

Transformational Tools and Technologies (T³) Project

Trajectory Planning and Online Performance Model Estimation for Advanced Air Mobility

Tenavi Nakamura-Zimmerer*, Andrew Patterson*,
Michael J. Acheson*, Irene M. Gregory*



*NASA Langley Research Center

AIAA SciTech, Orlando, FL
January 7, 2025

G&C for Advanced Air Mobility (AAM)

- Revolution in aviation enabled by diverse eVTOL aircraft
 - Over-actuated; nonlinear and uncertain dynamics
- Need high levels of *automation* and *autonomy* in *off-nominal* conditions
- Prior research explores *optimal control* for *integrated G&C* + fault detection and mitigation
 - High computational demand, uncertain convergence
- Realistically, G&C in *separate loops* and *abstraction levels*
 - *Bring your own controller!*
 - Optimal control used for high-level guidance with simplified *performance model*

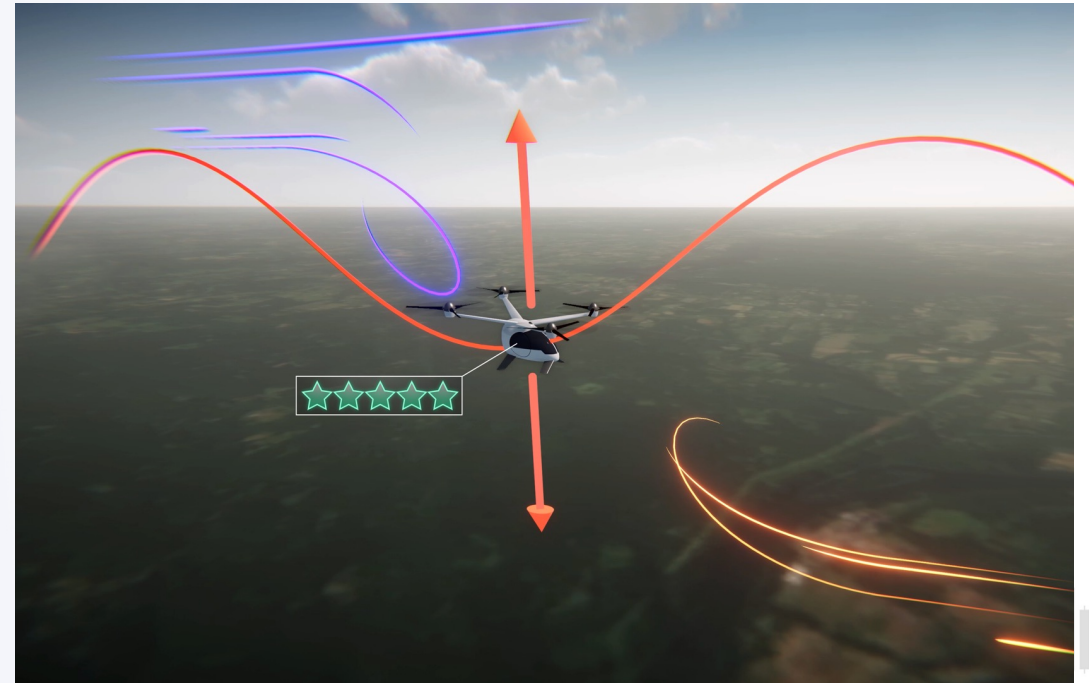
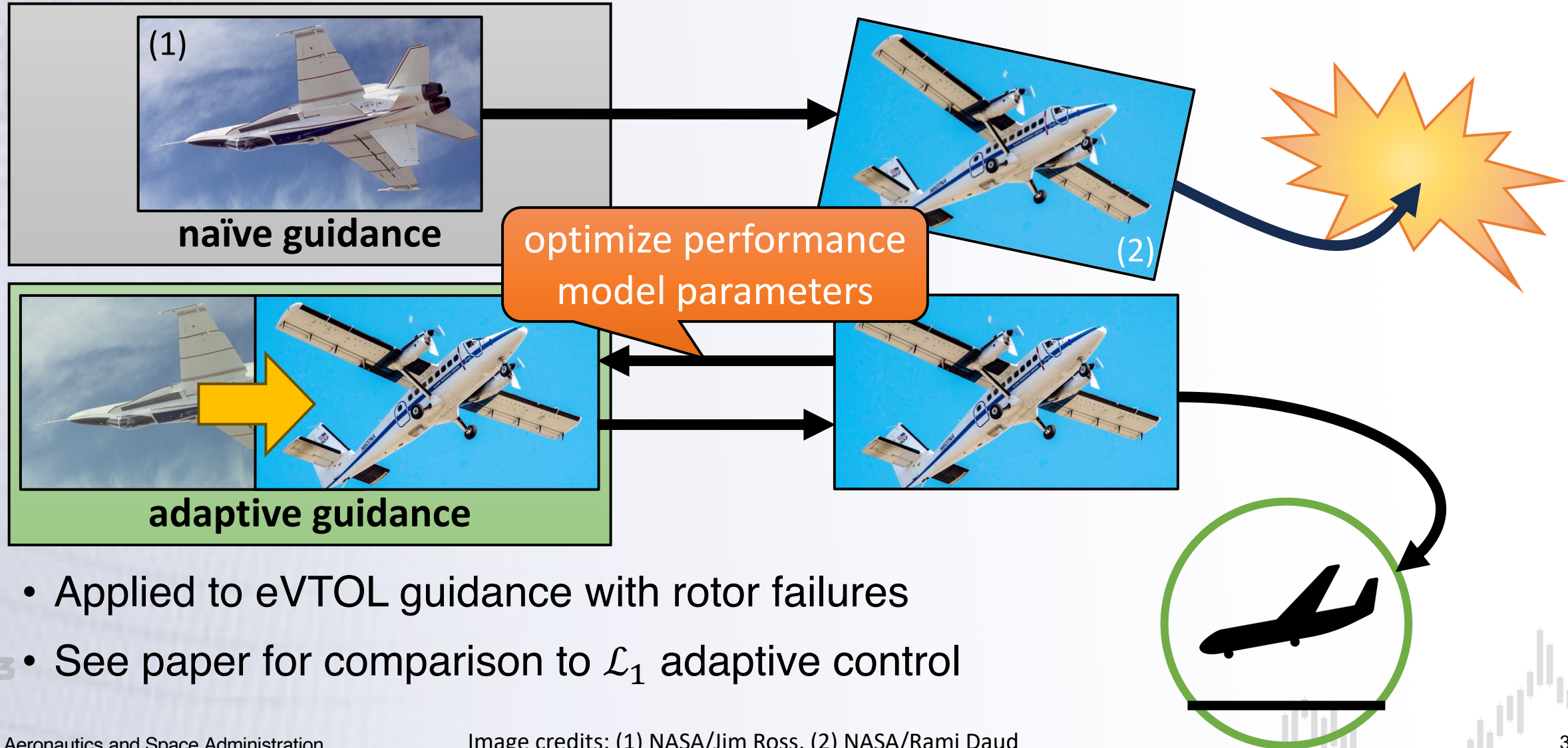


Image credit: NASA/Kyle Jenkins

Guidance and estimation with performance models



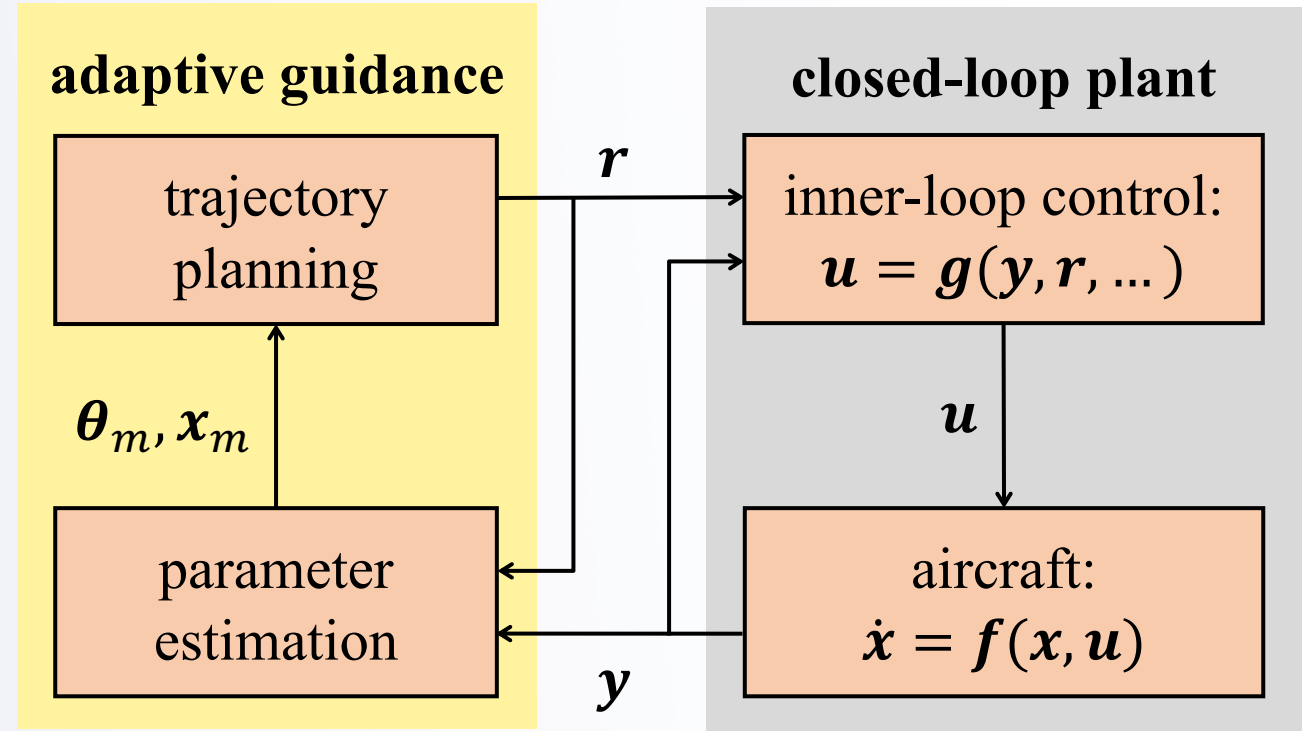
- Applied to eVTOL guidance with rotor failures
- See paper for comparison to $\mathcal{L}_1$ adaptive control

Methodology overview

Online, repeatedly solve *optimal control/estimation* problems with *parameterized dynamics model*:

$$\dot{\mathbf{x}}_m = \mathbf{f}_m(\mathbf{x}_m, \mathbf{r}; \boldsymbol{\theta}_m)$$

1. From measurements $\mathbf{y}$, optimize model state $\mathbf{x}_m$ and parameters $\boldsymbol{\theta}_m$
2. Optimize future trajectory and reference commands, $\mathbf{r}$



* In this study, optimal control problems solved with Differential Dynamic Programming (DDP)

** Guidance with simplified models is not new—novelty is optimal trajectory planning and performance model parameter estimation, with new inner-loop models for AAM

Aircraft performance models

Guidance model (e.g., aircraft kinematics):

$$\dot{\mathbf{x}}_g = \mathbf{f}_g(\mathbf{x}_g, \mathbf{u}_g; \boldsymbol{\theta}_g)$$

output of inner-loop control
(e.g., velocities, attitude),
tracks reference command, $\mathbf{r}$

Linear closed-loop performance model:

$$\dot{\mathbf{z}} = (\mathbf{A} + \hat{\mathbf{A}}_\Delta)\mathbf{z} + \mathbf{B}\hat{\boldsymbol{\omega}}\mathbf{r} + \boldsymbol{\sigma}, \quad \hat{\mathbf{u}}_g = \mathbf{C}\mathbf{z}$$

from closed-loop linear system

parameters estimated online

reference command

inner-loop state

Combined model:

$$\mathbf{x}_m = \begin{pmatrix} \mathbf{x}_g \\ \mathbf{z} \end{pmatrix}, \quad \mathbf{f}_m(\mathbf{x}_m, \mathbf{r}; \boldsymbol{\theta}_m) = \begin{pmatrix} \mathbf{f}_g(\mathbf{x}_g, \mathbf{C}\mathbf{z}; \boldsymbol{\theta}_g) \\ (\mathbf{A} + \hat{\mathbf{A}}_\Delta)\mathbf{z} + \mathbf{B}\hat{\boldsymbol{\omega}}\mathbf{r} + \boldsymbol{\sigma} \end{pmatrix}$$

Application example

- NASA Lift plus Cruise concept aircraft
- RSLQR (robust servomechanism LQR) inner-loop tracking control
- Aggressive collision avoidance maneuver in transition
- Compare kinematic, kinematic + inner loop, and 6DoF guidance models

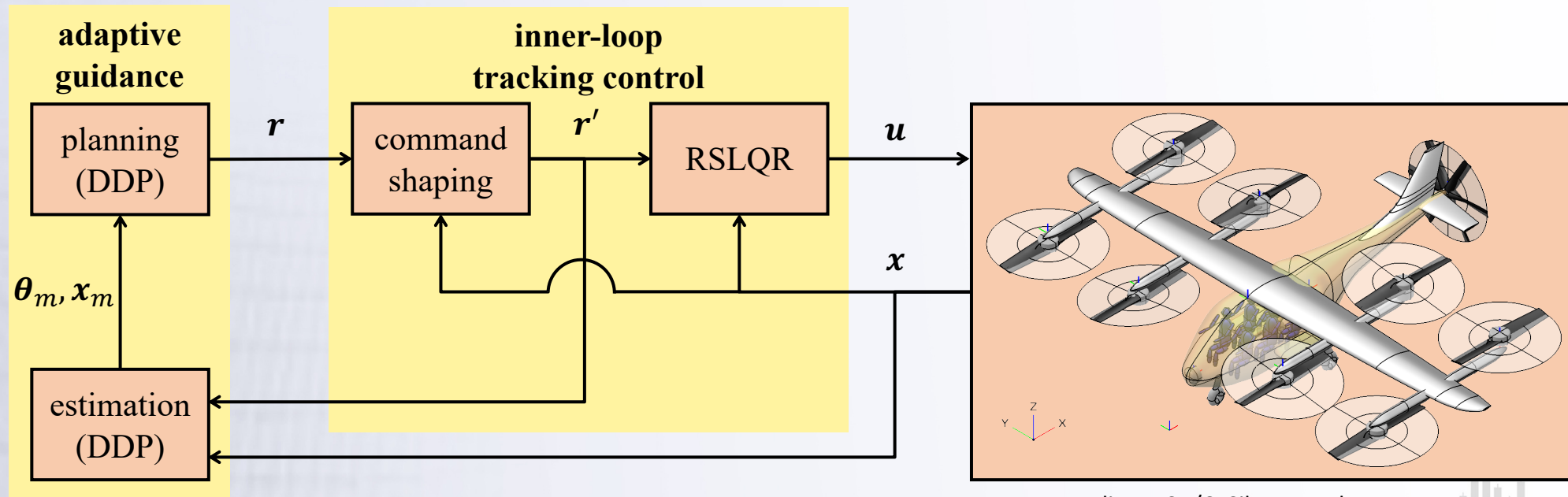


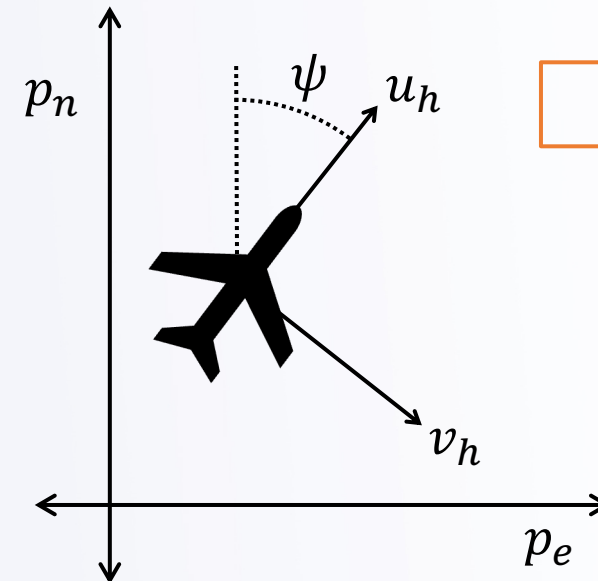
Image credit: NASA/C. Silva, W. Johnson, K. Antcliff, M. Patterson

Kinematic guidance model

Reduced-order *heading frame* dynamics valid in hover, transition, and cruise

$$\mathbf{x}_g = \begin{pmatrix} p_n \\ p_e \\ h \\ \psi \end{pmatrix} = \begin{pmatrix} \text{north} \\ \text{east} \\ \text{altitude} \\ \text{heading} \end{pmatrix}, \quad \mathbf{u}_g = \begin{pmatrix} u_{h,c} \\ v_{h,c} \\ w_{h,c} \\ \dot{\psi}_c \end{pmatrix} = \begin{pmatrix} \text{forward heading velocity} \\ \text{lateral heading velocity} \\ \text{vertical heading velocity} \\ \text{heading rate} \end{pmatrix}$$

$$\dot{\mathbf{x}}_g = \begin{pmatrix} \dot{p}_n \\ \dot{p}_e \\ \dot{h} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} u_{h,c} \cos \psi - v_{h,c} \sin \psi \\ u_{h,c} \sin \psi + v_{h,c} \cos \psi \\ -w_{h,c} \\ \dot{\psi}_c \end{pmatrix}$$



guidance commands

RSLQR inner-loop performance model

Inner-loop state (Δ := deviation from trim):

$$\mathbf{z} = (\Delta u_h \quad v_h \quad w_h \quad \phi \quad \Delta\theta \quad p \quad q \quad r \quad \underbrace{e_{I,u} \quad e_{I,v} \quad e_{I,w} \quad e_{I,\psi}}_{\text{integrator states}})^T$$

Linearized dynamics and RSLQR control:

$$\dot{\mathbf{z}} = \begin{pmatrix} \mathbf{A}_{ol} & \mathbf{0} \\ \mathbf{C}_{ol} & \mathbf{0} \end{pmatrix} \mathbf{z} + \begin{pmatrix} \mathbf{B}_{ol} \\ \mathbf{0} \end{pmatrix} \mathbf{u} + \begin{pmatrix} \mathbf{0} \\ -\mathbf{I} \end{pmatrix} \mathbf{r}, \quad \mathbf{u} = -(\mathbf{K}_P \quad \mathbf{K}_I) \mathbf{z}$$

Closed-loop performance model:

$$\dot{\mathbf{z}} = \left[\begin{pmatrix} \mathbf{A}_{ol} - \mathbf{B}_{ol} \mathbf{K}_P & -\mathbf{B}_{ol} \mathbf{K}_I \\ \mathbf{C}_{ol} & \mathbf{0} \end{pmatrix} + \hat{\mathbf{A}}_{\Delta} \right] \mathbf{z} + \begin{pmatrix} \mathbf{0} \\ -\mathbf{I} \end{pmatrix} \mathbf{r} + \boldsymbol{\sigma}, \quad \hat{\mathbf{u}}_g = (\mathbf{C}_{ol} \quad \mathbf{0}) \mathbf{z}$$

Command shaping for turn coordination (details in paper):

$$v'_{h,c} = v_{h,c} - \frac{V_c}{g} \dot{\psi}_c (u_{h,c} \sin \theta + w_{h,c} \cos \theta)$$

Simulation scenario

- Transition flight; maneuver specified by line segments
- Guidance updated at 4Hz
- Compare kinematic, kinematic + inner loop, and 6DoF guidance models
- Nominal and contingency flights (rotors 5 & 6 failed)

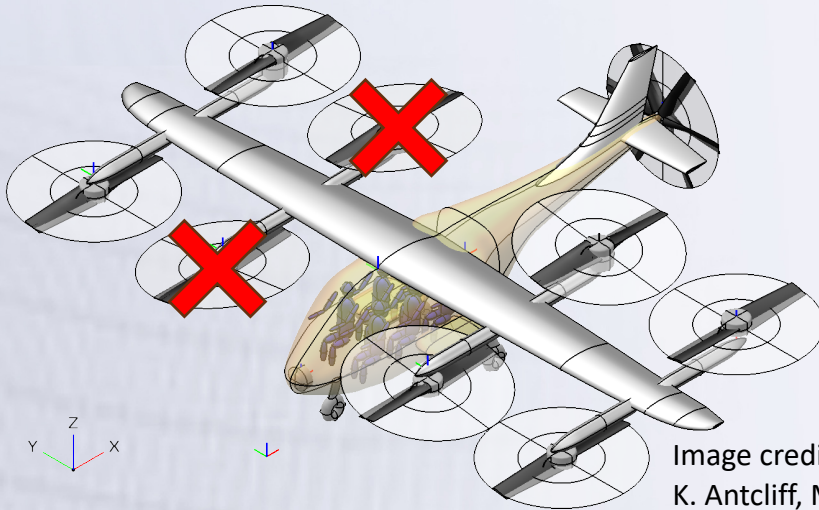
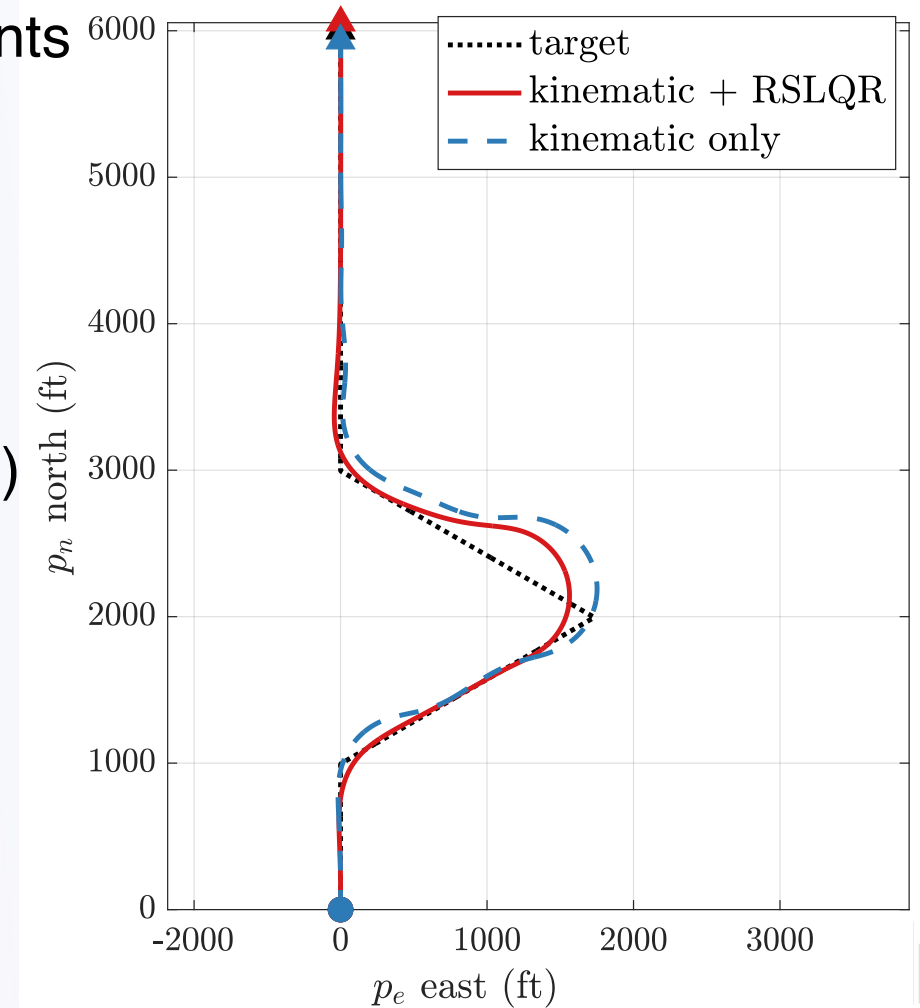
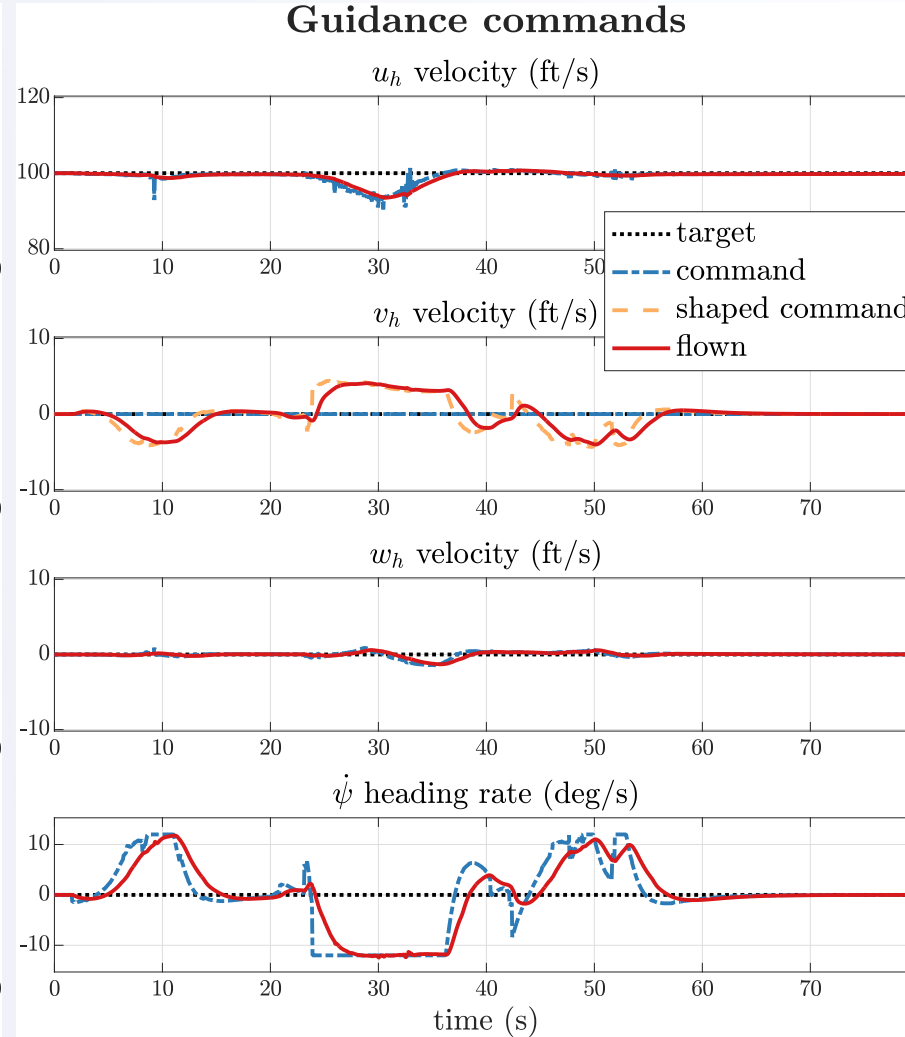
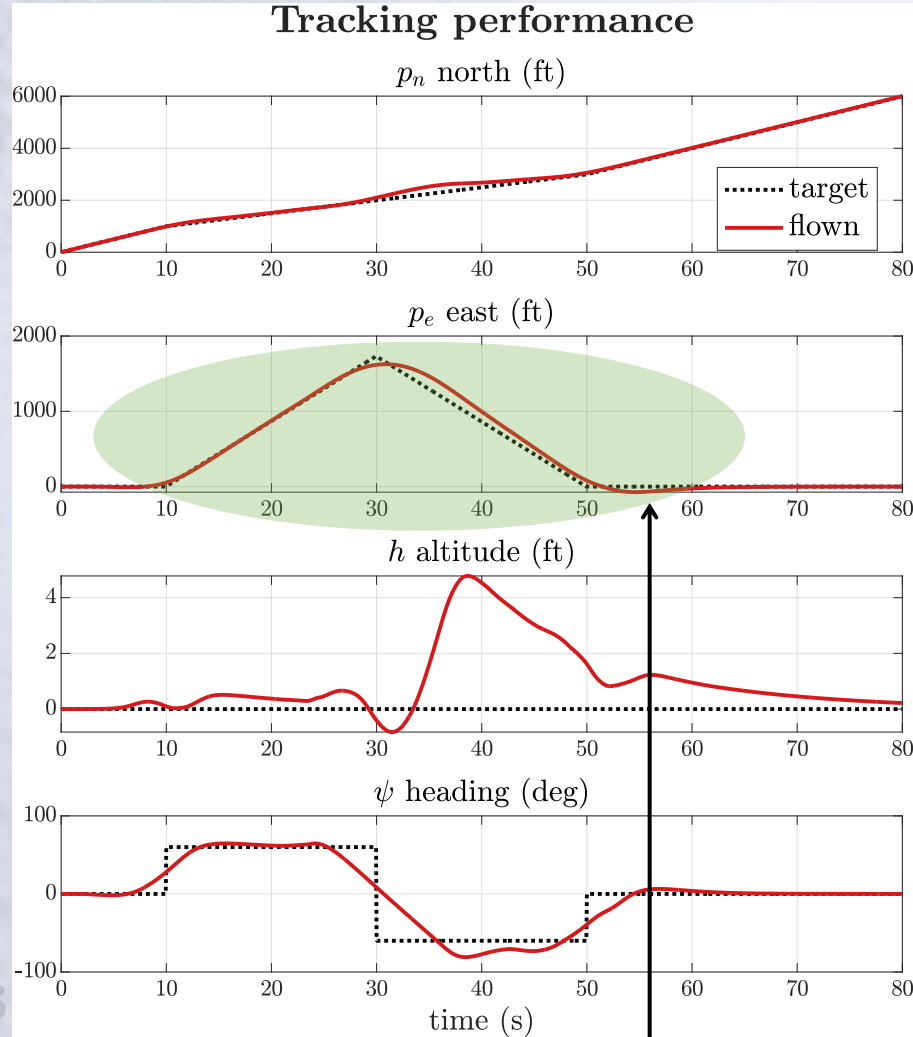


Image credit: NASA/C. Silva, W. Johnson, K. Antcliff, M. Patterson



6DoF baseline (nominal flight)



Nominal flight
total cost: 220
CPU time/iter: **1.9s**

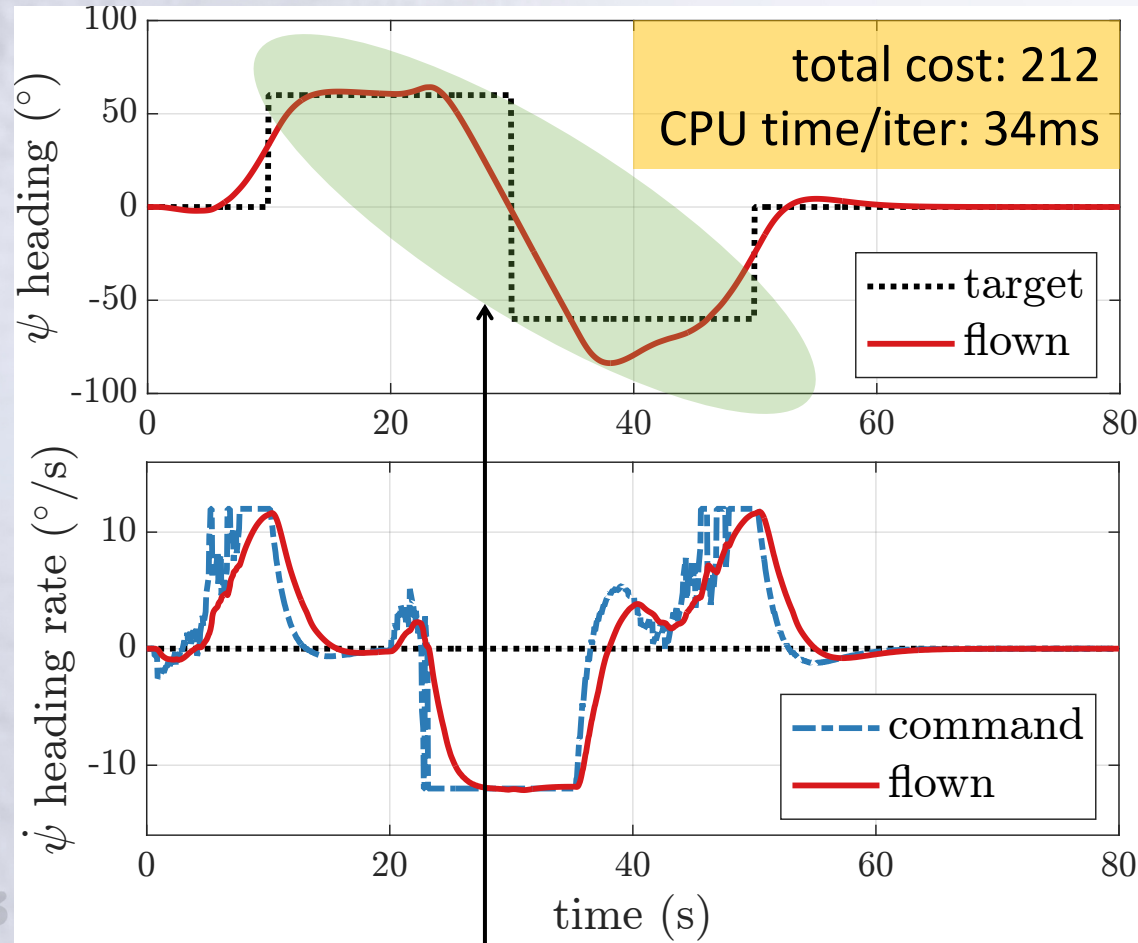
Contingency flight
total cost: 232
CPU time/iter: **2.9s**

total cost (from optimal control problem)
quantifies position tracking accuracy

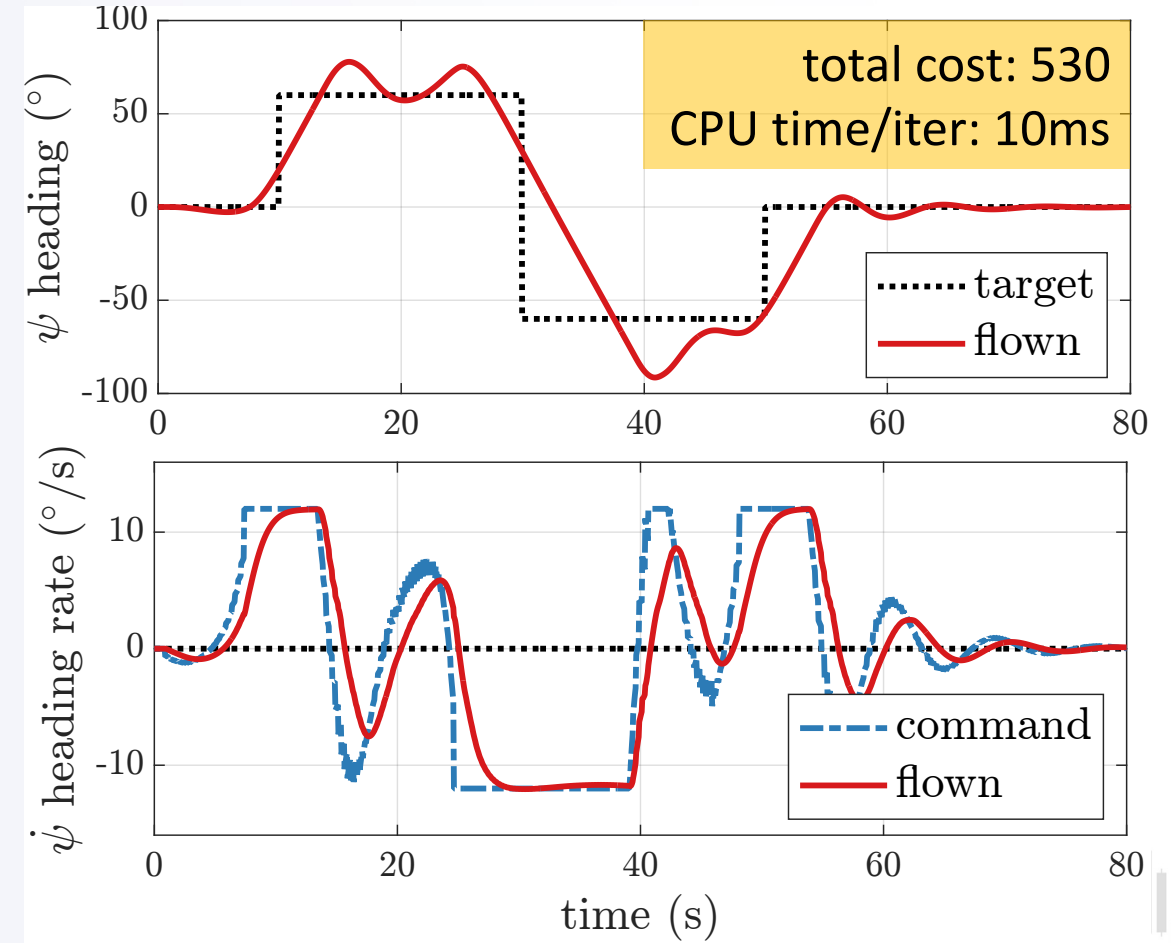
close position tracking; recovered in contingency flight

Results comparison (nominal flight)

kinematic + inner loop



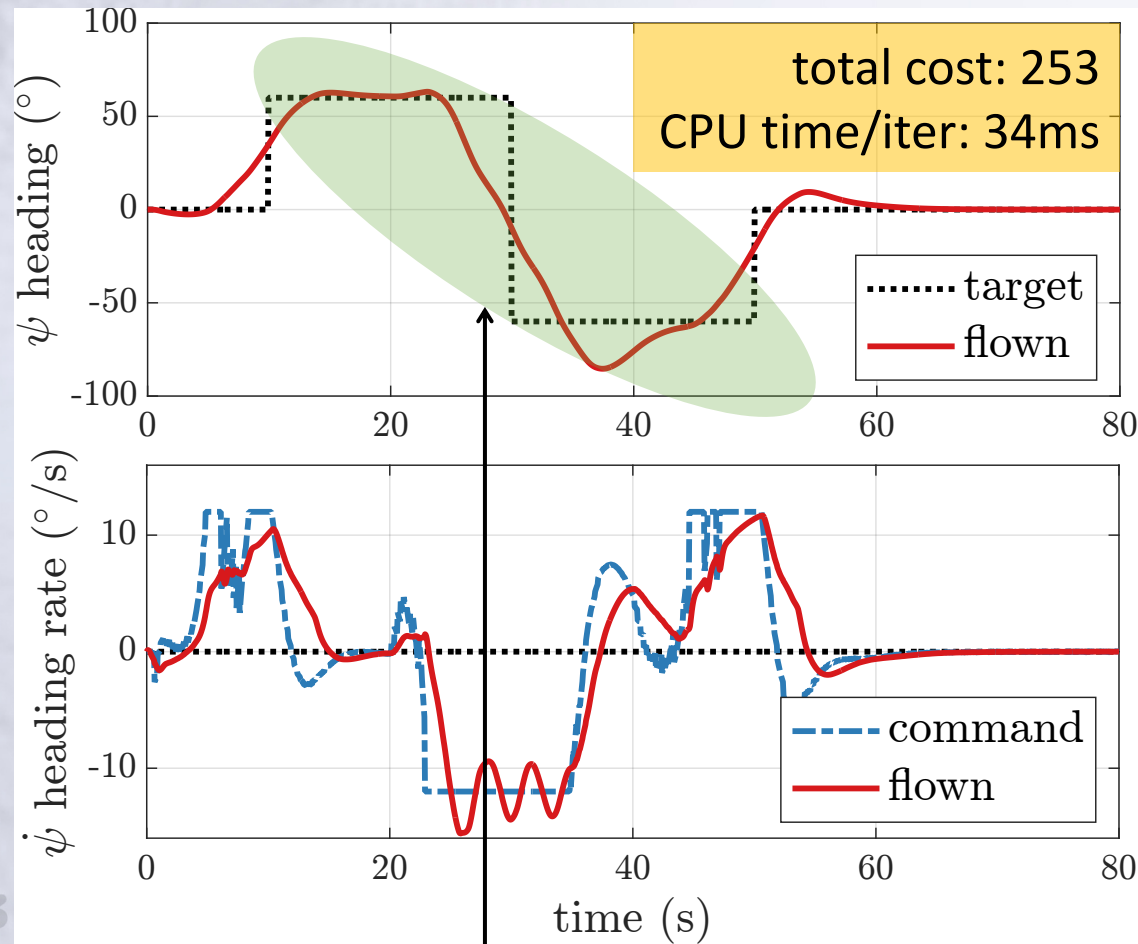
kinematic only



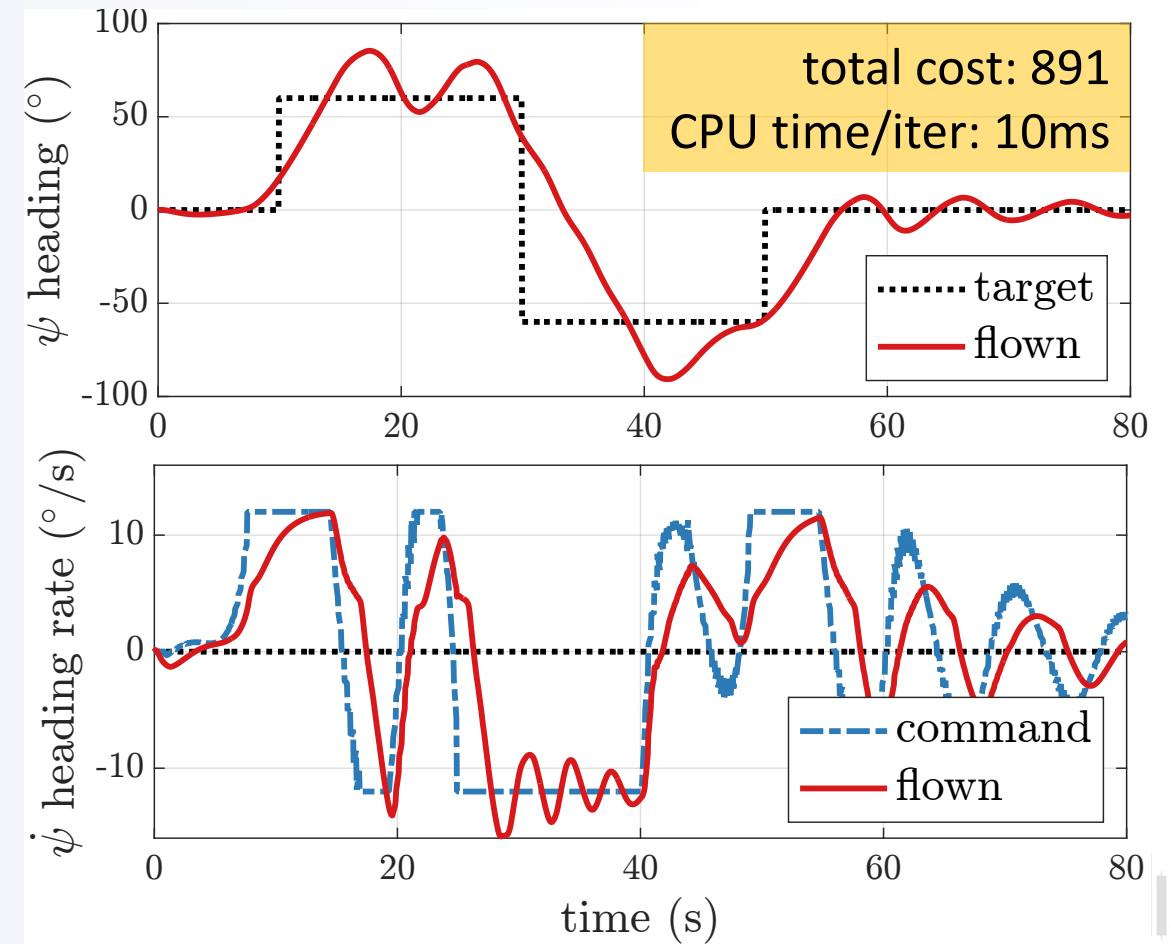
almost identical to 6DoF

Results comparison (contingency flight)

kinematic + inner loop



kinematic only

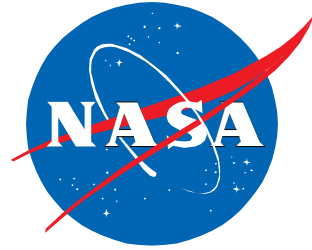


recovers nominal position tracking

Summary and future work

	kinematic only	kinematic + RSLQR	6DoF
total cost (nominal)	530	212	220
total cost (contingency)	891	253	232
CPU time/iteration	0.010s	0.034s	1.9 ~ 2.9s

- *Optimal control-based adaptive guidance* for AAM
 - eVTOL-compatible guidance model
 - linear inner-loop performance model naturally derived from RSLQR
- Poor stability and performance if inner-loop dynamics not modeled
- Guidance robustness fundamentally limited by inner-loop control capability
- Research needed on *parameter estimation, convergence analysis*



Contact Information:
tenavi.nakamura-zimmerer@nasa.gov



Backup slides

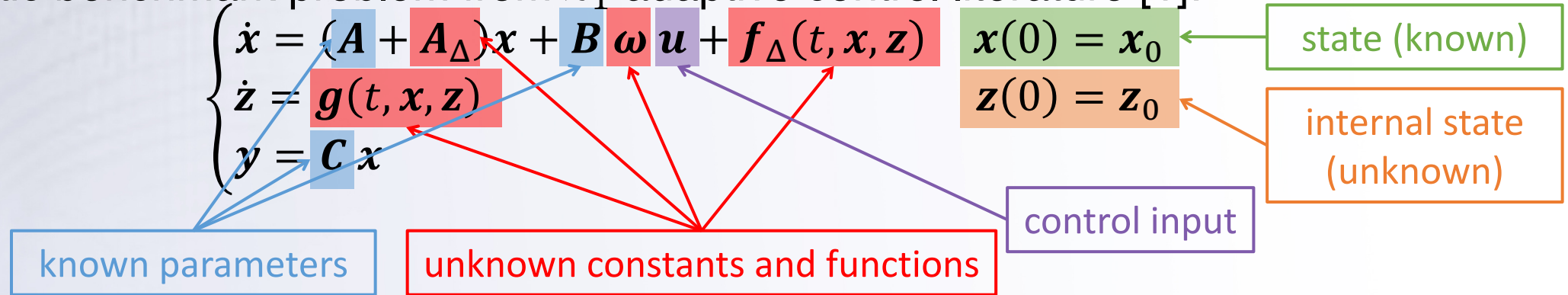


Adaptive control benchmark example



Problem description

- Synthetic benchmark problem from $\mathcal{L}_1$ adaptive control literature [1]:



- Parameters from “Scenario 1” in [1]
- Optimize u s.t. for given $r(t)$, y tracks the output of the reference system,

$$\dot{x}_{id} = Ax_{id} + BK_{DC}r(t), \quad y_{id} = Cx_{id}, \quad x_{id}(0) = x_0, \quad K_{DC} := -(CA^{-1}B)^{-1}$$

- Adaptive guidance model:

$$\dot{x}_m = (A + \hat{A}_\Delta)x_m + B\hat{\omega}u + \sigma$$

T³

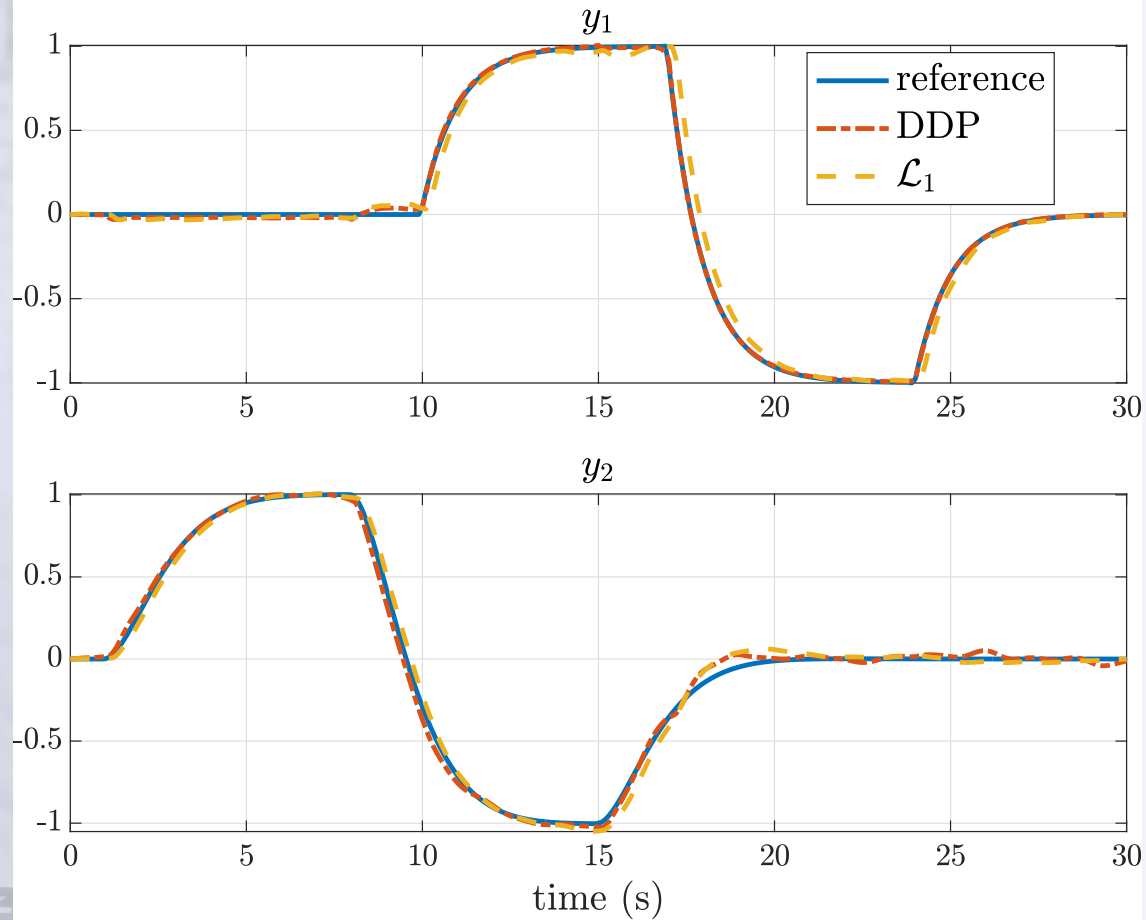
- Xargay, E., Hovakimyan, N., and Cao, C., “ $\mathcal{L}_1$ Adaptive Controller for Multi-Input Multi-Output Systems in the Presence of Nonlinear Unmatched Uncertainties,” *American Control Conference*, 2010, pp. 874–879.

Adaptive control benchmark example

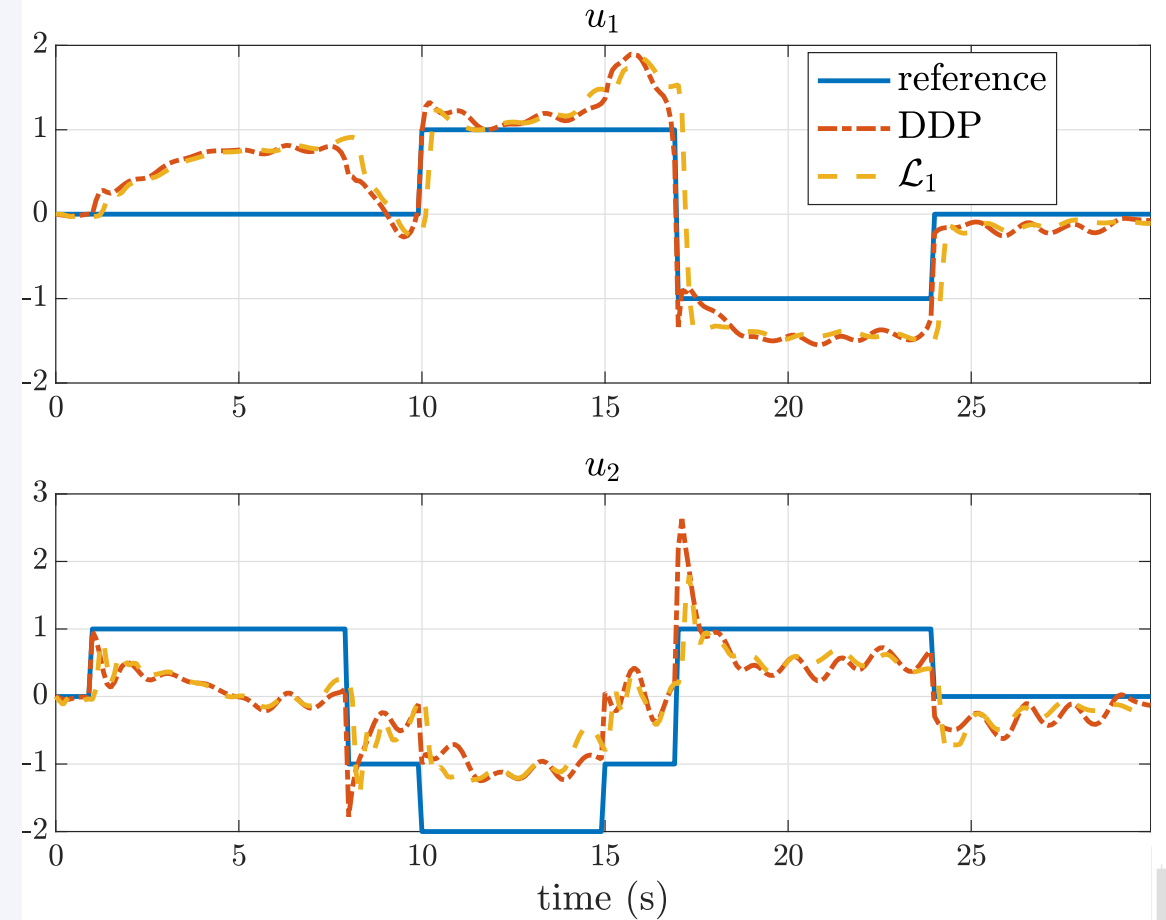
Tracking performance and control inputs



Reference tracking

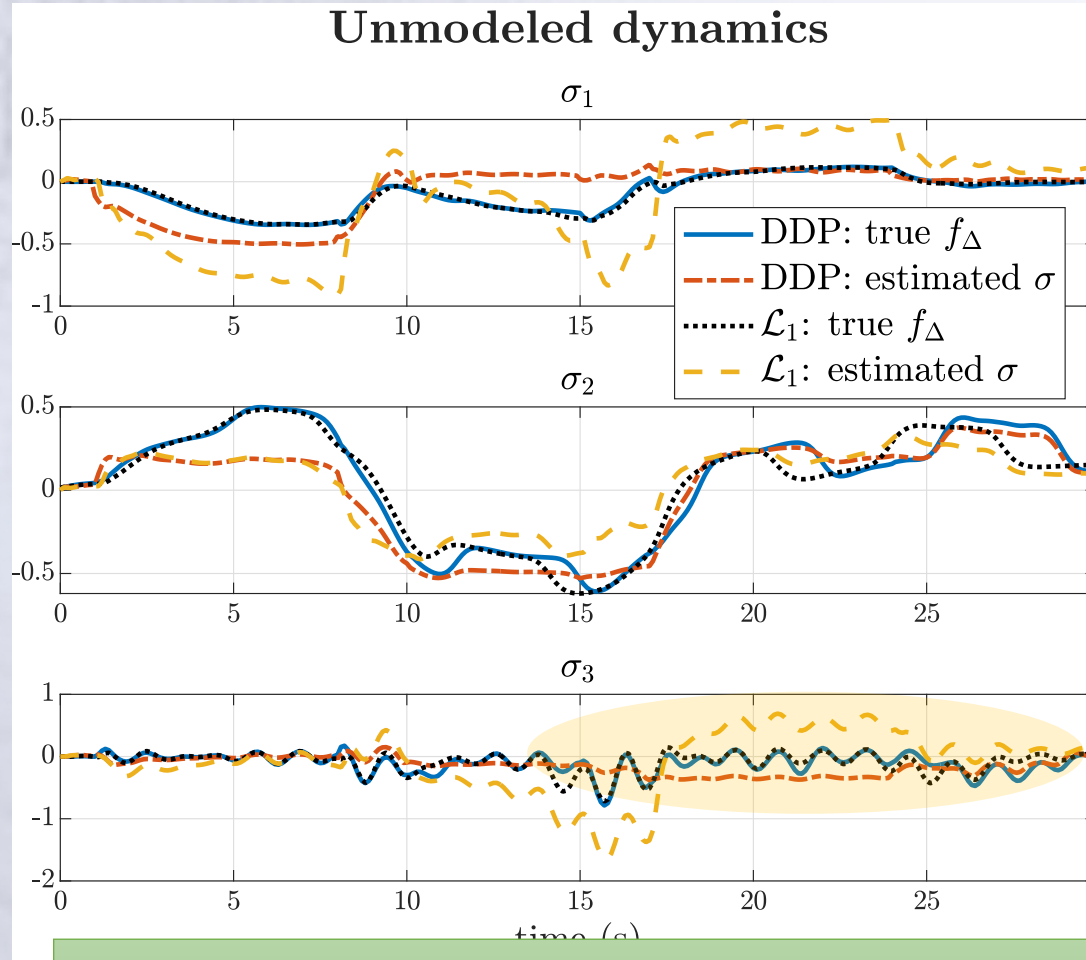


Controls



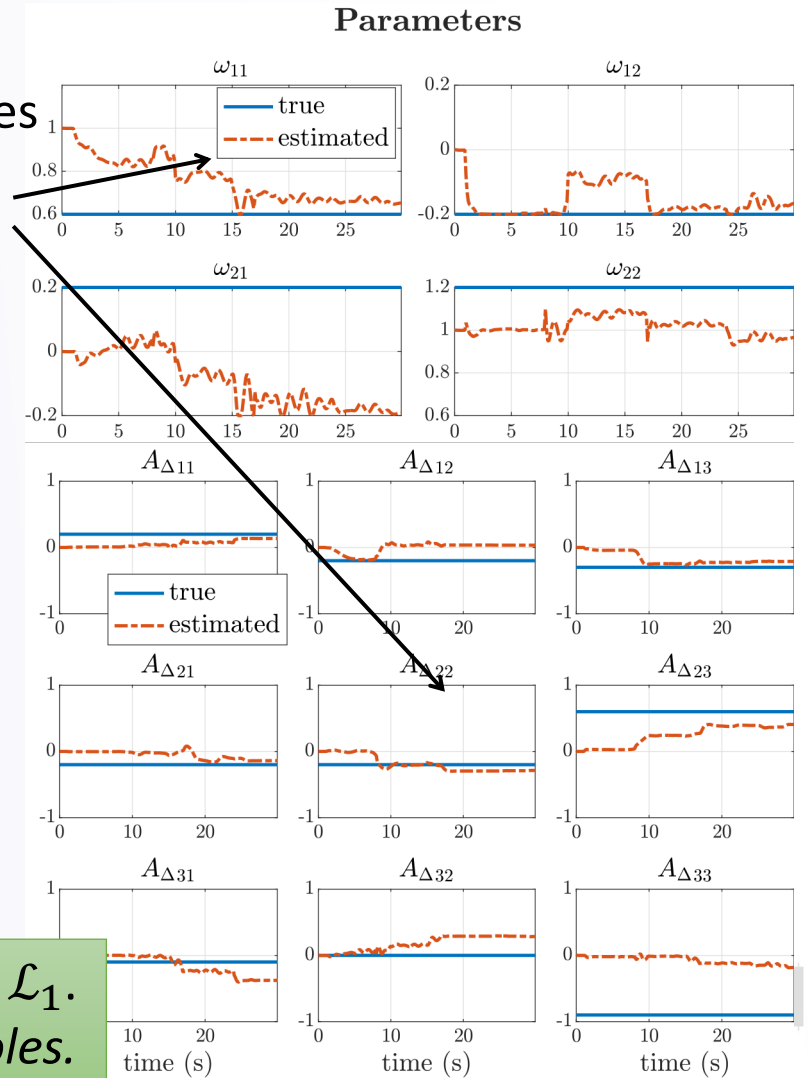
Adaptive control benchmark example

Parameter estimates



Some (but not all) parameter estimates converge to true values, results can be informative

$\mathcal{L}_1$ treats all uncertainty as additive



Optimal control and estimation can achieve similar performance as $\mathcal{L}_1$.
Proof of concept only: adaptive guidance and control fill different roles.