

ACERO

Robust Path Following Controller for Multirotor Vehicles in Uncertain Wind Conditions

Advanced Capabilities for Emergency Response Operations

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NOTES on Pictures



- Slides # 4 and 32
 1. IMPACT pix: [NASA-TM-20240000223.pdf](#) p. 6
 2. Weather drone pix: [NASA Armstrong Supports Wind Study - NASA](#)
 3. Bambi bucket / helicopter pix: [File:US Navy 110512-N-5226D-277 A CH-46E Sea Knight helicopter assigned to Marine Medium Helicopter Squadron \(HMM\) 364 drops water during an annual fire.jpg - Wikimedia Commons](#)
 - public domain: *This file is a work of a sailor or employee of the [U.S. Navy](#), taken or made as part of that person's official duties. As a [work](#) of the [U.S. federal government](#), it is in the [public domain](#) in the United States.*
- Slides # 12 and 13
 5. Pyrocumulus clouds pix: [File:Pine Gulch Fire.jpg - Wikimedia Commons](#)
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 6. Fire tornado pix: [File:5-fire whirl tornado devil 2.jpg - Wikimedia Commons](#)
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 7. Retardant drop / aircraft pix: [File:C-130E MAFFS dropping fire retardant Simi Fire Southern California DF-SD-05-14857.jpg - Wikimedia Commons](#)
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 - Bambi bucket / helicopter pix: See # 3 above
- Slide # 18
 - IMPACT pix: See #1 above

Motivation



ACERO Project: Improve wildfire fighting capabilities

- Accurate trajectory tracking in wildfires is important for:
 - Safe operation of vehicle
 - Accurate dispersal of fire retardant
- Wildfire scenario raises multiple issues that can influence vehicle trajectory
 - Convective winds or other external disturbances
 - Vehicle physical property changes
- Controller architecture must be able to accurately track a trajectory subject to these disturbances
 - Modular control architecture to allow for flexibility in controller objective and adaptive capabilities

Control Architecture: Needs

- Safety
- Controller(s) can remain research software
- Controller(s) and other “apps” can be *added* to vehicle of interest without changing vehicle’s certified controller
- Basic architecture proven



IMPACT
(2 kg gross)

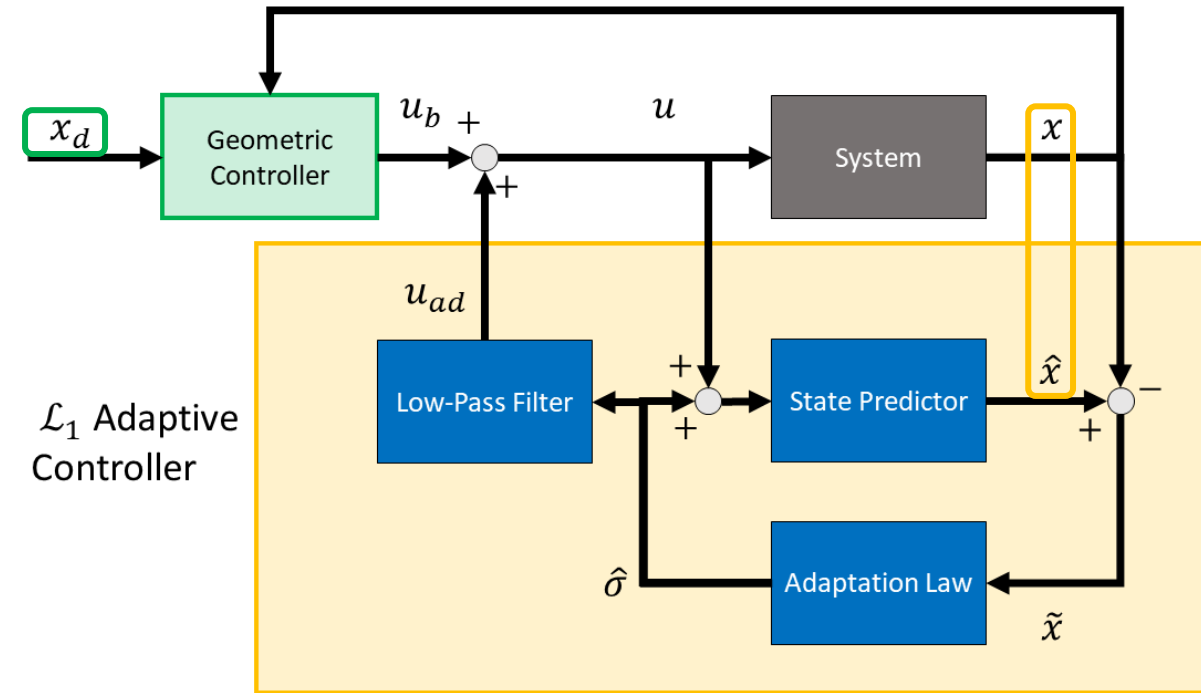


NASA/Carla Thomas
(34 kg gross)



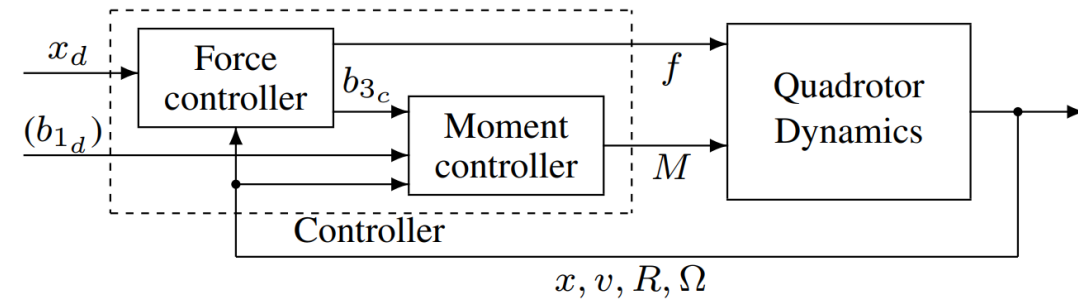
Control Architecture

- Geometric controller
 - Tracks a desired position and yaw
- $\mathcal{L}_1$ Adaptive Control:
 - Robustness to uncertainties and disturbances



Why Geometric Control?

- Control of nonlinear systems is difficult
 - Rotational dynamics of rotorcraft evolve on a nonlinear manifold
 - Linear controllers do *not* guarantee stability
- Geometric control is one method of controlling nonlinear systems
 - Popular controller design for quadrotors
 - Provides strong convergence guarantees to desired state



Geometric Control

- Inputs: desired vehicle
 - Position x_d
 - Yaw
- Outputs: desired vehicle
 - Thrust magnitude f
 - Moment vector M

$$f = (k_x e_x + k_v e_v + m g e_3 - m \ddot{x}_d) \cdot R e_3$$
$$M = -k_R e_R - k_\Omega e_\Omega + \Omega \times J \Omega$$
$$- J(\hat{\Omega} R^T R_c \Omega_c - R^T R_c \dot{\Omega}_c)$$



Geometric Control



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- Yaw

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Error terms:
want to minimize

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Geometric Control



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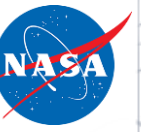
- Thrust magnitude f
- Moment vector M

$$\begin{aligned} f &= (k_x e_x + k_v e_v + m g e_3 - m \ddot{x}_d) \cdot R e_3 \\ M &= -k_R e_R - k_\Omega e_\Omega + \Omega \times J \Omega \\ &\quad - J(\hat{\Omega} R^T R_c \Omega_c - R^T R_c \dot{\Omega}_c) \end{aligned}$$

Error terms: want to minimize

Feed forward terms: proactive commands

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Diagram illustrating the control law components:

- Error terms: want to minimize** (Red box): Points to the terms $k_x e_x + k_v e_v$ in the thrust equation and $-k_R e_R - k_\Omega e_\Omega$ in the moment equation.
- Feed forward terms: proactive commands** (Blue box): Points to the terms $m g e_3 - m \ddot{x}_d$ in the thrust equation and $\Omega \times J \Omega - J(\hat{\Omega} R^T R_c \Omega_c - R^T R_c \dot{\Omega}_c)$ in the moment equation.
- Strong convergence guarantees to desired state** (Green box): Indicated by a dashed red arrow from the error terms and a dashed blue arrow from the feed forward terms.

Why $\mathcal{L}_1$ Adaptive Control?

Robustness to disturbances



Why $\mathcal{L}_1$ Adaptive Control?

Robustness to disturbances

In wildfire setting, vehicle will be subject to:

- Environmental Disturbances (e.g., convective winds)
- Vehicle physical property variations
 - Slosh loads
 - Mass reduction from release of fire retardant



Why $\mathcal{L}_1$ Adaptive Control?

Robustness to disturbances

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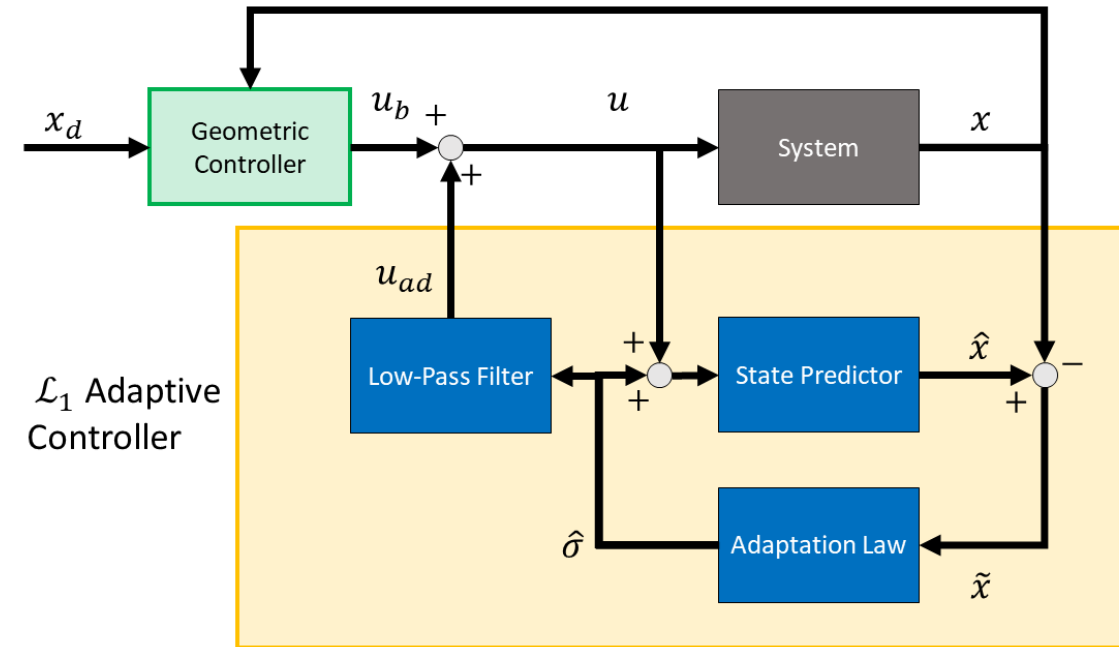
- Environmental Disturbances (e.g., convective winds)
- Vehicle physical property variations
 - Slosh loads
 - Mass reduction from release of fire retardant

The baseline controller has no knowledge of these disturbances

- $\mathcal{L}_1$ adaptive control can compensate for disturbances acting on vehicle
 - Vehicle will behave close to a nominal model
 - Graceful degradation in performance as disturbances become large

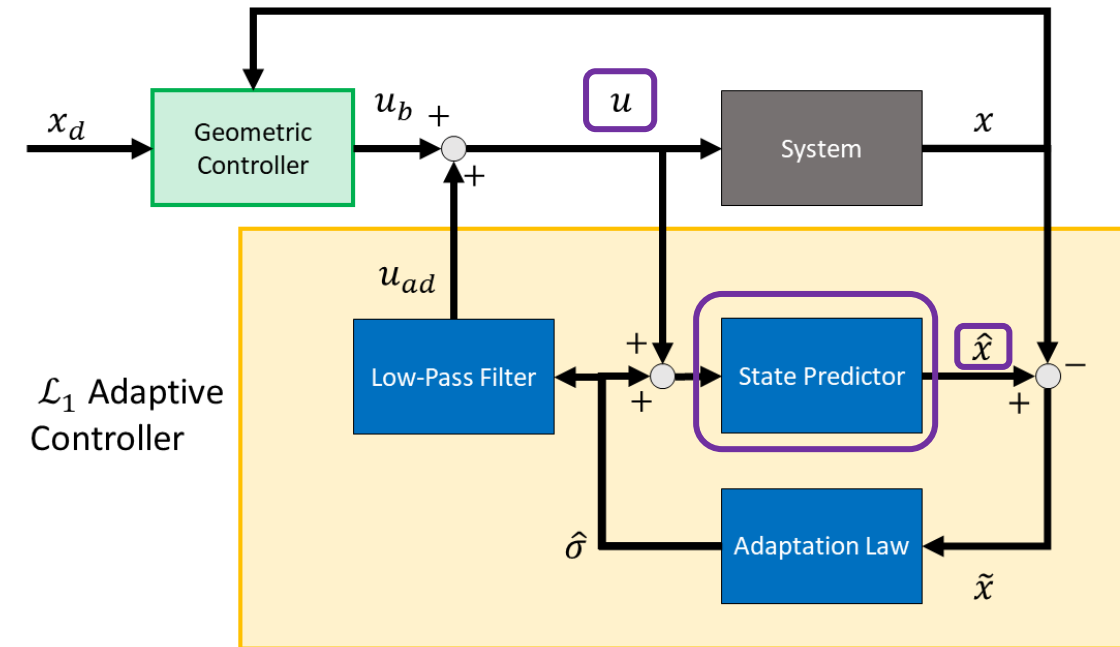


$\mathcal{L}_1$ Adaptive Control



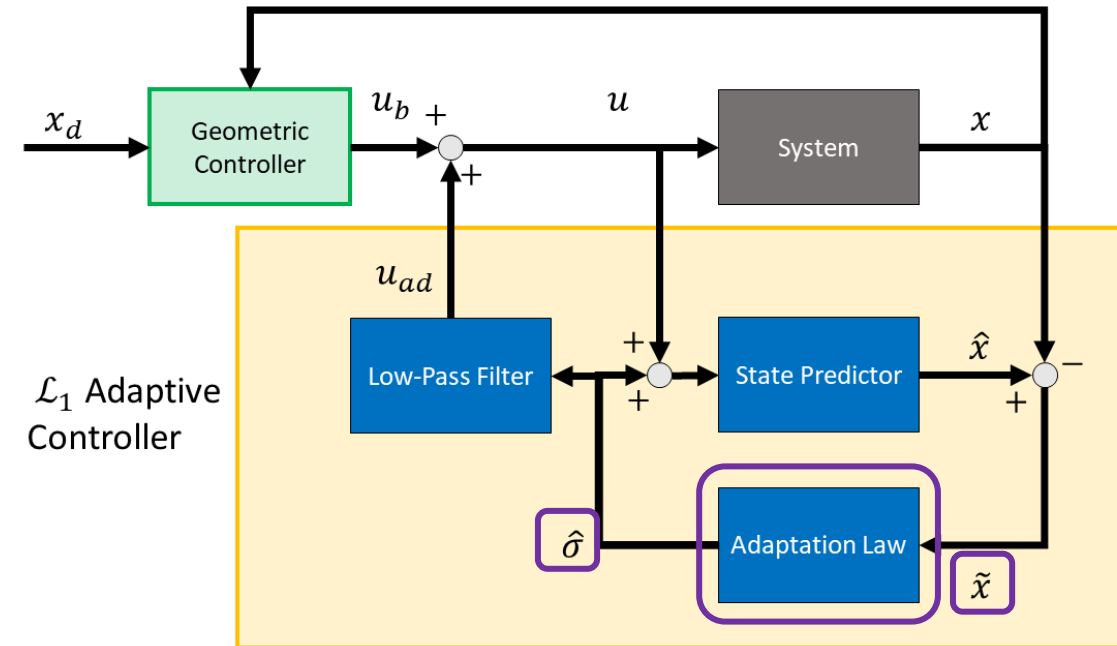
$\mathcal{L}_1$ Adaptive Control

- State Predictor
 - Given command u , where do we expect our system to be ($\hat{x}$)?



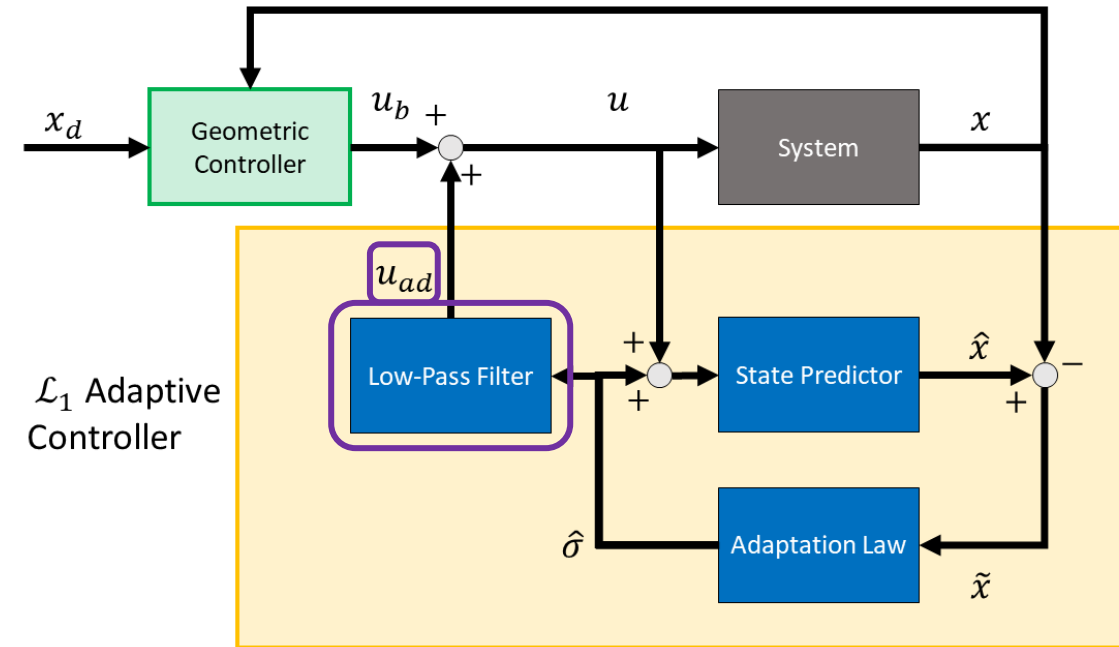
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- Adaptation Law
 - Solves for estimated uncertainty $\hat{\sigma}$ which led to difference between predicted and measured states ($\tilde{x} = \hat{x} - x$)

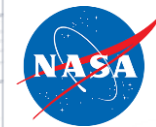


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- Low-Pass Filter
 - Computes smooth adaptive command u_{ad} which compensates for uncertainties within filter bandwidth



Simulation Testing Environment

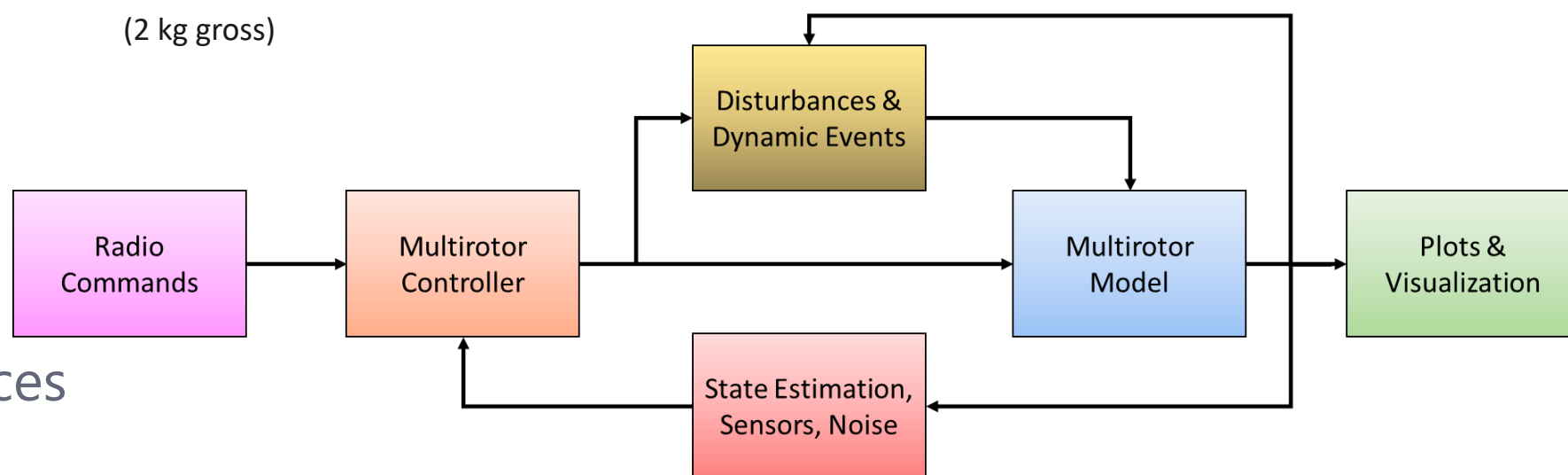


- IMPACT vehicle



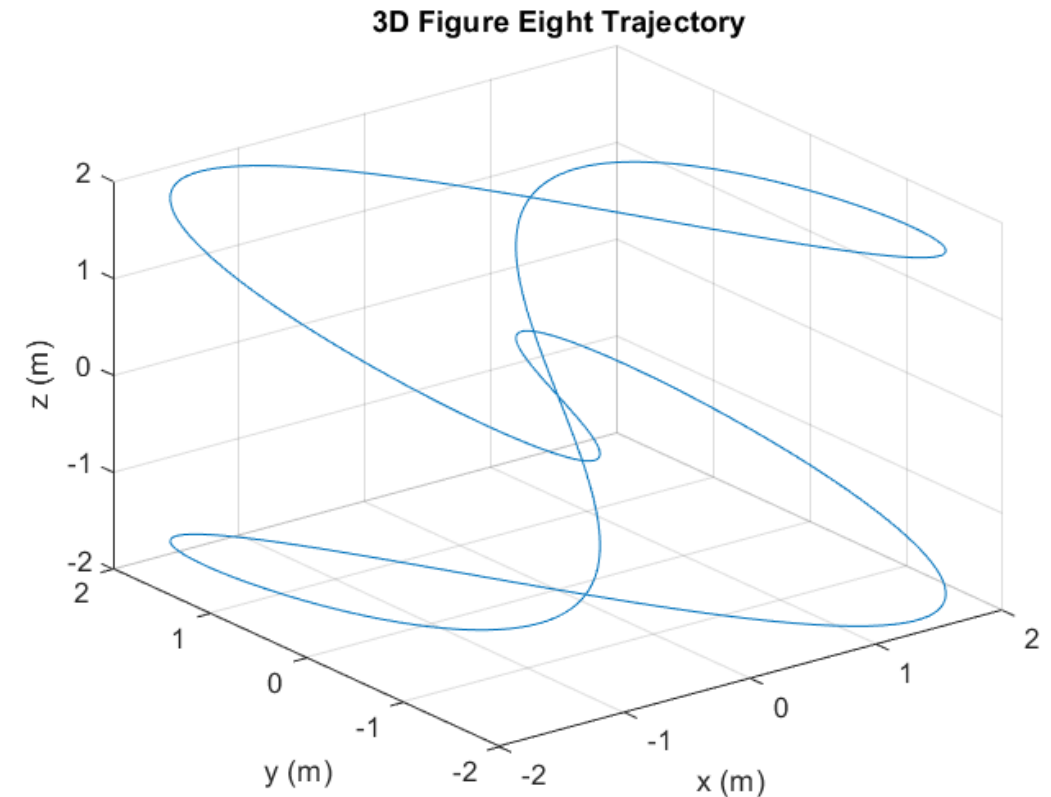
IMPACT
(2 kg gross)

- MATLAB/Simulink
 - Industry standard
 - Simulate disturbances



Sample Trajectory

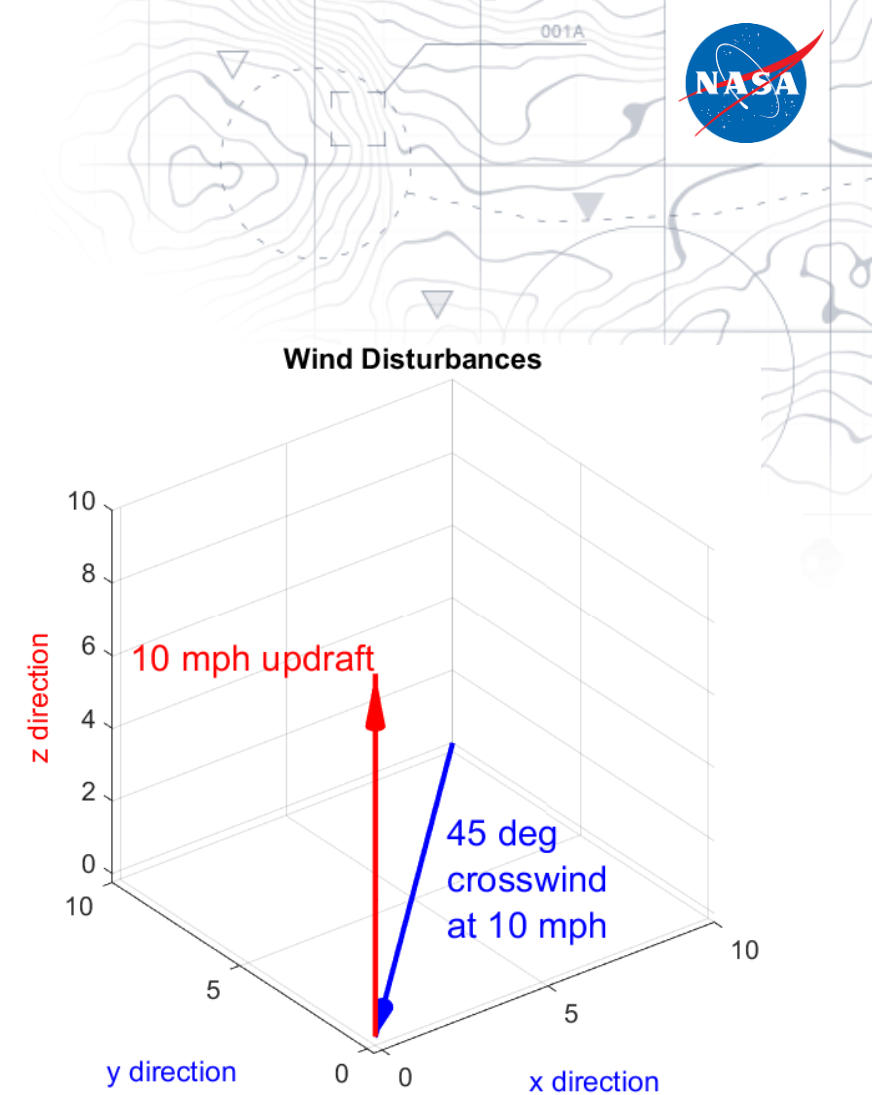
- 3D figure 8 used to demonstrate trajectory tracking
- The simulation can track a variety of trajectories
 - Trajectory must be twice-differentiable
 - Differentiability is a common requirement for reference trajectories



Simulated Disturbances

1. Wind Disturbance

- Simulates nominal horizontal wind and nominal vertical wind (updraft), each at 10 mph (~200% of max desired velocity)
- Horizontal wind comes at 45° angle (Northeast)



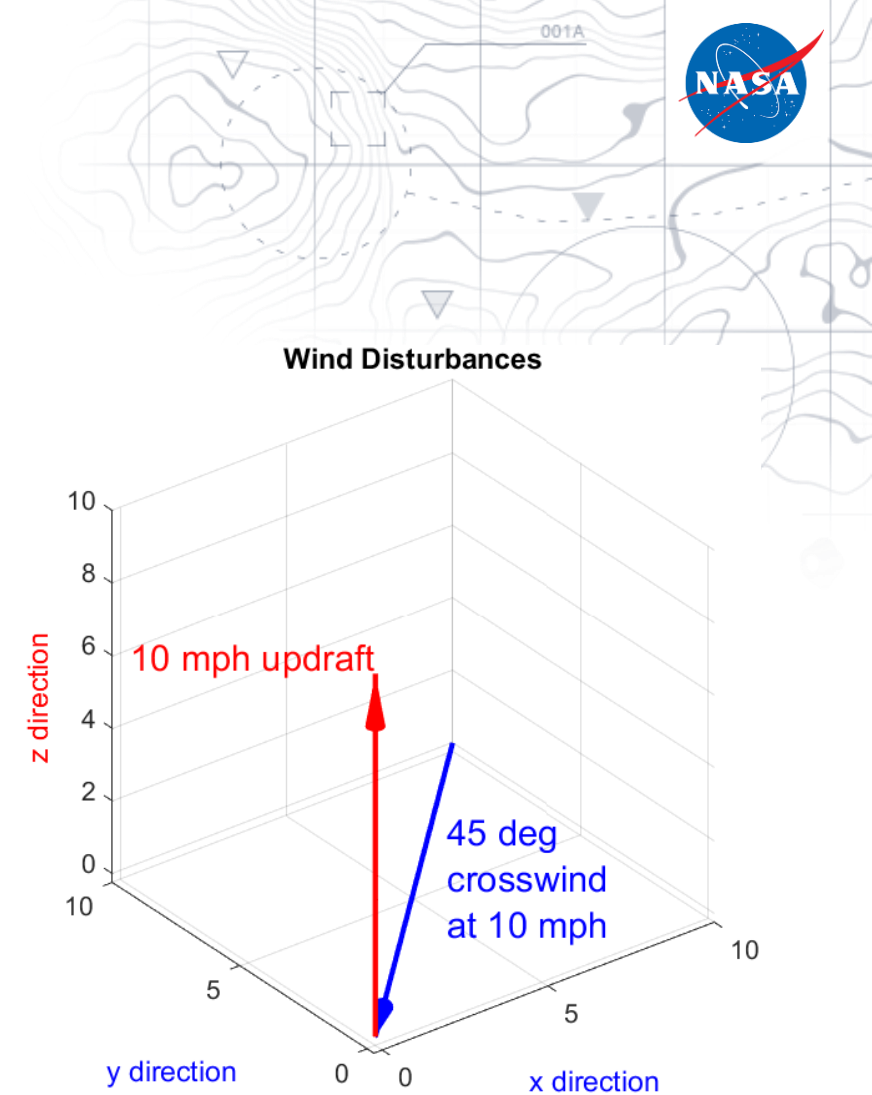
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2. Wind Disturbance and Time-Varying Mass

- Same wind disturbance as above
- Simulate a sudden 0.3 kg decrease (14%) in mass halfway through flight
 - Analogous to a payload drop



BLUF: RMS Path Errors



- Adaptive control reduces error in the z-direction
 - Thrust command acts in the same channel as the z-direction uncertainty
 - Control commands can compensate for uncertainties in the z-direction
 - None of the commands directly affect the x- and y-directions
 - Control commands cannot directly compensate for uncertainties in x- or y-direction

	Wind Disturbance			Wind & Mass Disturbances		
	No $\mathcal{L}_1$	$\mathcal{L}_1$	Error Reduction with $\mathcal{L}_1$	No $\mathcal{L}_1$	$\mathcal{L}_1$	Error Reduction with $\mathcal{L}_1$
X-Position	0.200 m	0.196 m	2.0%	0.202 m	0.180 m	10.9%
Y-Position	0.640 m	0.621 m	3.0%	0.695 m	0.581 m	16.4%
Z-Position	0.469 m	0.030 m	93.6%	3.093 m	0.113 m	96.3%
Yaw	12.410°	12.300°	0.9%	12.353°	12.340°	0.1%

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Trajectory Tracking Comparison

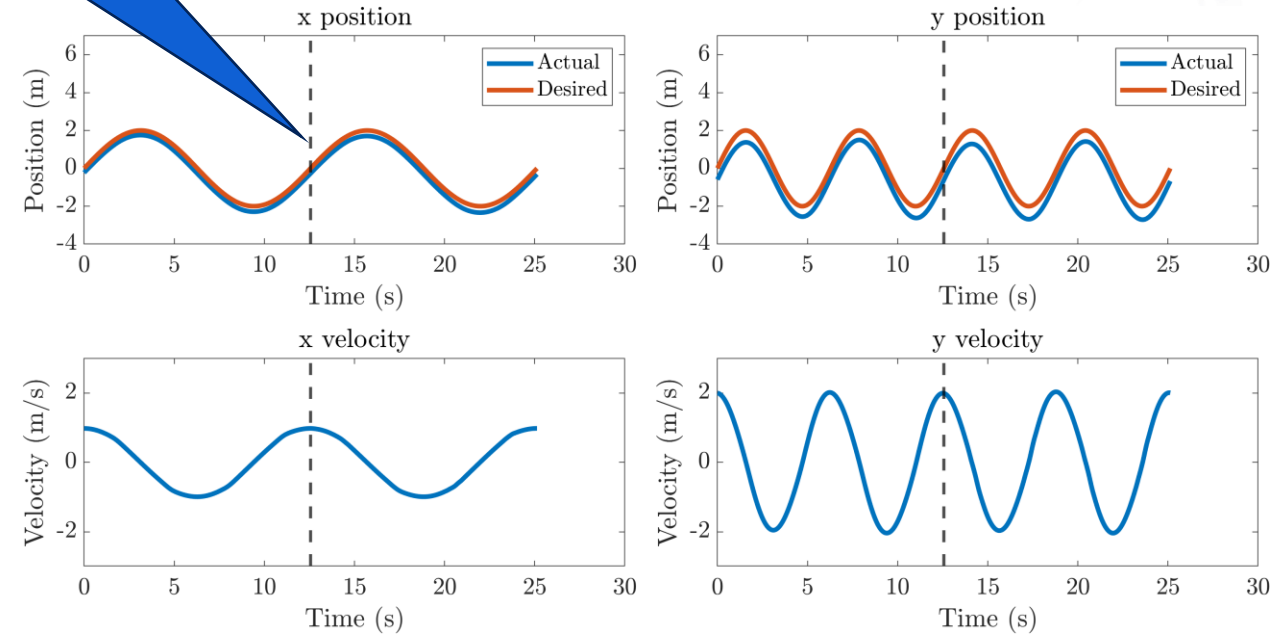
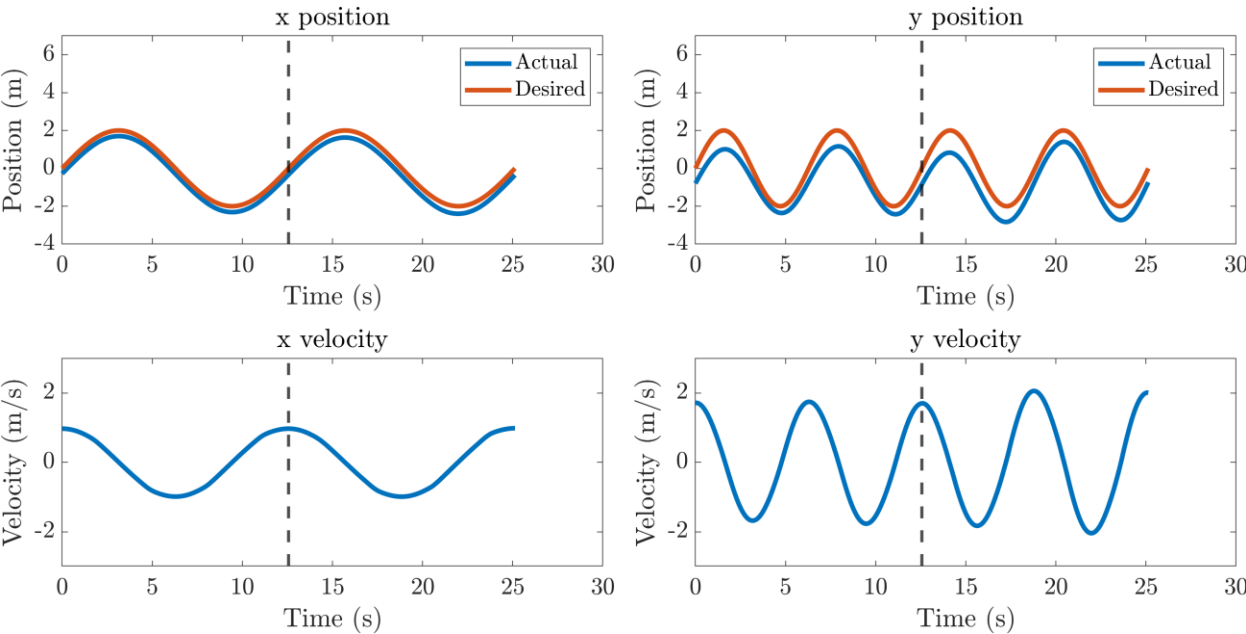
Wind + Mass Disturbances



Without $\mathcal{L}_1$

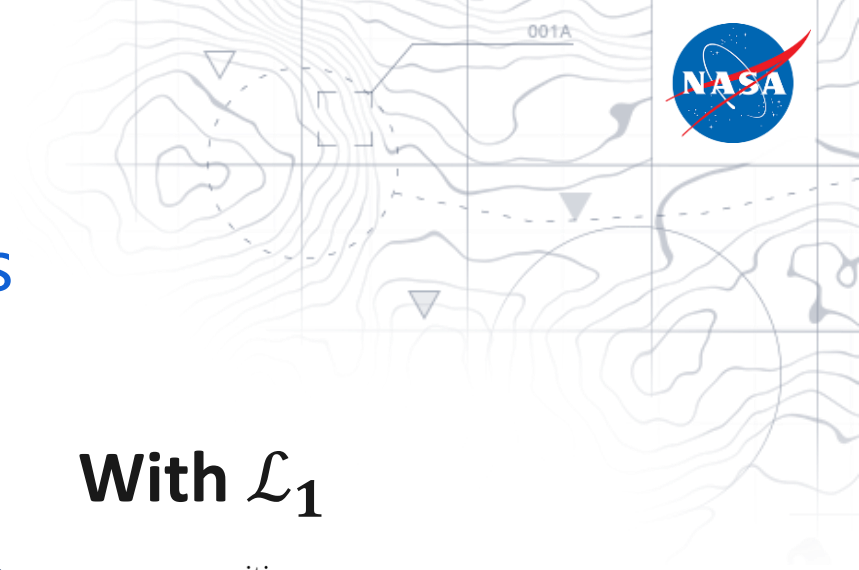
Load Release

With $\mathcal{L}_1$



Trajectory Tracking Comparison

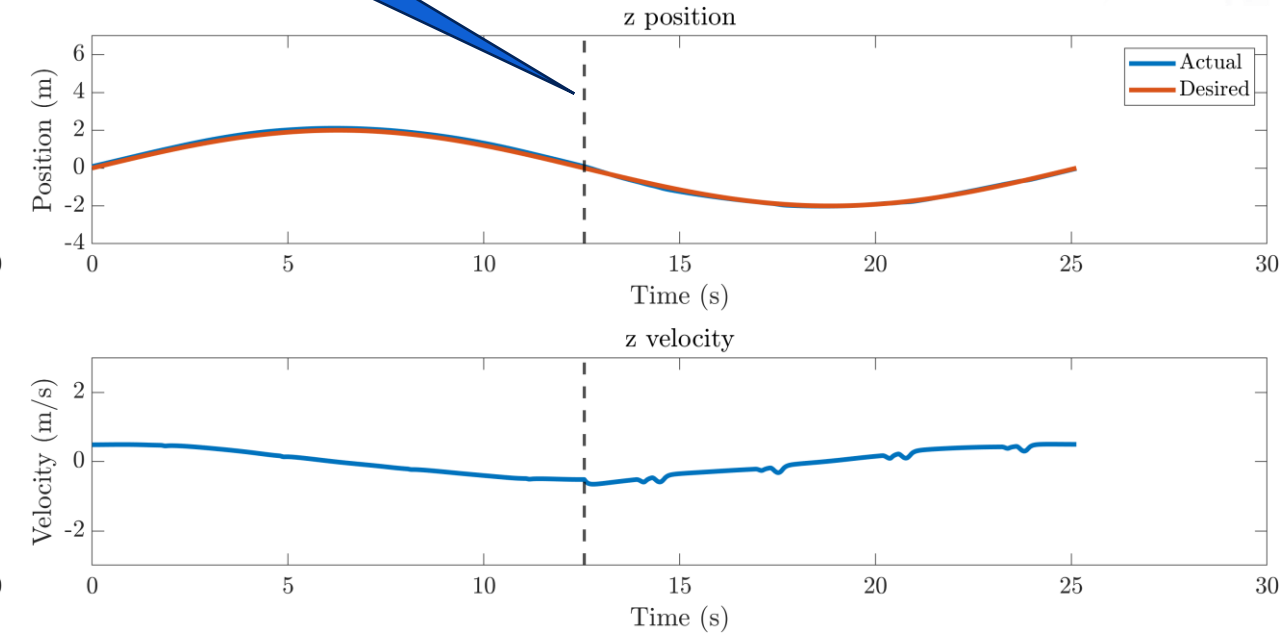
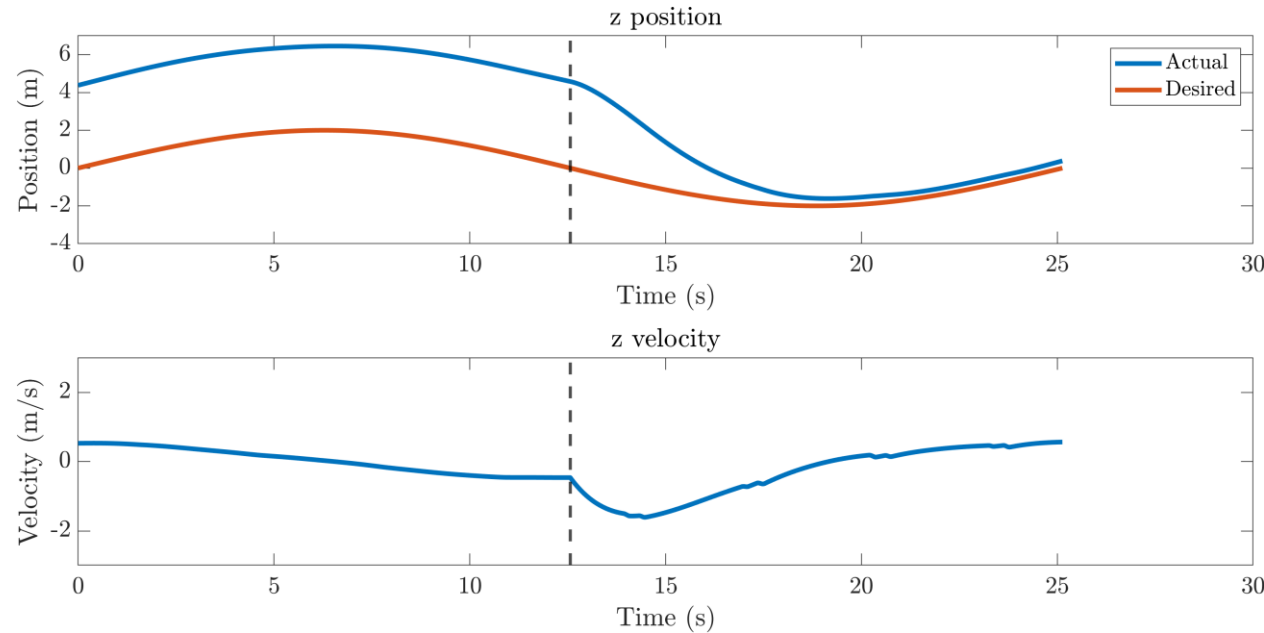
Wind + Mass Disturbances



Without $\mathcal{L}_1$

Load Release

With $\mathcal{L}_1$



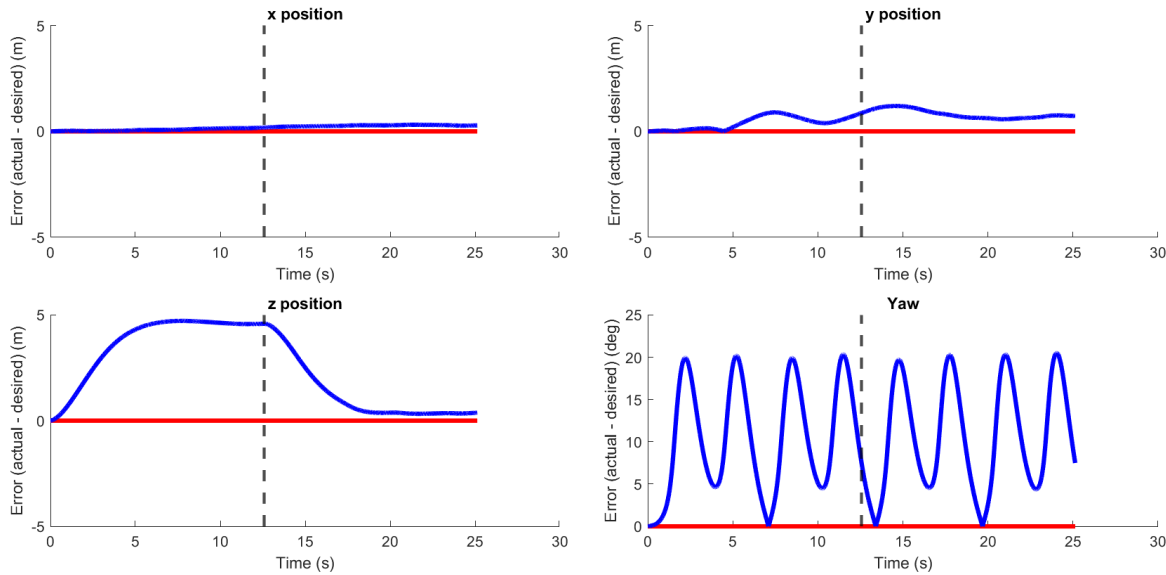
Tracking Error Performance

Wind + Mass Disturbances



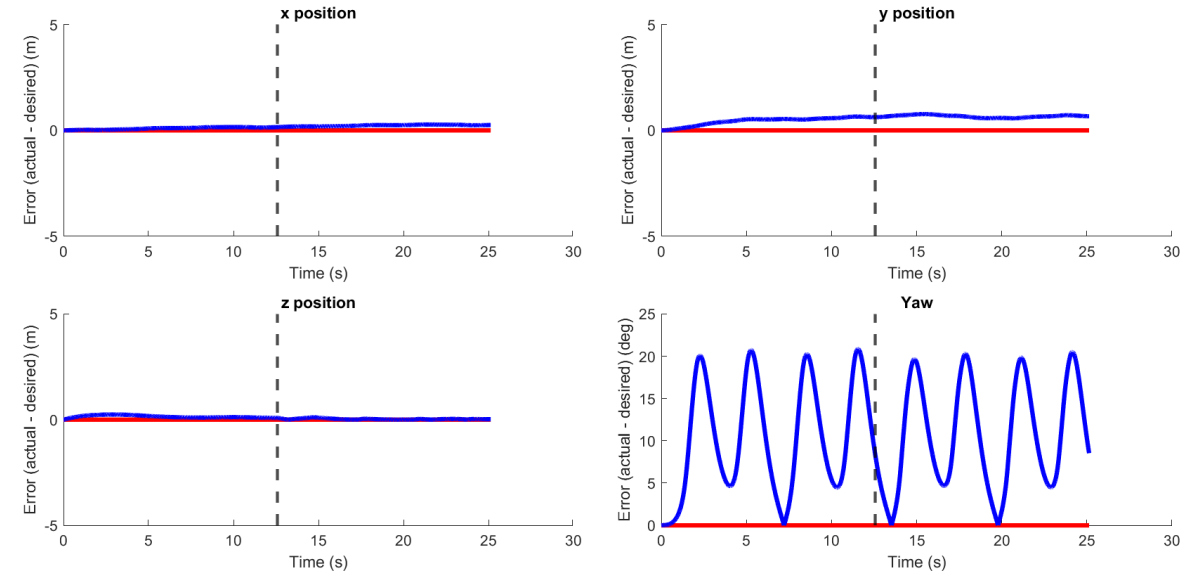
Without $\mathcal{L}_1$

Error Plots



With $\mathcal{L}_1$

Error Plots



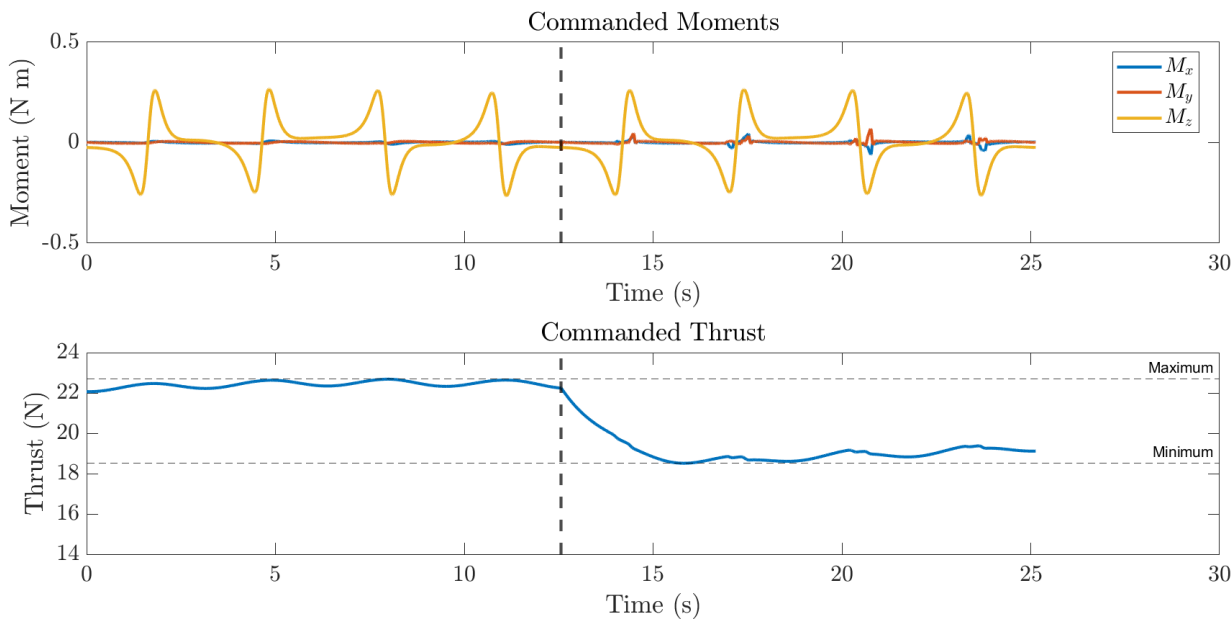
Force and Moment Commands



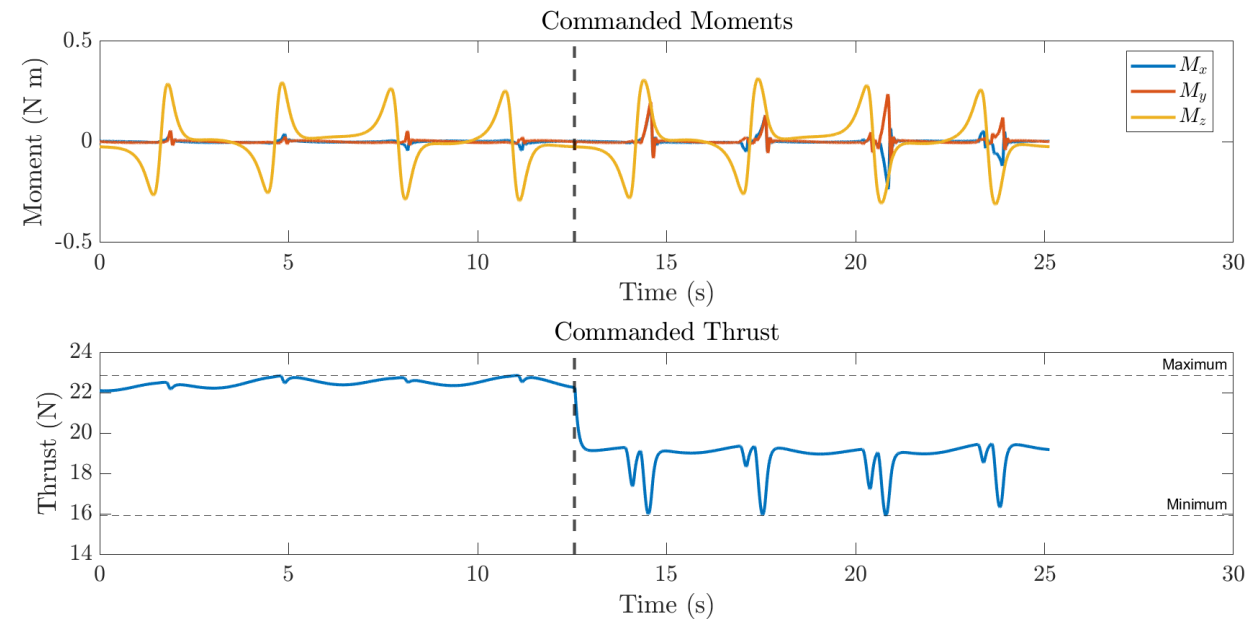
Wind + Mass Disturbances

- Max thrusts with and without $\mathcal{L}_1$ are both feasible values
 - No $\mathcal{L}_1$: 23.22 N
 - $\mathcal{L}_1$: 22.86 N

Without $\mathcal{L}_1$

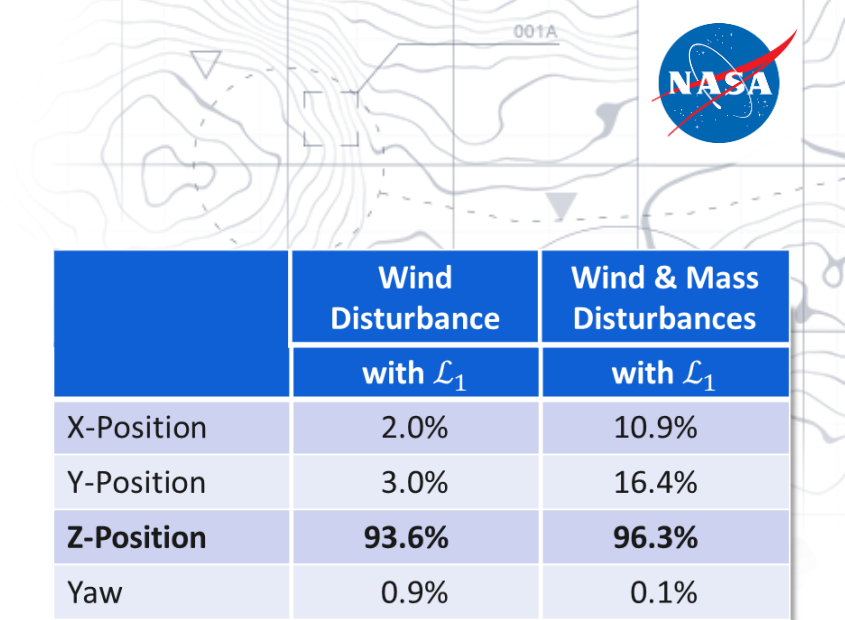


With $\mathcal{L}_1$



Conclusions

- Adaptive control reduces error in the z-direction (~93%) with unknown disturbances found in wildland fires
 - Focused on z-direction since altitude is important for firefighting operations and ground obstacle avoidance
- Next Steps:
 - Develop process to implement and tune the controllers
 - Add sling and slosh load dynamics
- Next Steps, Long Term:
 - Scale up to larger vehicles
 - Incorporate additional technology to enhance firefighting capabilities
 - Multi-agent operations



	Wind Disturbance	Wind & Mass Disturbances
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X-Position	2.0%	10.9%
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Thank you and Questions

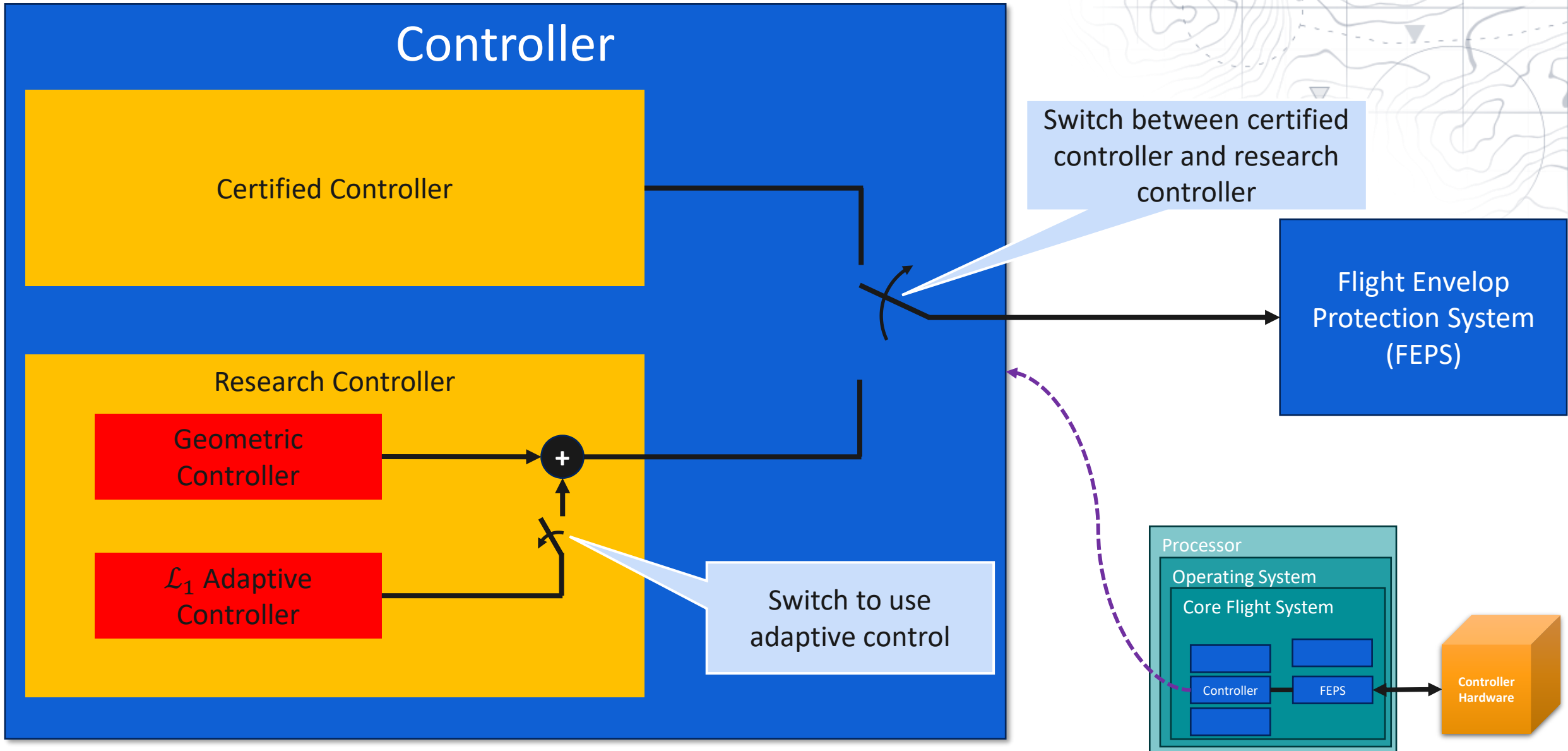
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Backup

Control Architecture: Research Development



Control Architecture: Benefits

- Safety
 - At any time, ability to easily to revert to certified controller
- Controller(s) can remain research software
 - FEPS (Flight Envelop Protection System) is Class C software
- Controller(s) and other “apps” can be *added* to vehicle of interest without changing vehicle’s certified controller
 - NASA will provide algorithms & procedures to manufacturers
- Basic architecture proven on AirSTAR
 - IMPACT is also using this general framework



IMPACT
(2 kg gross)



NASA/Carla Thomas
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