Comparison of Acoustic Models and Trajectory Generation Methods for an Acoustically-Aware Aircraft

Kasey A. Ackerman and Irene M. Gregory
NASA Langley Research Center
Hampton, VA 23681

AIAA SciTech Forum
National Harbor, MD
January 2023

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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
Objective

- Create framework for trajectory generation integrating location-based acoustic metrics and vehicle performance limitations
  - Multiple trajectory optimization methods and acoustic noise models
  - 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
Comparison of Models and Methods

- Two acoustic source noise models
  - Omni-directional model based on propeller tip Mach Number
  - Directional hemisphere-based model

- Two trajectory planning methods
  - Pre-mission full-trajectory planner using polynomial parameterization
  - Receding horizon (near) real-time nonlinear model predictive control (MPC) trajectory planner

- Compare trajectory planning performance using both noise models and trajectory generation methods
Vehicle Dynamics

- Fixed-wing distributed propulsion aircraft
  - Can represent tilt-wing or split-propulsion vehicle in forward flight
  - Coordinated flight aircraft model*
    - Basic aerodynamic model
    - Simplified motor/propeller model
    - Assumes underlying tracking controller

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

Acoustic Models

- Metric is *sound pressure level (SPL)*
- Model data from the Propeller Analysis System of the Aircraft Noise Prediction Program (PAS-ANOPP)
- Omni-directional model
  - Based on effective propeller tip Mach number
- Hemisphere model
  - Directional noise emission
  - Interpolation over airspeed, angle of attack, propeller speed, direction to observer
- Optional frequency weighting
Pre-Mission Trajectory Planner*

- Full trajectory optimization with polynomial parameterization
  - Simplified (differentially flat) vehicle dynamics, acoustic source model, and propagation model
  - Implemented as a 2nd order Hermite interpolation problem
  - Bézier polynomial representation of spatial path and parametric speed
  - Numeric (discrete) evaluation of mid- to high-fidelity acoustic source and propagation models

MPC Motion planner*

- Model Predictive Path Integral Control (MPPI)**
  - Stochastic optimization technique used as nonlinear MPC
  - Framework to efficiently solve a finite horizon nonlinear optimal control problems
  - State cost function can be arbitrarily complex
  - Sampling-based optimization leverages GPU for efficient computation


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

**Omni-Directional Model**
- Obs. 1
- Obs. 2

**Hemisphere Model**

- Pre-mission Planner
- MPC Planner

- Max SPL w/o Constraint

- Colorbar:
  - Flight Path
  - Target Flight Path
  - Observer Location
  - Start
  - End

- SPL [dB] (Constraint is 65.0 dB)

kasey.a.ackerman@nasa.gov

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Comparison – Acoustic Constraint Active

Omni-Directional Model

Hemisphere Model

Pre-mission Planner

MPC Planner

Obs. 1

Obs. 2

kasey.a.ackerman@nasa.gov

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Planner Comparison – Hemisphere Model

Hemisphere Model

Omni-Directional Model

Pre-mission Planner

MPC Planner

SPL at Observers

Obs. 1 w/o constraint
Obs. 1 w/ constraint
Obs. 2 w/o constraint
Obs. 2 w/ constraint
Constraint

Time [s]

SPL [dB]

SPL at Observers

Obs. 1 w/o constraint
Obs. 2 w/o constraint
Obs. 1 w/ constraint
Obs. 2 w/ constraint
Constraint

Time [s]

SPL [dB]
Planner Comparison – Hemisphere Model

**Pre-mission Planner**

- **Hemisphere Model**
- **Omni-Directional Model**

**MPC Planner**

- **Hemisphere Model**
- **Omni-Directional Model**
Noise Model Comparison

- Omni-directional propeller speed model

SPL Hemisphere w/o Constraint

SPL Hemisphere w/ Constraint

Max SPL w/o Constraint

Max SPL w/ Constraint

Max SPL w/o Constraint

Max SPL w/ Constraint

Max SPL w/o Constraint

Max SPL w/ Constraint

Max SPL w/o Constraint

Max SPL w/ Constraint

kasey.a.ackerman@nasa.gov

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Noise Model Comparison

- Hemisphere model

Max SPL w/o Constraint

Max SPL w/ Constraint

Max SPL w/o Constraint

Max SPL w/ Constraint

SPL Hemisphere w/ Constraint

SPL Hemisphere w/o Constraint
Summary

- Compared two different trajectory planning methods and two acoustic noise models
  - Full trajectory planning with guaranteed constraint satisfaction
  - Finite horizon planning has greater freedom in trajectory planning
    - Better able to exploit directionality of hemisphere model
  - Directionality of noise emission makes large difference in maximum noise levels seen on ground
    - Higher peak noise, but shorter duration with hemisphere model
- Future efforts focused on combining planner methods to leverage advantages of each
- Acknowledgements
  - Dr. Kyle Pascioni (NASA Langley Research Center)
  - Dr. Javier Puig Navarro (National Institute of Aerospace)
POC: Kasey Ackerman
kasey.a.ackerman@nasa.gov