An L1 Adaptive Control Augmentation for a Lift + Cruise Vehicle

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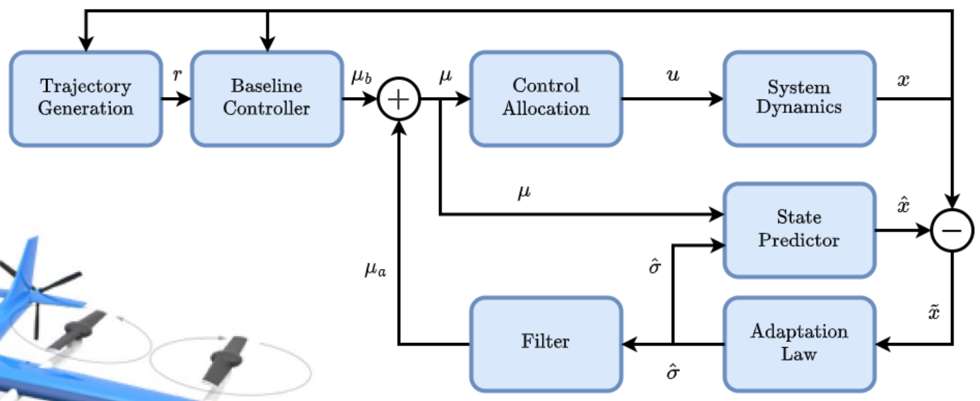
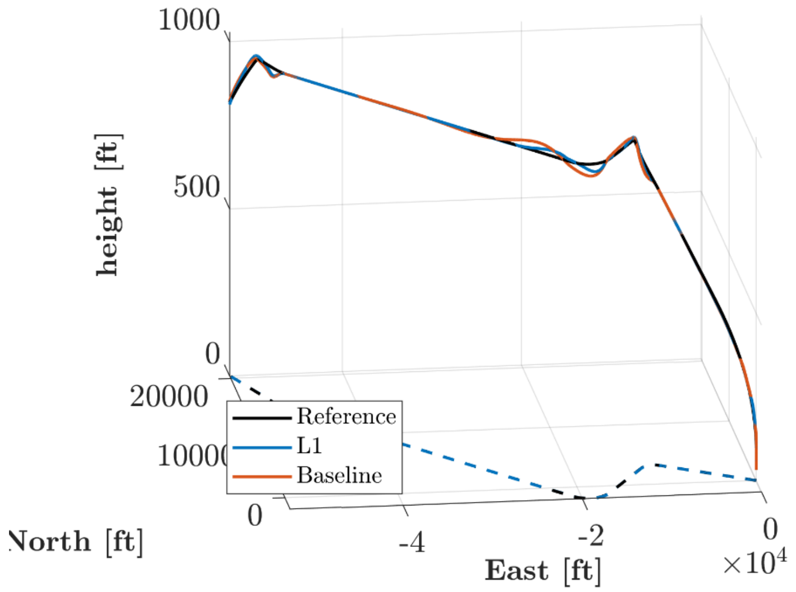




Background

- Electric vertical takeoff and landing (eVTOL) vehicles use new and dynamic configurations to meet performance and efficiency requirements.
- These configurations may require different controllers to be designed for multiple different vehicle concepts and often require different control structures for each mode of flight.
- The uniform control framework allows a controller to be designed across vehicles and modes of flight.
- However, this controller is still limited by the quality of the dynamic model used for design and must compensate for many environmental factors.

Goal: Develop an adaptive control augmentation in the uniform control framework to compensate for time and state dependent uncertainties.

L1 Adaptive Control

Goal: Develop an adaptive control augmentation in the uniform control framework to compensate for time and state dependent uncertainties.

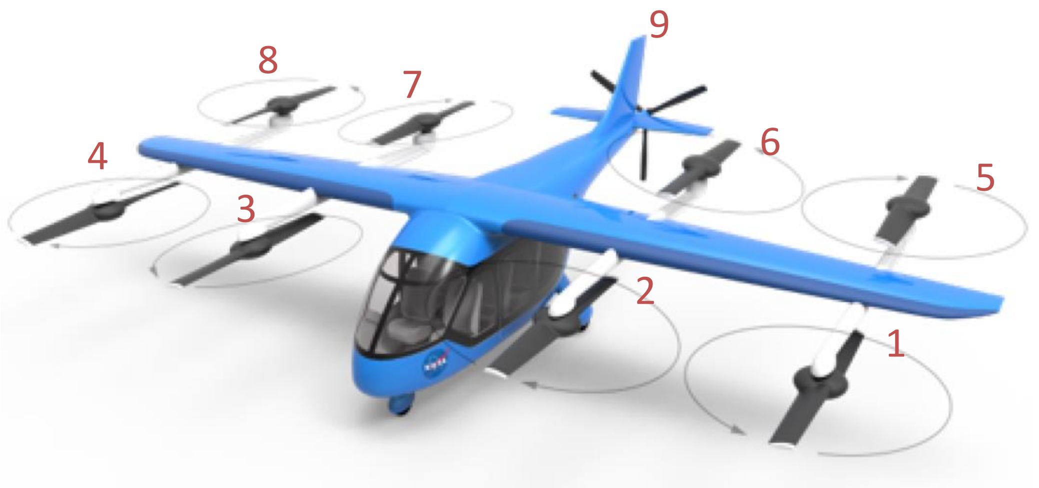
- L1 adaptive control is a design method for robust adaptive control using fast uncertainty estimation.
- Systematic design guidelines simplify trade-offs between performance, robustness, and adaptation.
- Combined with the uniform control framework, L1 can be designed for all phases of flight for AAM vehicles.

Dynamic Model

- We consider rigid body dynamics of the form:

$$\dot{p} = \mathbf{v},$$
$$\dot{\eta} = S\omega,$$
$$\dot{\bar{\mathbf{v}}} = -\dot{\psi}e_3 \times \bar{\mathbf{v}} + g + m^{-1}\bar{F}(X,u),$$
$$J\dot{\omega} = -\omega \times J\omega + \tau(X,u)$$

- Force and moment equations depend on the vehicle and the control input.
- These equations vary for each vehicle, but the structure of the dynamics and the controller stay the same.
- A strip theory approach is used to create an initial aerodynamic model[7].



NASA Reference Configuration, Lift+Cruise geometry used for demonstration

Generic dynamic model allows consideration for a large class of vehicles.

[7] Cook, J., "A Strip Theory Approach to Dynamic Modeling of eVTOL Aircraft," *AIAA SciTech*, Virtual, 2021, pp. AIAA 2021–1720.

Control Design Overview

- Select vehicle specific dynamics
- Linearize throughout flight envelope
- Select control allocation method
- Design robust uniform controller as a baseline controller[2]
- Augment the baseline controller with an L1 adaptive controller[14]

[2] Cook, J., and Gregory, I., "A Robust Uniform Control Approach for VTOL Aircraft," *VFS Autonomous VTOL Technical Meeting and Electric VTOL Symposium*, Virtual, 2021.

[14] Xargay, E., Hovakimyan, N., and Cao, C., "$\mathcal{L}_1$ Adaptive Controller for Multi-Input Multi-Output Systems in the Presence of Nonlinear Unmatched Uncertainties," *American Control Conference*, Baltimore, MD, USA, 2010, pp. 874–879.

Linearization

- Assumptions:
  - Non-turning assumption, $\dot{\psi} \equiv 0$
  - Decoupled lateral/longitudinal dynamics
- Linearized at operating points
- Linear interpolation between operating points

- Subset of state considered in control augmentation
  - Inner-loop linear and angular rate control
  - Velocities given in heading frame
- Control effectors:
  - Nine rotors, ailerons, flaps elevators, rudder

Linearized Dynamic Equations

$$\dot{x}_{\text{lon}} = A_{\text{lon}} x_{\text{lon}} + B_{\text{lon}} u$$

$$\dot{x}_{\text{lat}} = A_{\text{lat}} x_{\text{lat}} + B_{\text{lat}} u$$

Inner-loop states

$$x_{\text{lon}} = [\bar{u},\ \bar{w},\ q]^\top$$

$$x_{\text{lat}} = [\bar{v},\ p,\ r]^\top$$

Controller must change with each flight mode

Control Allocation

- Reformulate to normalize system inputs into linear and angular acceleration commands.
- Pseudo-inverse allocation maps these acceleration commands into control effector commands:

$$u_{\mathrm{lon}} = W_{\mathrm{lon}}^{-1} B_{\mathrm{lon}}^{\top} \left(B_{\mathrm{lon}} W_{\mathrm{lon}}^{-1} B_{\mathrm{lon}}^{\top} \right)^{-1} \mu_{\mathrm{lon}} .$$

- We can rewrite the system dynamics as if we were sending acceleration commands directly:

$$\dot{x}_{\mathrm{lon}} = A_{\mathrm{lon}} x_{\mathrm{lon}} + \mu_{\mathrm{lon}},$$

$$\dot{x}_{\mathrm{lat}} = A_{\mathrm{lat}} x_{\mathrm{lat}} + \mu_{\mathrm{lat}}.$$

- These equations describe the performance system.

Control Substitution

$$\mu_{\mathrm{lon}} = B_{\mathrm{lon}} u_{\mathrm{lon}}$$

Normalized control commands across all flight modes

Baseline Control Design

- Linear quadratic regulator with integrator states
- Integrator states accumulate error vs a reference state from a guidance system
- Reference command includes position and angle targets

Uniform controller structure and design across all flight modes!

Feedback Control Law

$$\mu_{\text{lon}} = -\left[K_{i,\text{lon}},\ K_{x,\text{lon}}\right] \begin{bmatrix} x_{i,\text{lon}} \\ x_{\text{lon}} \end{bmatrix}$$

Integrator Dynamics

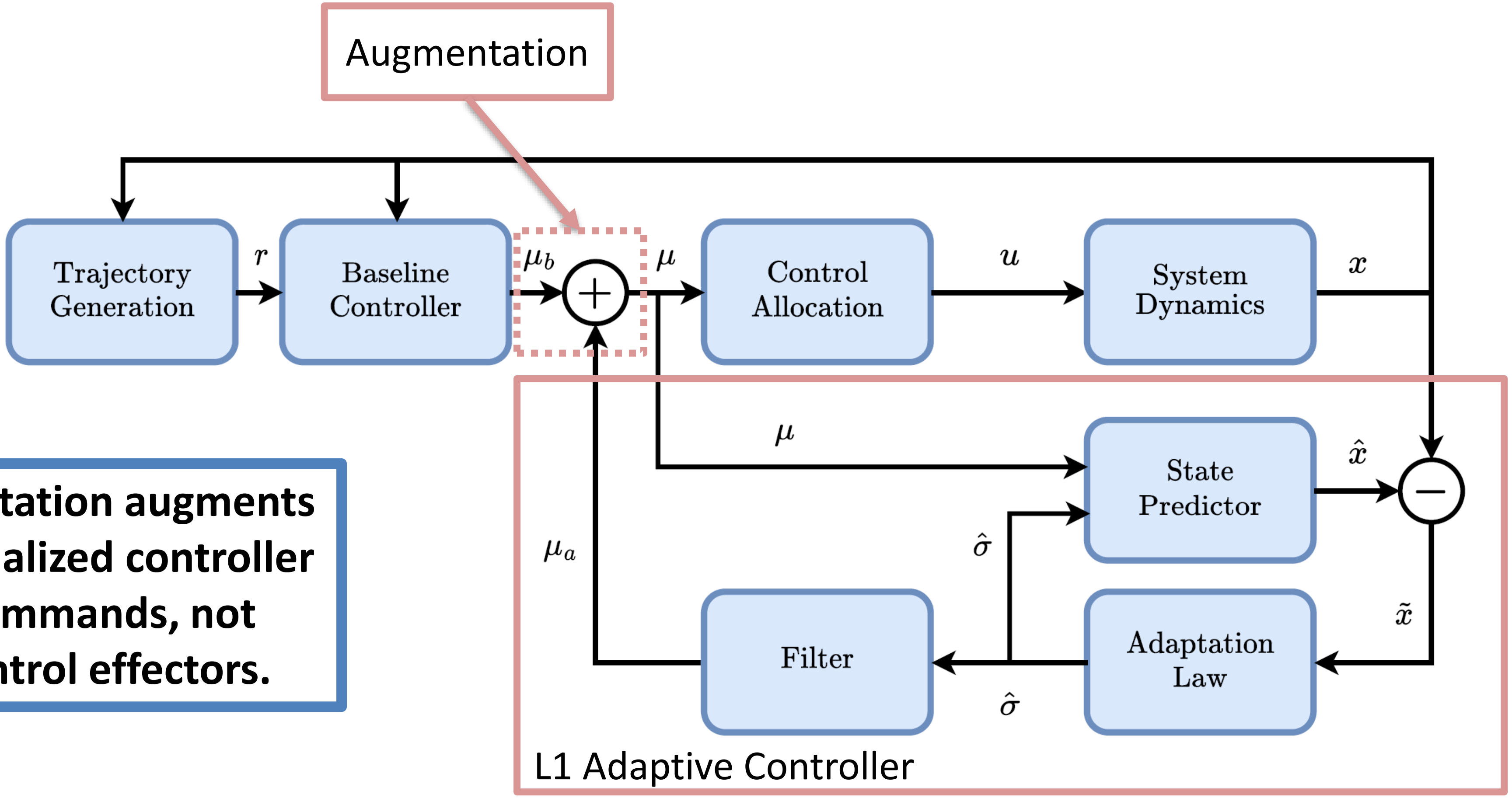
$$\dot{x}_{i,\text{lon}} = x_{i,\text{lon}} - r_{\text{lon}}$$

[2] Cook, J., and Gregory, I., "A Robust Uniform Control Approach for VTOL Aircraft," *VFS Autonomous VTOL Technical Meeting and Electric VTOL Symposium*, Virtual, 2021.

[3] Acheson, M., Gregory, I., and Cook, J., "Examination of Unified Control Incorporating Generalized Control Allocation," *AIAA SciTech*, Virtual, 2021, pp. AIAA 2021–0999.

L1 Design Overview

Adaptive controller takes system state and computes an adjustment to the baseline control command to attenuate disturbances and uncertainties.



Adaptation augments normalized controller commands, not control effectors.

L1 Design – State Predictor

- The state predictor is based on the performance system dynamics

$$\dot{\hat{x}}(t) = Ax(t) + \mu(t) + \hat{\sigma}(t) + L\tilde{x}(t)$$

Performance Model — Uncertainty Estimate — Direct prediction error gain

State Prediction Error

$$\tilde{x} := \hat{x} - x$$

- **Uncertainty estimate** from adaptation law – nonparametric estimate of uncertainty that led to system errors.
- **Prediction error** gain – design parameter, allows designer to improve convergence of state prediction. Chosen so that As=A+L is a Hurwitz matrix.

State predictor structure fixed throughout all flight modes.

L1 Design – Adaptation Law

- Piecewise constant adaptation formulation, uses a gain based on discrete time solution of linear system.
- Prevents need to solve additional dynamic equations with projection law.

$$K_a = -\left(A_s^{-1}\left(\text{expm}(A_s T_s) - \mathbb{I}\right)\right)^{-1} \text{expm}(A_s T_s)$$

- The gain projects state predictor error into uncertainty estimate.

$$\hat{\sigma}(t) = \hat{\sigma}(iT_s) = K_a \tilde{x}(iT_s), \quad \forall t \in [iT_s, (i+1)T_s)$$

- This gain can be scheduled with in the same way as the system dynamics.
- Note that there is no control effectiveness matrix due to our choice of the performance system as the reference model.

L1 Design – Control Law

- While we compute the full uncertainty estimate from the adaptation law, a filtered uncertainty is used in the control law.
- The filter must be a lowpass filter with a DC gain of 1.
- In this work, we choose a 4^{th} order Butterworth filter with a fixed cutoff frequency of 0.5 Hz.

Control Law

$$\mu_a(s) = C(s)\hat{\sigma}(s)$$

Tuning Parameters

- The tunable parameters in this formulation are the filter, C(s), which can be chosen using knowledge of the system dynamics and the prediction error gain, L, which can be chosen arbitrarily up to solver speed constraints.
- Adjustments due to controller sample rate are automatically compensated for in the structure of the adaptation gain.

Simulation Experiment Setup

Simulation
- Simulink®-based 6-DOF nonlinear rigid body
- Strip-theory aero-propulsive model of the Lift+Cruise aircraft
- Unified control architecture across all three modes of flight (hover, transition and cruise)

Uncertainties
- Motor dynamics (1st order)
- linearization/assumptions
- winds

Wind Velocity

x – 50 [ft/s], y – 0 [ft/s], z – 0 [ft/s]

Operating Point Turbulence Distribution
(Dryden Wind Turbulence Model, low altitude)

x ~ Normal(0,100) [ft/s], BW = 0.25 Hz

y ~ Normal(0,100) [ft/s] , BW = 0.25 Hz

z ~ Normal(0,33) [ft/s] , BW = 0.25 Hz

Exp. No.	Description
1	Position hold
2	Fwd velocity: 50 fps
3	Fwd velocity: 100 fps
4	Fwd velocity: 200 fps
5	Accelerate: 0 to 50 fps
6	Accelerate: 0 to 100 fps
7	Accelerate: 0 to 200 fps

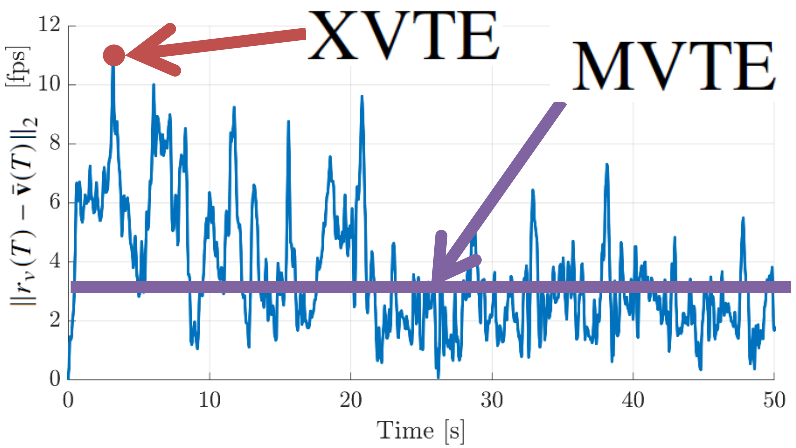
Trajectory Definition
- Multiple tests, defined in table
- Each experiment has fixed duration

Number of trials per experiment (variation in turbulence)
- ~50 trials

Performance Metrics

- Mean and Max Velocity Tracking Error

$$\mathrm{MVTE}(r, \bar{\mathbf{v}}) = \mathrm{mean}\left(\|r_v(T) - \bar{\mathbf{v}}(T)\|_2\right)$$
$$\mathrm{XVTE}(r, \bar{\mathbf{v}}) = \max\left(\|r_v(T) - \bar{\mathbf{v}}(T)\|_2\right),$$



- These metrics are evaluated for each trial individually.
- The 2-norm captures the pointwise-in-time velocity tracking errors across all spatial dimensions.
- The mean and max operations are taken across all times, creating a single value.
- To discuss the performance in a specific experiment, the average may be taken across all trials as well.

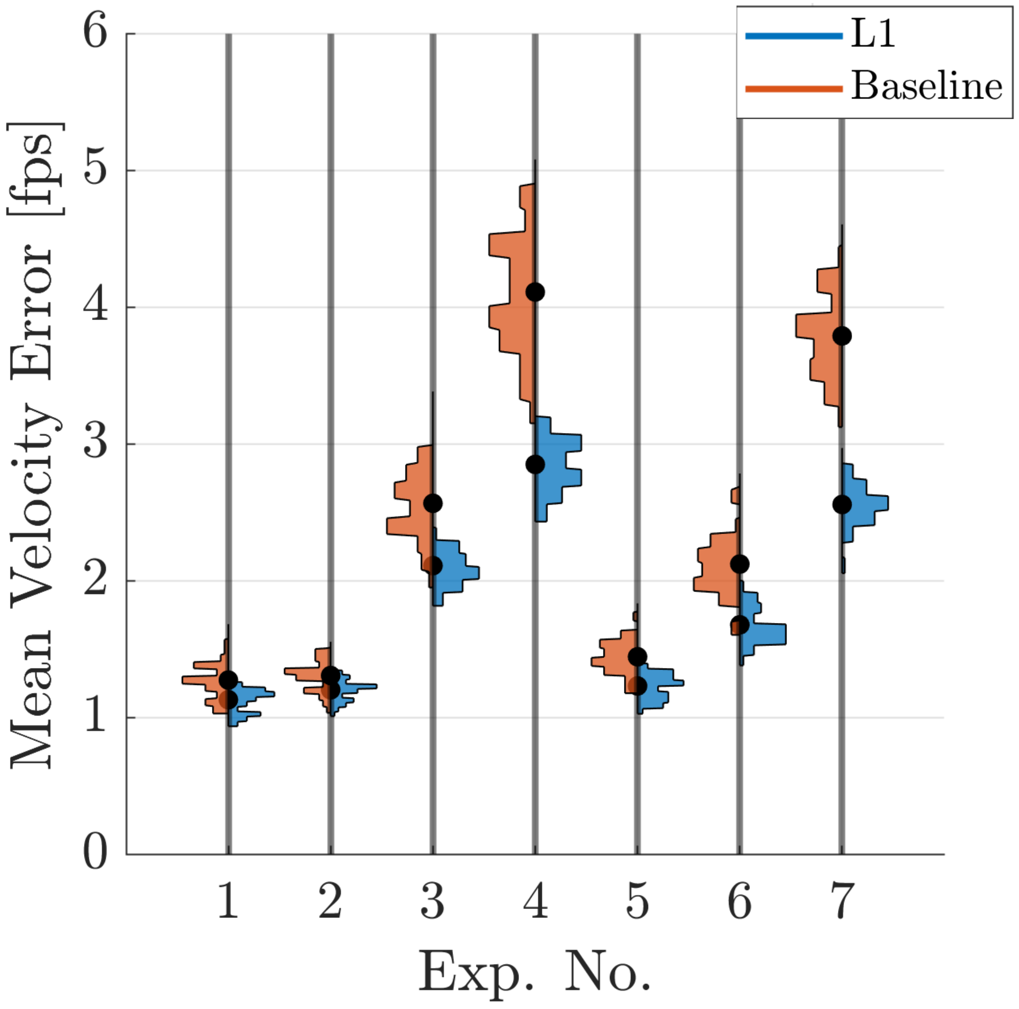
Results – Nominal Trajectories

Exp. No.	Description
1	Position hold
2	Fwd velocity: 50 fps
3	Fwd velocity: 100 fps
4	Fwd velocity: 200 fps
5	Accelerate: 0 to 50 fps
6	Accelerate: 0 to 100 fps
7	Accelerate: 0 to 200 fps

The L1 controller performs better across the board.

- **Better on average**
- **Smaller dispersion**
- **Lower error scaling**

The differences are more pronounced with larger trajectory velocities.



Histograms of performance in each trial of the experiments.

Results – Nominal Trajectories

Exp. No.	Description
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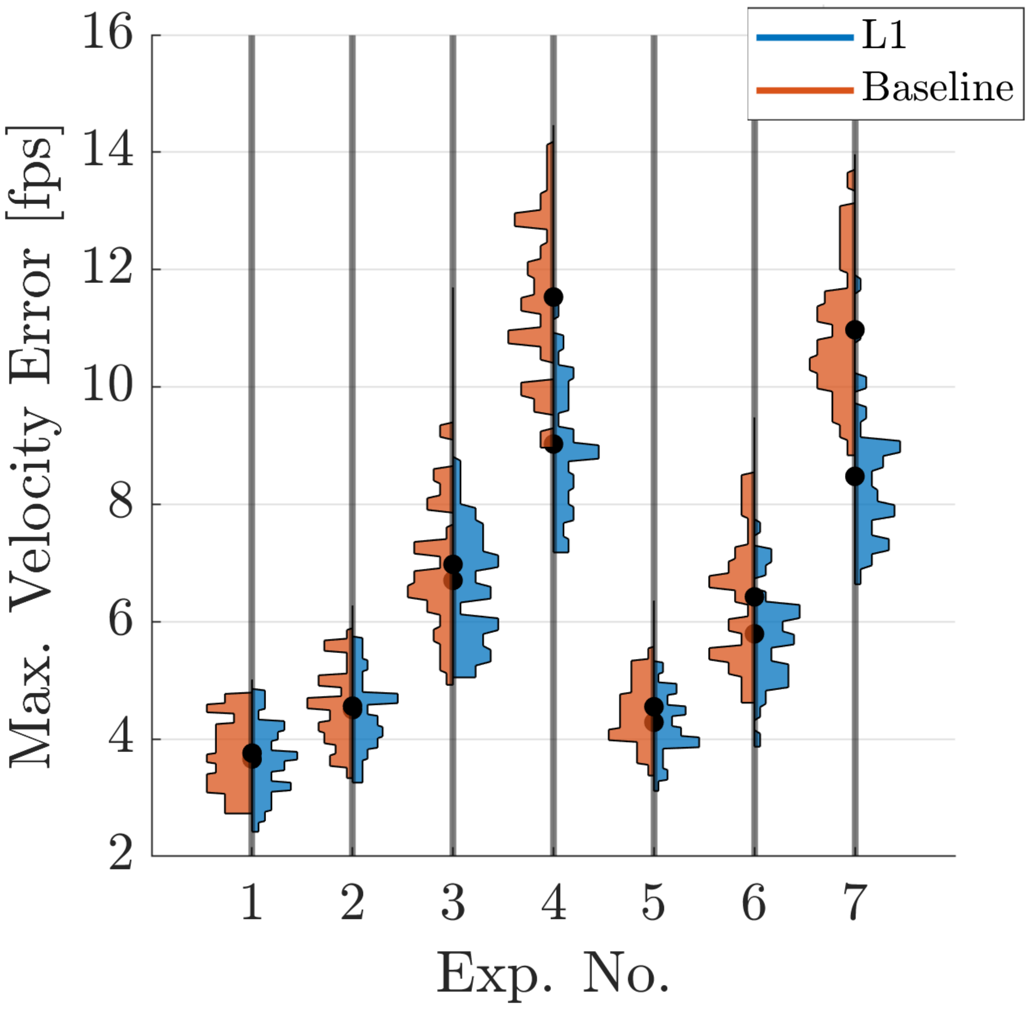
5	Accelerate: 0 to 50 fps
6	Accelerate: 0 to 100 fps
7	Accelerate: 0 to 200 fps

The L1 controller performs similarly to the baseline in Experiments 1 and 2. L1 performs better in experiments with larger trajectory velocities.

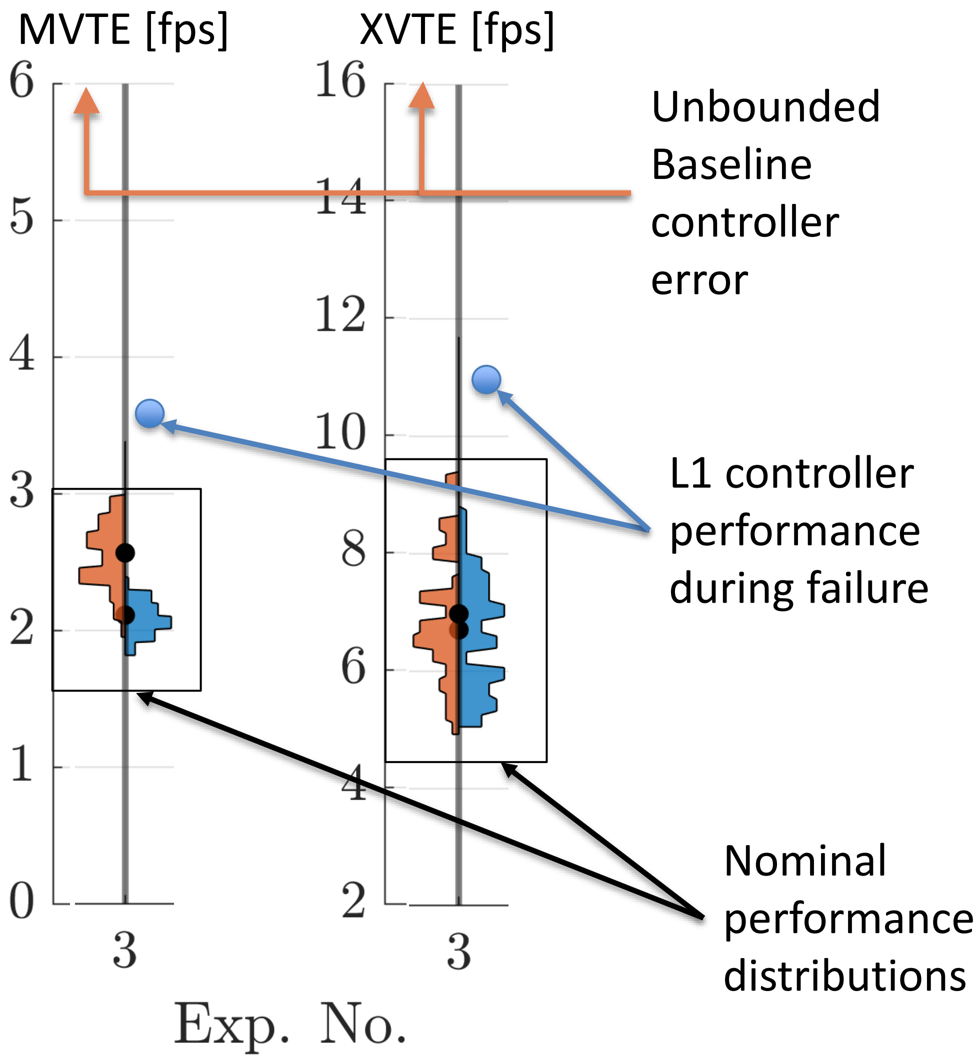


Histograms of performance in each trial of the experiments.

Results – Rotor Failure

- Fail two inboard, forward rotors during an Experiment 3 trial.
- Not a sympathetic failure, chosen to generate unstable longitudinal behavior.
- L1 controller runs for full experiment duration.

- **Baseline controller is unstable without adaptation. Unrecoverable in <10 s.**
- **No time for system identification or smart allocation.**



Conclusion

- We have presented an L1 adaptive control design that augments the unified control framework for advanced air mobility vehicles.
- The control design is demonstrated in a high-fidelity dynamic simulation for a Lift + Cruise vehicle.
- The adaptive controller is shown to reduce velocity tracking error metrics.
- Future work will focus on integrating L1 with a nonlinear baseline controller and incorporating learning methods into the control framework.

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NASA