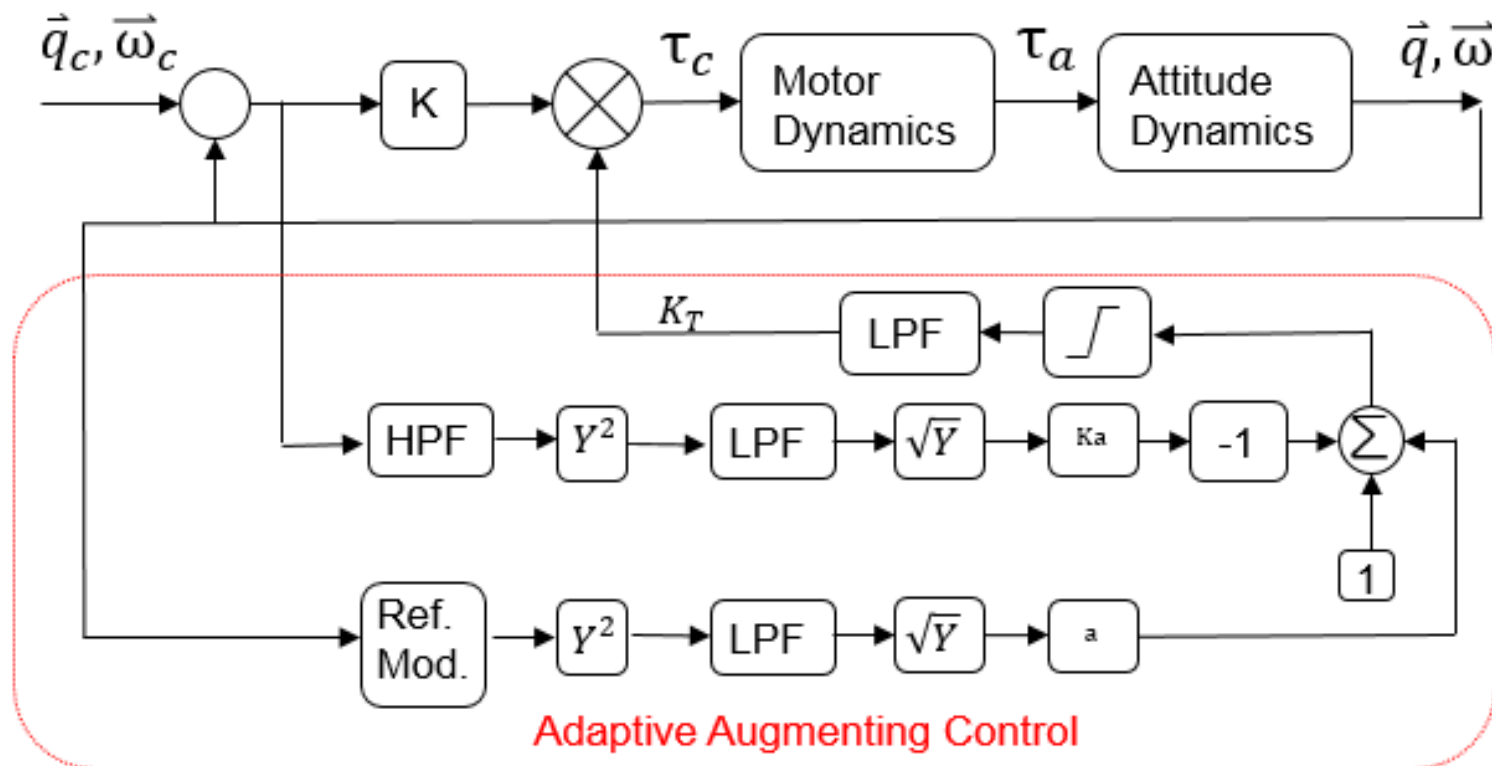


Pair of complex poles representing the actuator dynamics

- Poles begin as neutrally stable
- Migrate toward right hand plane as loop gain increases

Note: linear model shows poor phase margin but the quad flies extremely well.

	LF GM (abs)	HF GM (abs)	HF GM Frequency (HZ)	Phase Margin (deg)	Gain Crossover Frequency (Hz)
Linear Model	0	1.639	2.31	9.39	1.72
Nonlinear simulation	0	1.34	1.75	6.76	1.93
Hardware	0.68	1.38	2.03	11.06	1.54



Parameters	SLS (DAC-3R)	Quad-Rotor
Gain crossover Freq	0.2 Hz	1.54 Hz
SD HPF	0.4 Hz, $\xi = 0.9$	3 Hz, $\xi = 0.9$
SD LPF	0.25 Hz, $\xi = 1$	1 Hz, $\xi = 1$
Err LPF	0.2 Hz, $\xi = 1$	0.7 Hz, $\xi = 1$
K (ratio between err and SD gain) $\alpha=K_a$	1.45	5
a, Err gain	100	10
Selectivity Function Zero	0.35 Hz	1.5 Hz
AAC LPF	0.15 Hz, $\xi = 1$	1.25 Hz, $\xi = 1$

◆ Objective 1

- Test 1, AAC Off, Gain Shift Parameter = 1
- Test 2, AAC On, Gain Shift Parameter = 1

◆ Objective 2

- Test 3, AAC Off, Gain Shift Parameter = 0.68
- Test 4, AAC Trigger, Gain Shift Parameter = 0.68

◆ Objective 3

- Test 5, AAC Off, Gain Shift Parameter = 1.38
- Test 6, AAC Trigger, Gain Shift Parameter = 1.38

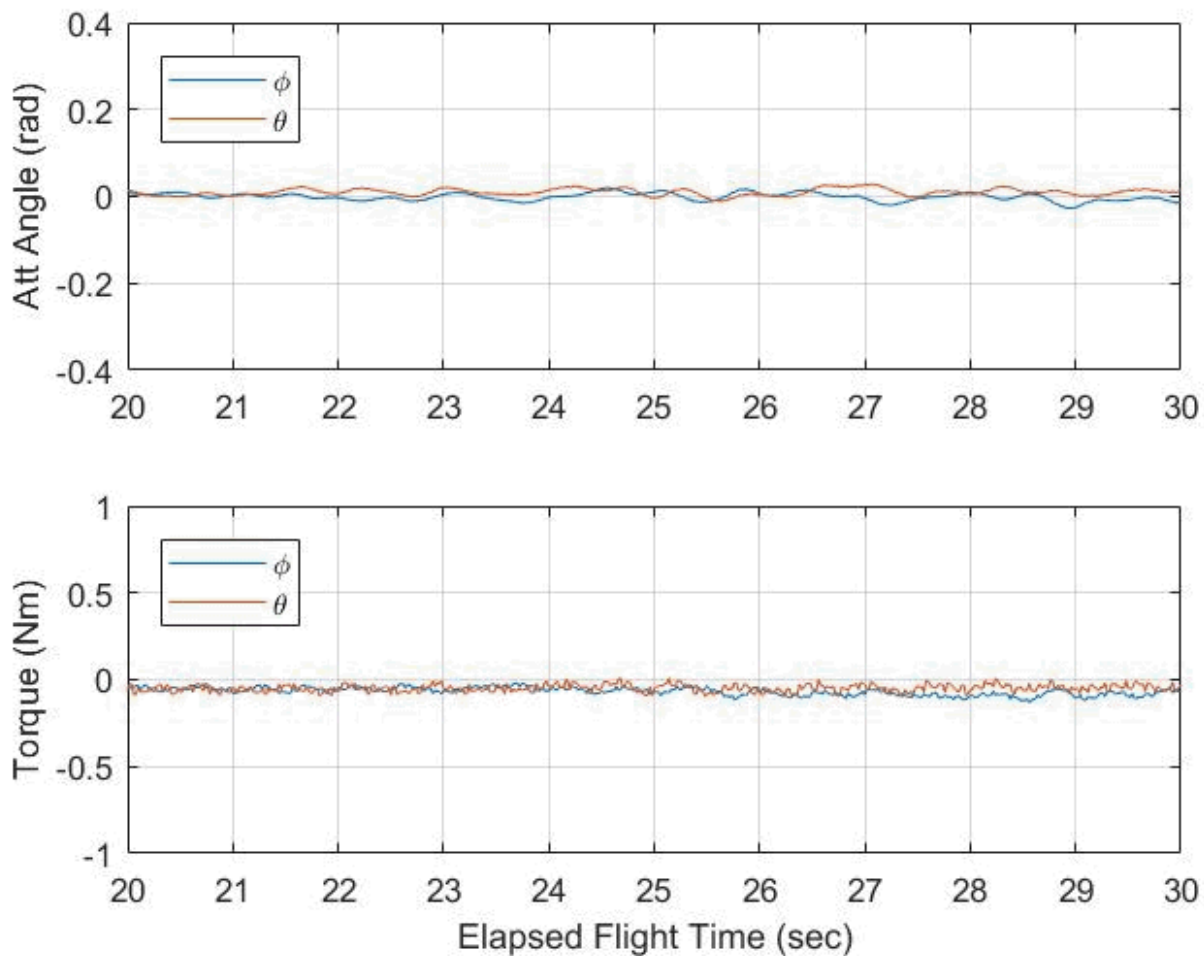
◆ AAC Trigger

- Quadrotor is initially free to oscillate with the AAC not being fed into the controller.
- When oscillations reach $\pm 0.2 \text{ rad}$ a software switch triggers and the AAC is fed into the controller.
- Intended to show before/after picture of AAC.

Gain Shift Parameter = 1



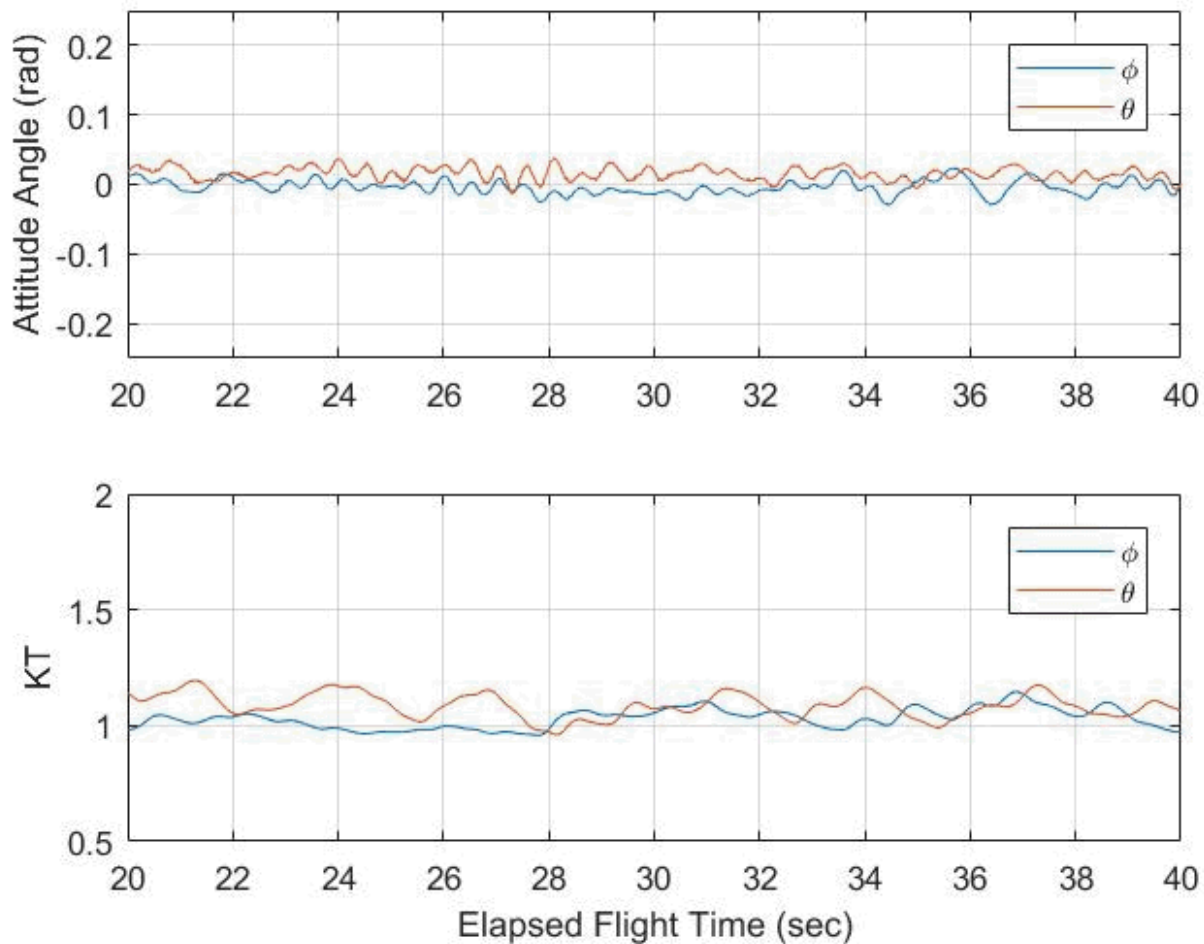
Gain Shift Parameter = 1



Gain Shift Parameter = 1



Gain Shift Parameter = 1

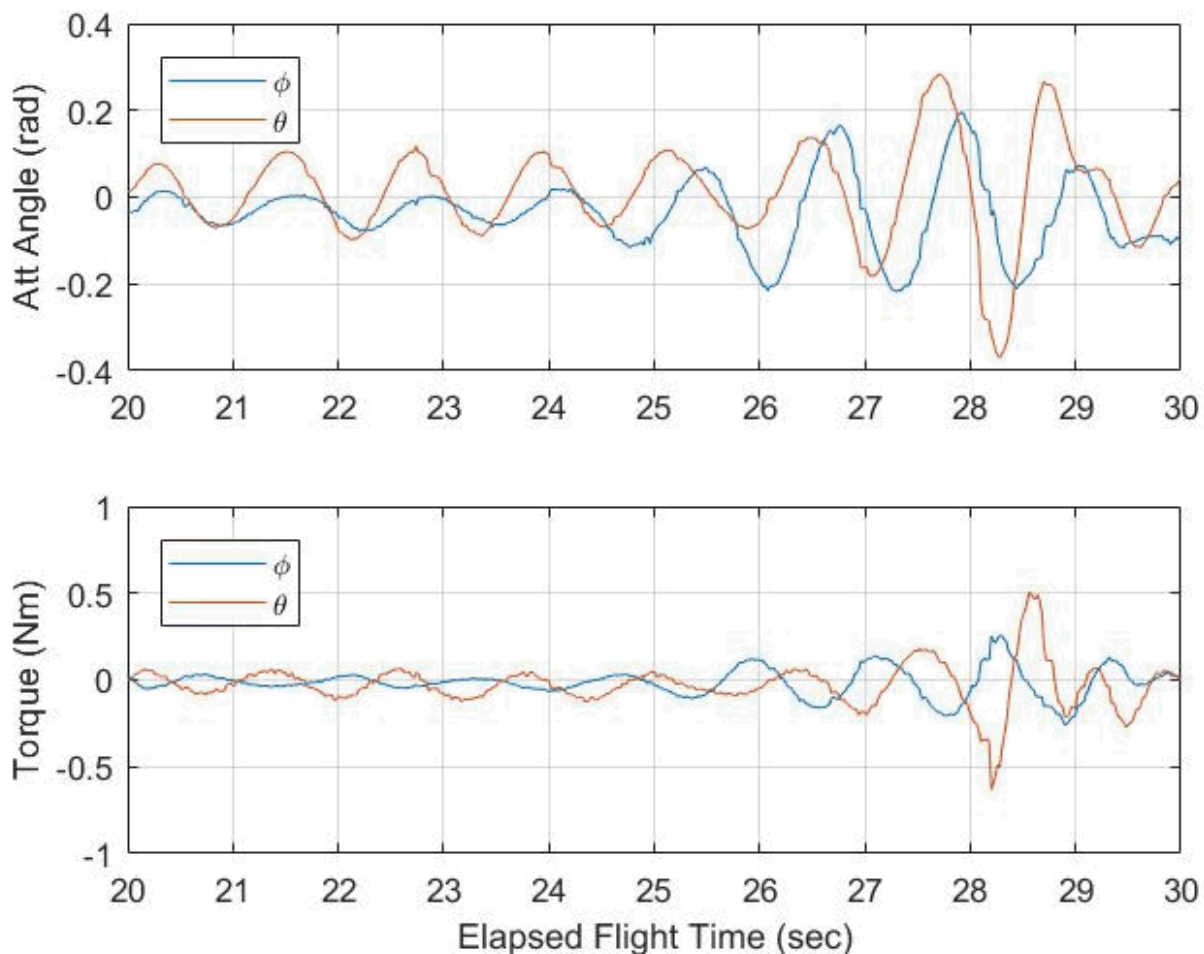


Gain Shift Parameter = 0.68



- This is caused by motor imbalance/degradation
- These effects are not captured in the simulation, Thus The rigid body instability does not exist in simulation

Gain Shift Parameter = 0.68

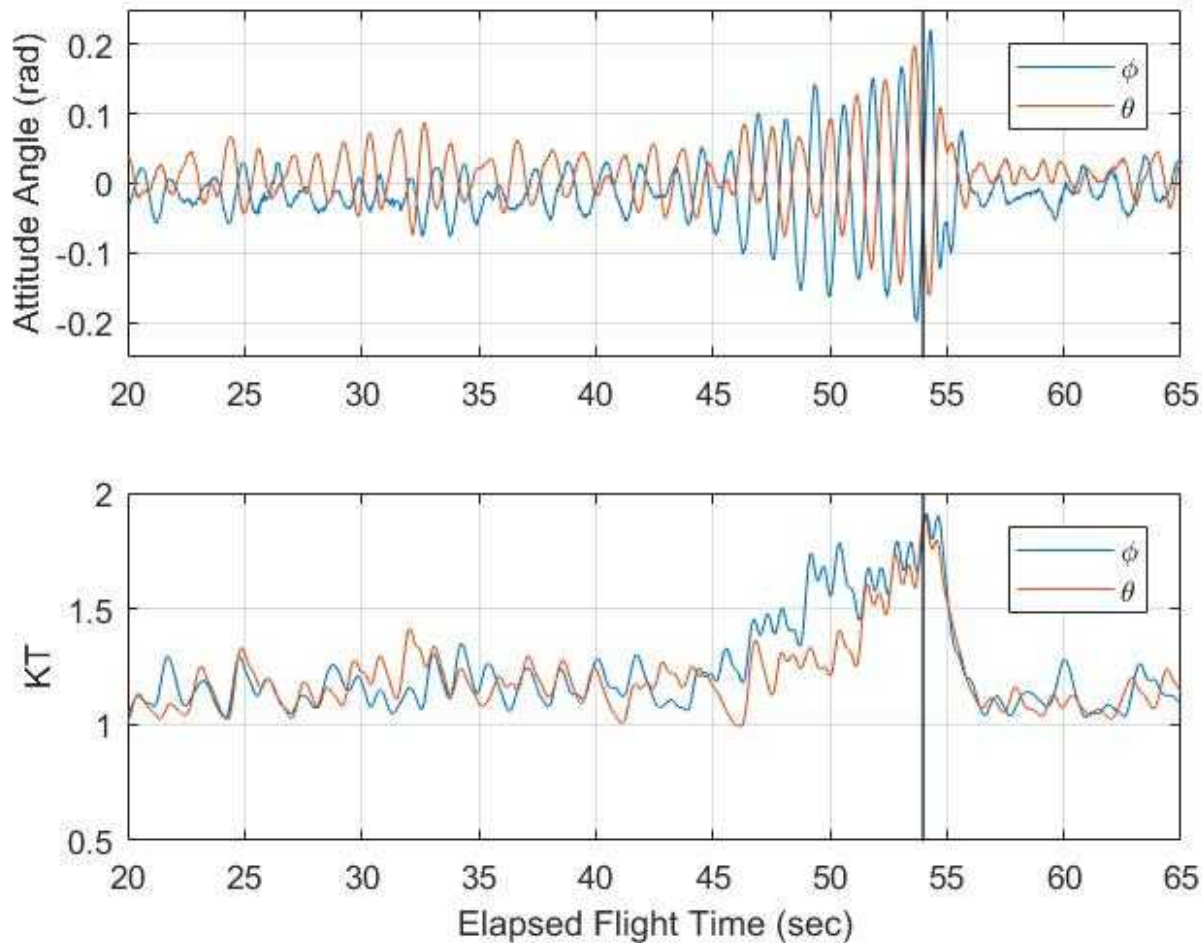


Gain Shift Parameter = 0.68



Objective #2: Response to Rigid Body Instability

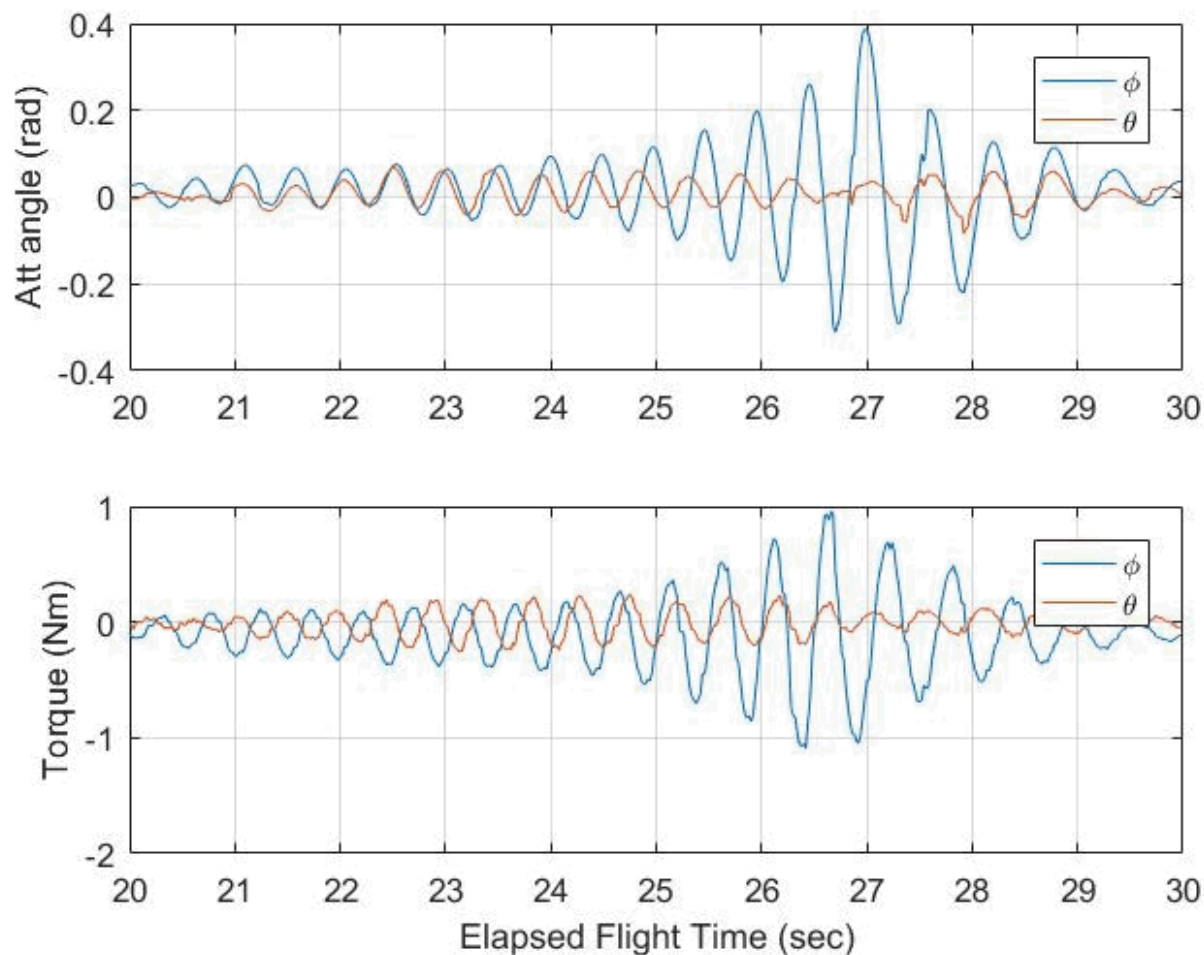
Gain Shift Parameter = 0.68



Gain Shift Parameter = 1.38



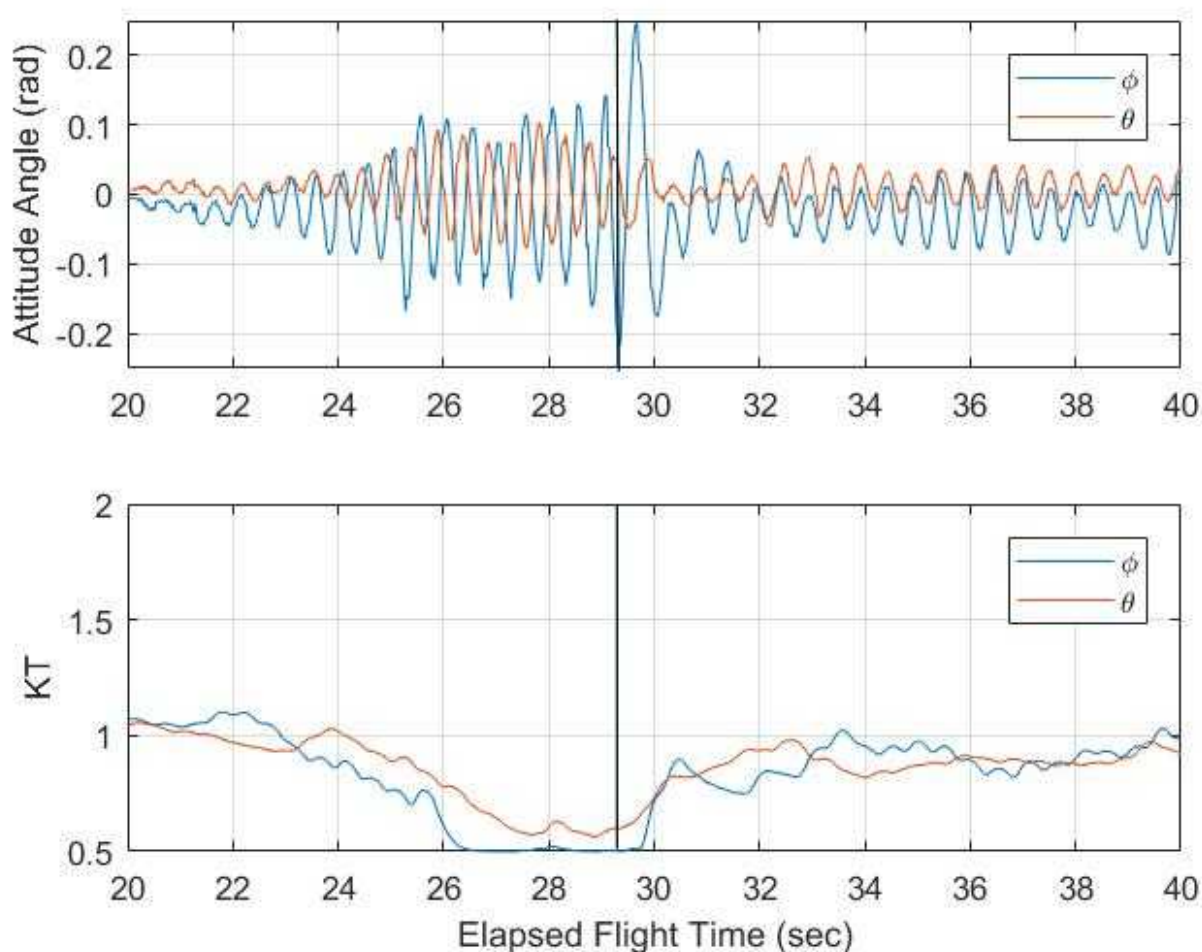
Gain Shift Parameter = 1.38



Gain Shift Parameter = 1.38



Gain Shift Parameter = 1.38



◆ Key functionalities of the AAC were demonstrated on the quadcopter

- Objective 1: Show the AAC provides minimal adaptation when not needed.
- Objective 2: Show the AAC regain stability in the presence of rigid body instability.
- Objective 3: Show the AAC regain stability in the presence of control-structure interaction.

◆ Current Work:

- Better quantification of the system parameters
- Replicating other launch vehicle dynamics
 - Use the Quad-Rotor to stabilize an inverted pendulum (IP).
 - Use the AAC to extend the stability margins of the IP.
 - Make the IP semi-rigid and attach sensor at tip (to mimic flexibility and non-minimum phase behaviors).