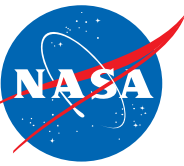


A Model Predictive Control Approach for In-Flight Acoustic Constraint Compliance



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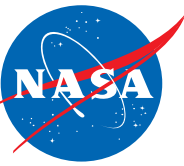
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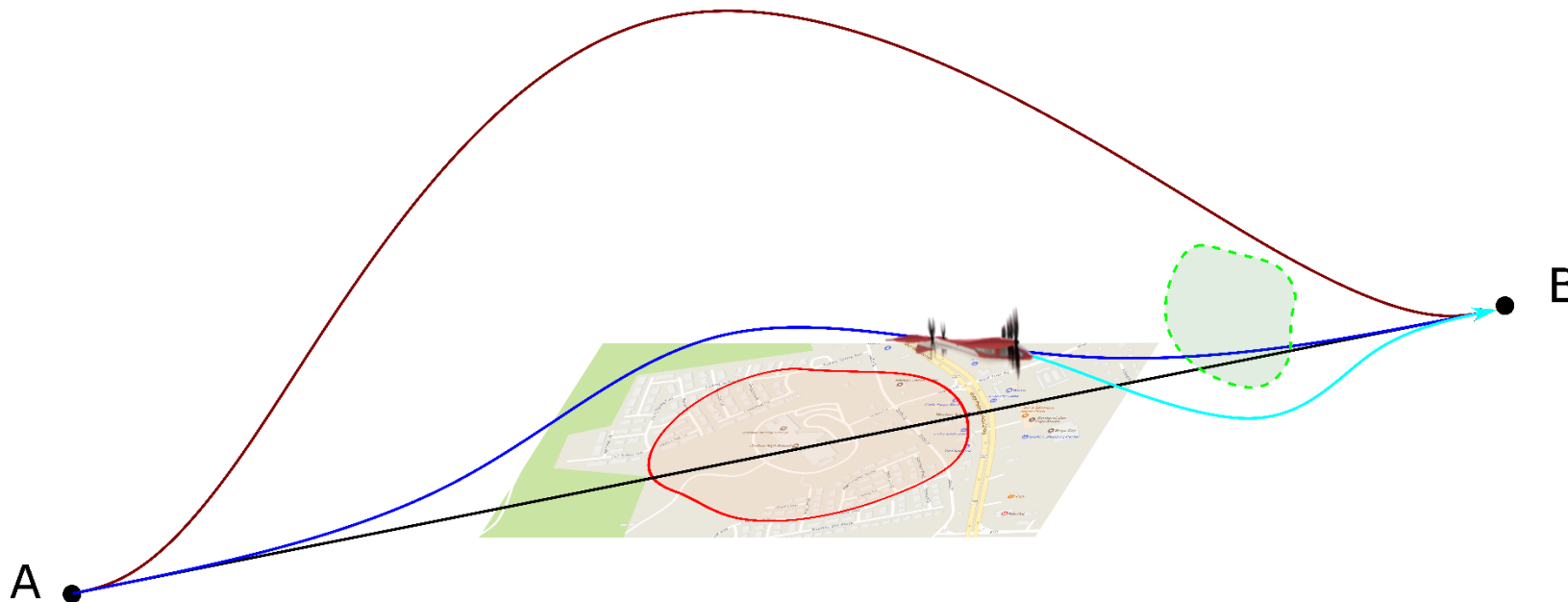
January 21, 2021

2021 AIAA SciTech Forum

Motivation



- Noise management is one of the major barriers to Urban Air Mobility
- Approaches to noise mitigation (non-exhaustive)
 - Vehicle configuration
 - Directivity control via propeller phase synchronization
 - *Trajectory optimization*



- Create framework for trajectory generation integrating location-based acoustic metrics and vehicle performance limitations
 - Mission-relevant constraints
 - Mission duration, airspace restrictions, ...
 - Vehicle dynamic constraints
 - Aircraft structural limitations, min/max airspeed, ...
 - Vehicle separation/obstacle avoidance
 - Acoustic constraints at a number of discrete observer locations

- Nonlinear stochastic model predictive control for finite horizon trajectory optimization
 - Model Predictive Path Integral control (MPPI)*
 - Optimal control approximated via importance sampling
 - Computed trajectory is suboptimal
 - Arbitrarily complex dynamics and state cost function
 - “Soft” constraint enforcement through cost function
 - No differentiation of cost or constraint functions required
 - Computationally efficient through massive GPU parallelization

*G Williams, P Drews, B Goldfain, JM Rehg, EA Theodorou, “Information Theoretic Model Predictive Control: Theory and Applications to Autonomous Driving,” IEEE Transactions on Robotics, 2018.

- Fixed-wing distributed propulsion aircraft
 - Can represent tilt-wing or split-propulsion vehicle in forward flight
 - Coordinated flight aircraft model*
 - Includes basic aerodynamics model
 - Assumes underlying tracking controller
 - Dynamics:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{v} \\ \dot{\mathbf{v}} &= \mathbf{g} + \mathbf{R}\mathbf{a}_v \\ \dot{\mathbf{q}} &= \frac{1}{2}\mathbf{q} \otimes \begin{bmatrix} 0 \\ \boldsymbol{\omega}_v \end{bmatrix} \\ \boldsymbol{\omega}_v &= [p_s \quad -\mathbf{e}_3 (\mathbf{a}_v + \mathbf{g}) / V \quad \mathbf{e}_3 \mathbf{g} / V]^\top \\ \begin{bmatrix} T & \alpha & p_s \end{bmatrix}^\top &= \mathbf{u}\end{aligned}$$

Coordinated flight
constraint

$\mathbf{e}_3 = [0 \quad 0 \quad 1]^\top$

*Adapted from J Hauser, R Hindman, "Aggressive Flight Maneuvers," IEEE Conference on Decision and Control, 1997.

- Aerodynamic model:

$$\mathbf{a}_v = \begin{bmatrix} \frac{T}{m} \cos \alpha - \frac{\rho V^2 S}{2m} (\sin \alpha (C_{N_0} + C_{N_\alpha} \alpha) + \cos \alpha (C_{A_0} + C_{A_{\alpha^2}} \alpha^2)) \\ 0 \\ -\frac{T}{m} \sin \alpha - \frac{\rho V^2 S}{2m} (\cos \alpha (C_{N_0} + C_{N_\alpha} \alpha) - \sin \alpha (C_{A_0} + C_{A_{\alpha^2}} \alpha^2)) \end{bmatrix}$$

Highlighted variables:

Thrust – blue

AoA – red

Aero Coeff - green

- Propeller/motor model:

$$T = c_2(J)\omega_p^2 + c_1(J)\omega_p + c_0(J)$$

$$J = \frac{2\pi V \cos \alpha}{\omega_p d_p}$$

Advance ratio

- Parameter values taken from model of NASA's GL-10 aircraft



Acoustic Model

- Metric is *overall sound pressure level (OASPL)*
- Model data fit from the Propeller Analysis System of the Aircraft Noise Prediction Program (PAS-ANOPP)
- Based on effective propeller tip Mach number
- Optional frequency weighting

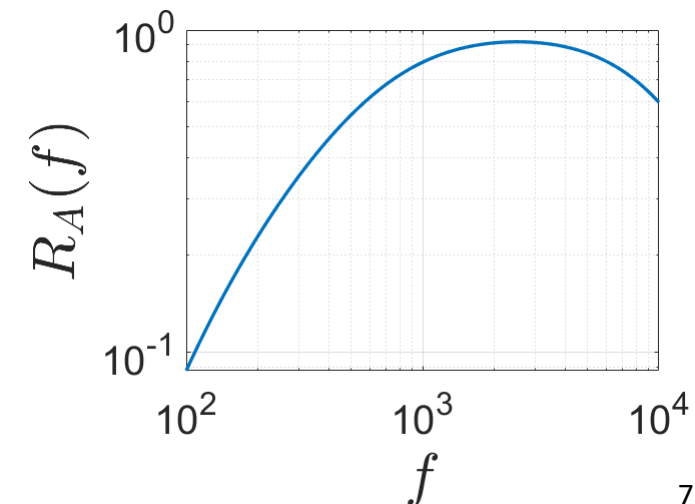
$$OASPL = 10 \log_{10} \left(\frac{1}{\hat{p}^2} \sum_{k=0}^{N_f} \left[\hat{p}_{\text{rms},k}^2 \left(\frac{M_{\text{eff}}}{\hat{M}_{\text{eff}}} \right)^{\xi_k} R_A(f_k) \right] \left(\frac{\hat{r}}{r} \right)^2 N_p \right)$$

Diagram illustrating the components of the OASPL equation:

- Frequency weighting** (red box) points to $R_A(f_k)$.
- Number of propellers** (blue box) points to N_p .
- Propeller speed** (green box) points to M_{eff} .
- Distance to observer** (purple box) points to $\left(\frac{\hat{r}}{r} \right)^2$.

$$M_{\text{eff}} = \frac{M_t}{1 + J(1 - M_t)}$$

$$M_t = \omega_p d_p / 2c$$



■ Model Predictive Path Integral Control (MPPI)

- Sample thousands of control sequences, $\nu_t \sim \mathcal{N}(\mathbf{u}_t, \Sigma)$, propagate trajectories in parallel
- Exponential cost-weighted averaging to update mean of optimal control distribution, $\mathbf{u}_t$
- Propagate mean optimal control sequence to obtain nominal trajectory

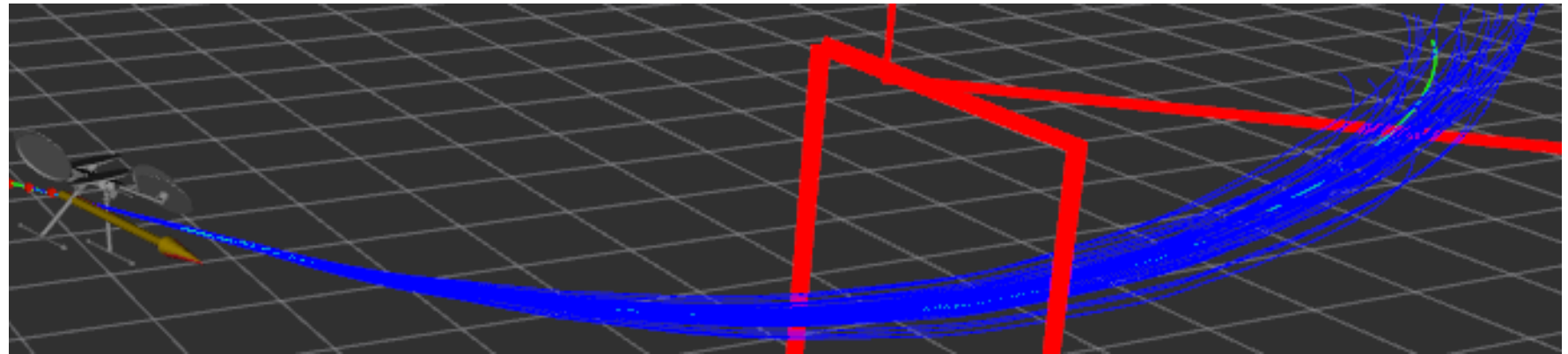
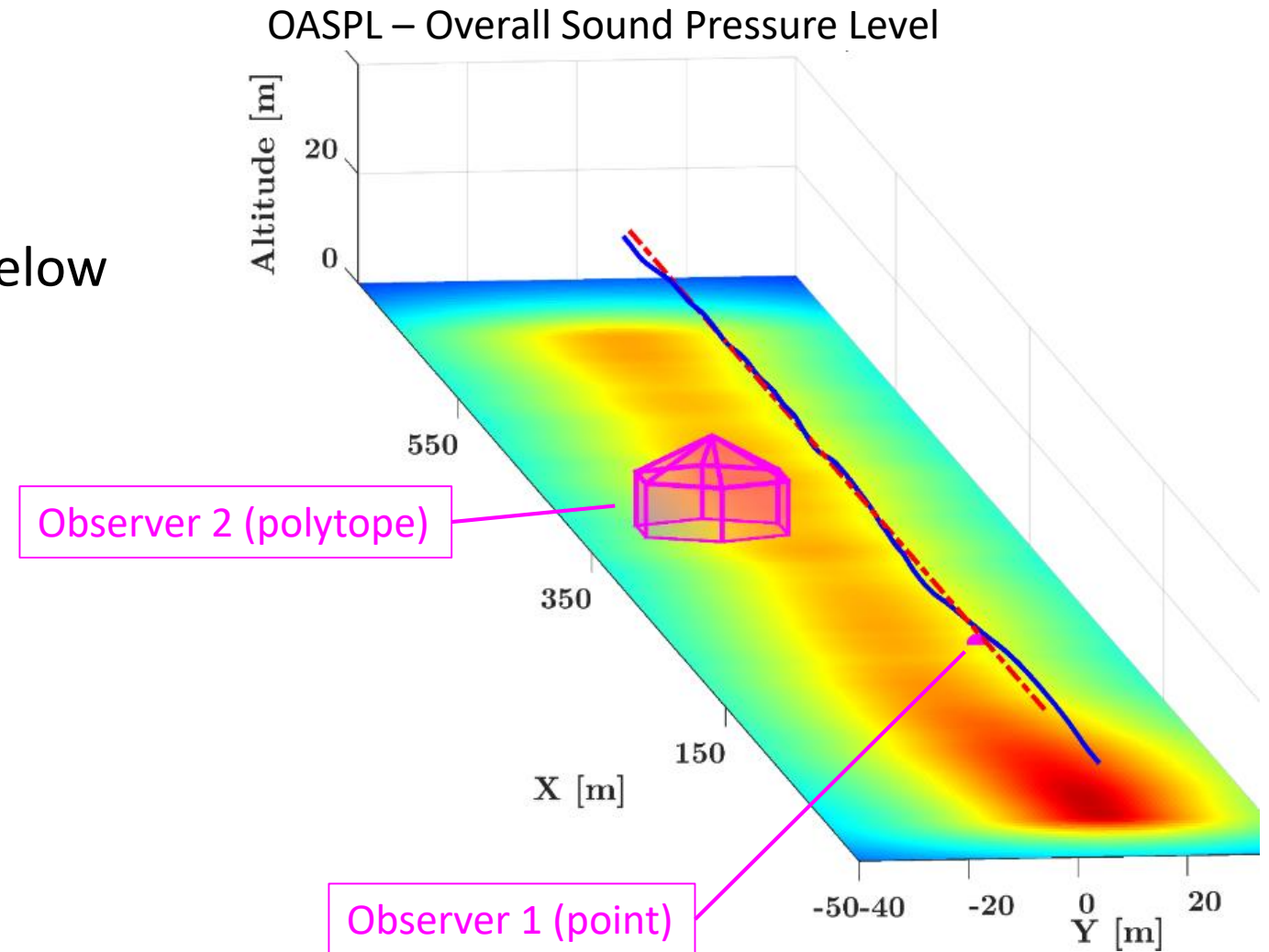


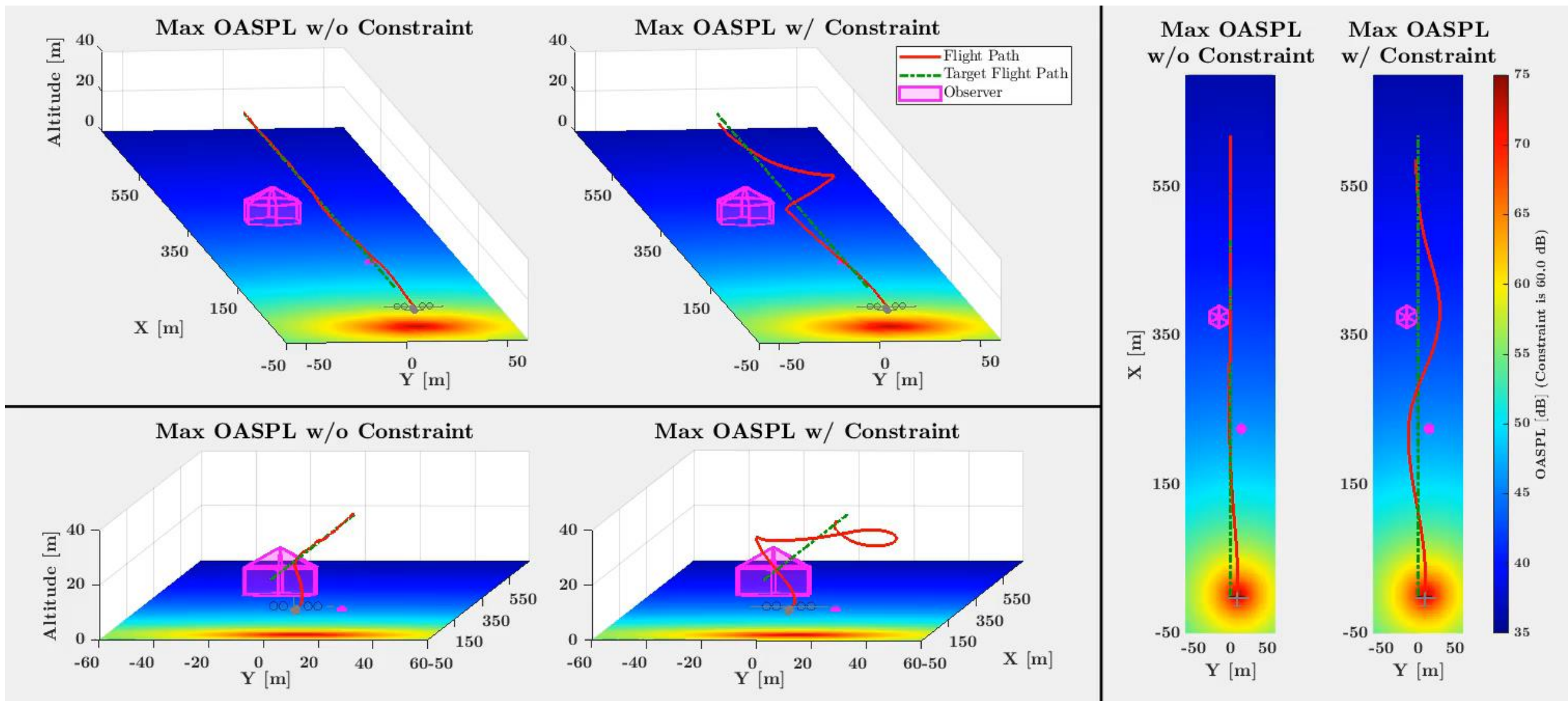
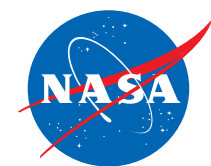
Figure credit: J Pravitra, KA Ackerman, N Hovakimyan, EA Theodorou, “L1-Adaptive MPPI Architecture for Robust and Agile Control of Multirotors,” IROS, 2020.

Motion Planning – Simulation

- Running cost –
 - Track spatial path
 - Constant speed
 - Maintaining noise at observers below threshold
- Acoustic observers defined as polytopes to leverage efficient distance query algorithms



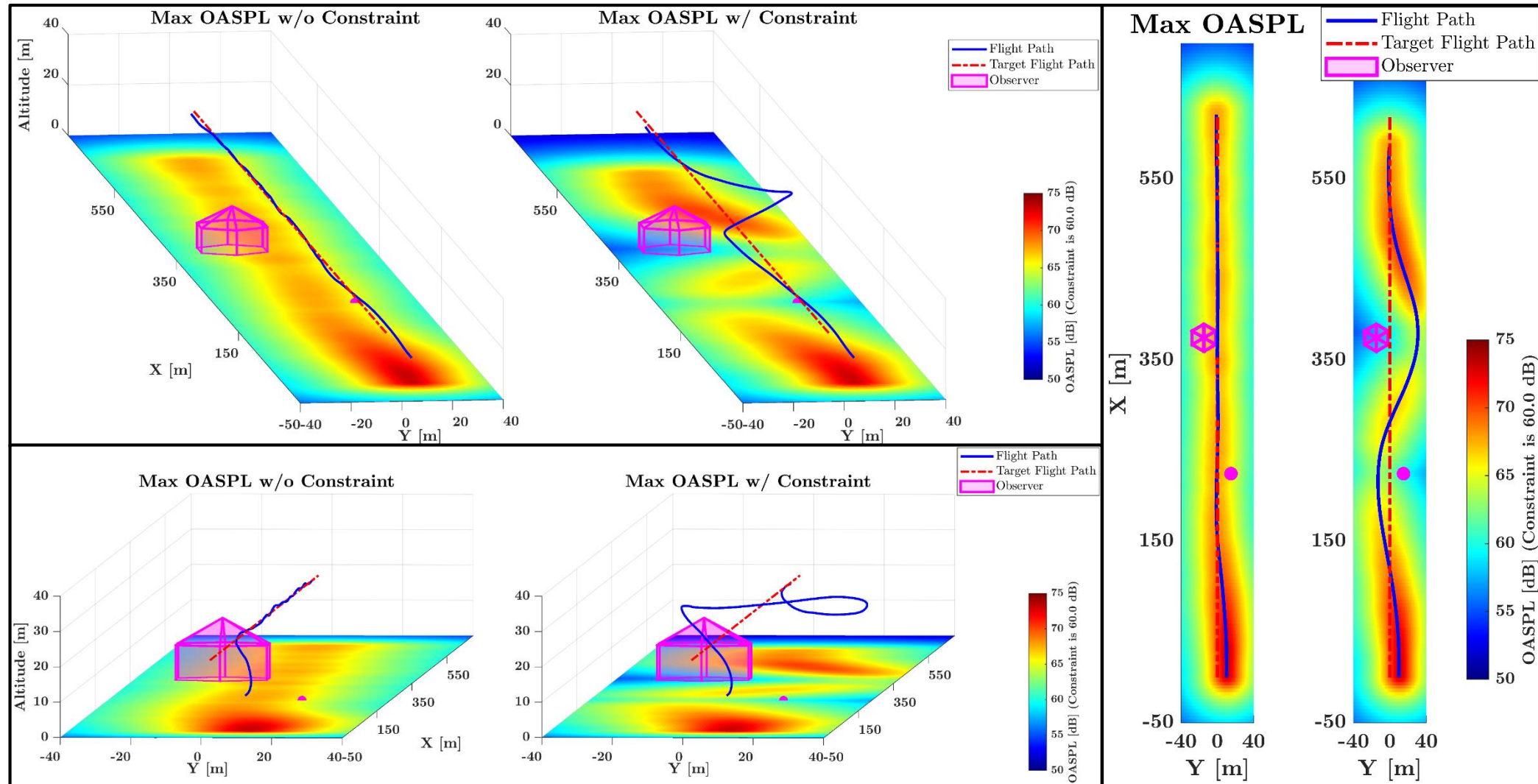
Simulation Results – Video



*Aircraft is animation only, not to scale or representative

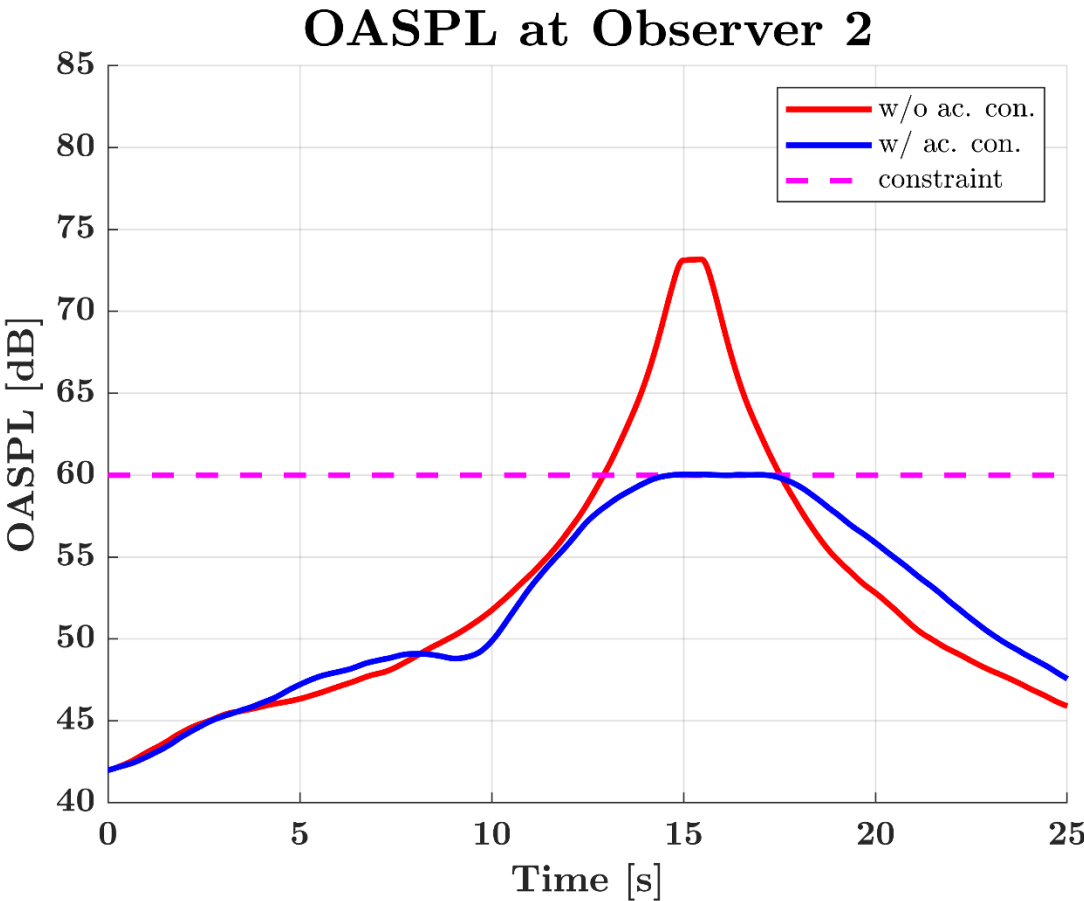
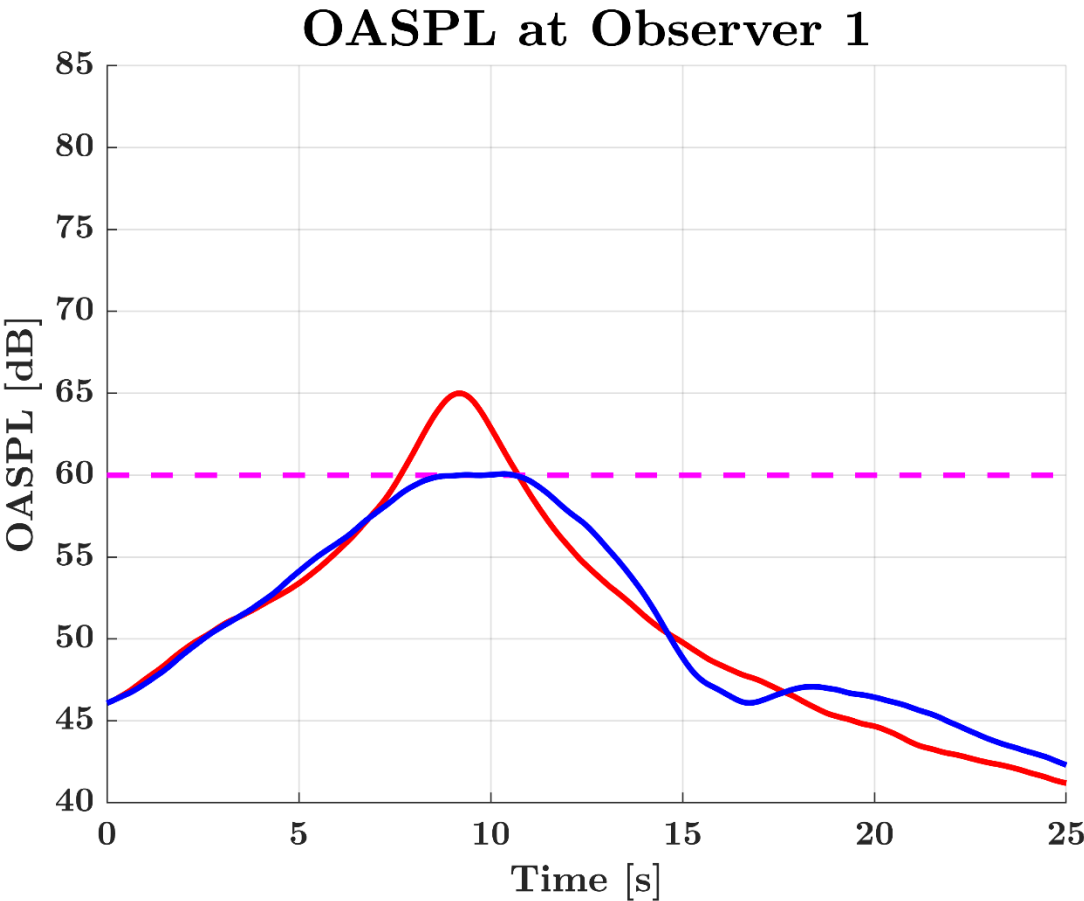
Simulation Results

- Side-by-side flight path comparison with maximum OASPL footprint



Simulation Results

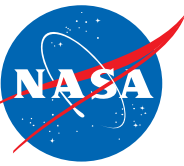
- Overall sound pressure level (OASPL) at both observers



- Motion planning with nonlinear stochastic MPC
 - Fixed-wing, coordinated-flight aircraft
 - MPPI control law for trajectory optimization
- Multiple 3D observers
 - Polytope definition for efficient distance queries
- Multiple-fidelity acoustic model
 - Harmonics and frequency weighting optional
- Simulation results demonstrate ability to modify trajectory in real-time to satisfy acoustic constraints

- Higher fidelity acoustic models
 - Source hemisphere database
- Additional vehicle dynamics and low-level controller design
- Integration with directivity control
 - Propeller phase control under development at University of Illinois at Urbana-Champaign
- Flight testing
 - Targeting single tilt-wing design under development at NASA Langley Research Center

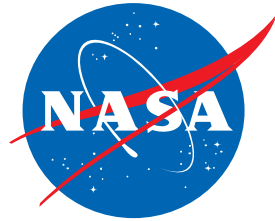
Acknowledgments



- Kyle Pascioni – NASA Langley Research Center
 - Acoustic model

- Javier Puig Navarro – NASA Langley Research Center
– University of Illinois at Urbana-Champaign
 - Polytope distance query algorithm

- NASA's Revolutionary Vertical Lift Technology Project



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