AI/ML for Safe and Scalable Human Autonomy Teaming with UAVs

PURDUE UNIVERSITY | Center for Artificial Intelligence for Digital, Autonomous and Augmented Aviation
WINDRACERS

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OVERVIEW

Autonomous operations for uncrewed aerial vehicles (UAVs) serve a larger interest in the aerospace industry with the demand to further expand its capabilities to provide not only efficient but also safe missions. Yet current solutions for human autonomy teaming (HAT) greatly restrict UAV capabilities, resulting in inefficient and unsafe operations. Thus, we propose a HAT research project consists of two main goals. The end result is realizing highly intelligent HAT in multi-vehicle control (m:N) operations.

Topic 1

Real-time modeling of human behavior & cognition in HAT

Modeling human cognition of individuals

Efficient real-time models for CL & SA
- Sensor fusion
- New modular ML architectures

CL & SA

Intended actions & uncertainties

Goal

AI-based shared intelligence & control for next-gen HAT

Teaming models for 1-1 HAT
Human-centric intelligence & control
- Shared intelligence
- Dynamic task reallocation

Teaming models for m:N HAT
- Human-centric intelligence & control
- Shared intelligence
- Dynamic task reallocation

Topic 2

Modeling UAVs autonomous intelligence & awareness

Efficient real-time models for autonomous sensing
- Sensor fusion
- Efficient on-board algorithms

Modeling autonomous intelligence for UAV swarms
- Situational awareness of UAV swarms
- AI-based autonomous mission planning
- Safe landing control

Airspace tracking of UAV

Ground target tracking

Real-time Cognitive Modeling of UAV Operators

Background

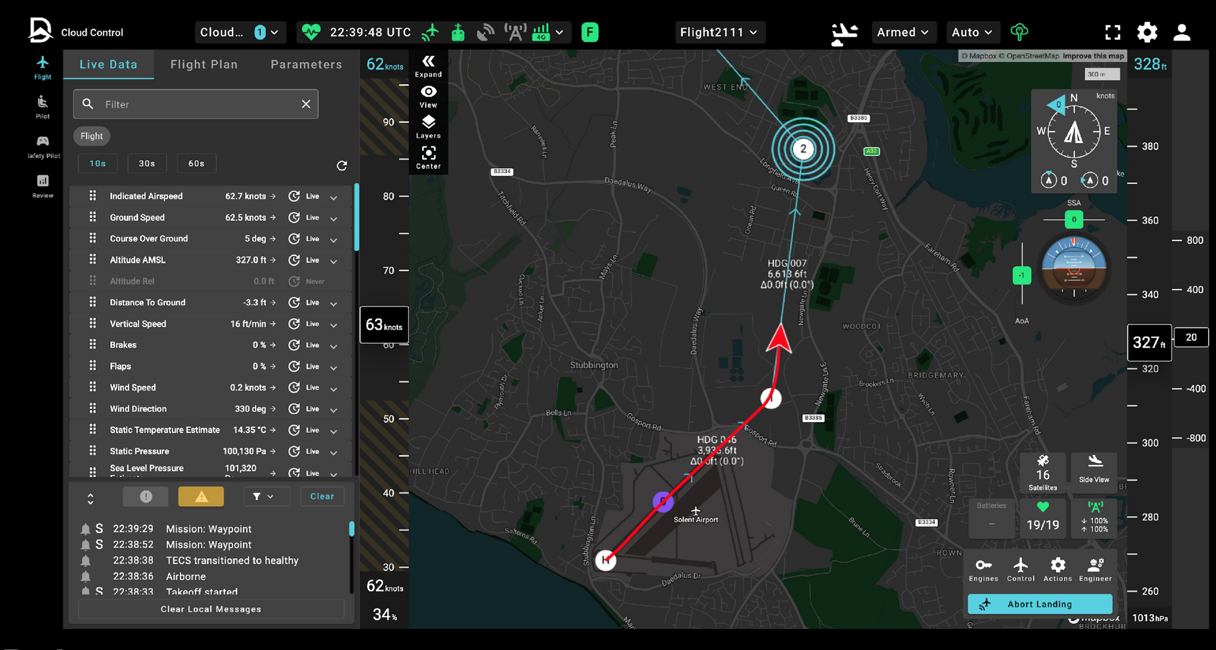
There has been major progress in increasing the autonomy of UAVs. Nevertheless, there will remain situations where human intelligence with strength in induction and judgment plays a critical role in realizing scalable UAV operations [1]. However, in situations where human is cognitively overloaded, the attempt to re-engage a human operator may fail. In order to prevent such failures, we need human-autonomy teaming models that consider humans' current and expected cognitive states: Multi-modal machine-learning models relying on real-time sensing of physiological data (e.g., brain waves, eye movements) offer new possibilities for such context-aware HAT.

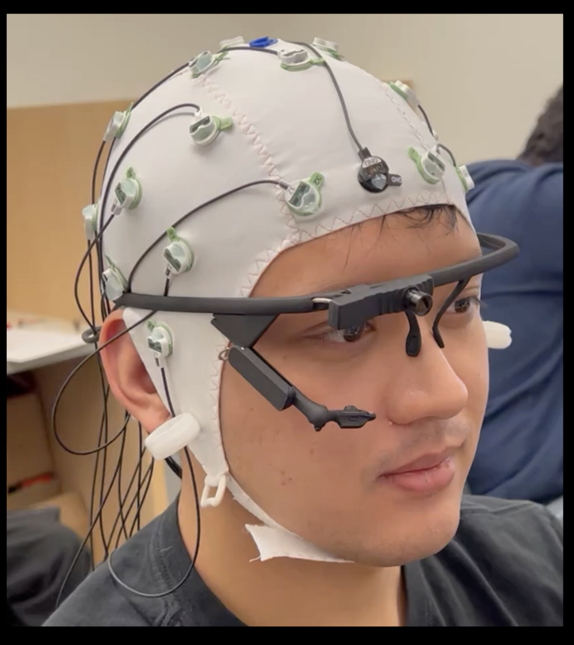
Research Needs & Motivations

Existing research on modeling human behavior and cognition using physiological data and machine learning models to model key cognitive states like cognitive load (CL) and situational awareness (SA) [2-5] have shortcomings. Examples are: 1) Reliance of single modes of physiological data (e.g. only eye tracking) 2) Insufficient real-time modeling/sensing and lack of predictiveness 3) Limited explainability and interpretability of models (e.g. how physiological measures and cognitive states interrelate 4) Interdependence of CL and SA with human's actions and performance is ignored. To address the shortcomings, our ongoing research is guided by the following question: *What ML is best suited to model human cognitive states and actions in real-time in the most explainable and interpretable way?*

Experiment Design

To answer the research question, we design an experiment. The experiment is designed based on the cloud control interface that is currently used by Windracers for real UAV operations. The experiment consists of two tasks, both aimed to control subjects' CL and SA, and utilizes a multi-modality approach where an electroencephalogram, eye tracker, webcam camera, and microphone will be used to collect brain activities, eye movements, upper body movements, and voice of subjects. For learning the data, we choose modern deep learning models that can capture the temporal information in the time-series data such as long short-term memory and the Transformer and its variants.





References
[1] Fitts, Paul M. "Human engineering for an effective air-navigation and traffic-control system." (1951).
[2] Bernhardt, Kyle A., et al. "The effects of dynamic workload and experience on commercially available EEG cognitive state metrics in a high-fidelity air traffic control environment." *Applied ergonomics* 77 (2019): 83-91.
[3] Aricò, Pietro, et al. "Adaptive automation triggered by EEG-based mental workload index: a passive brain-computer interface application in realistic air traffic control environment." *Frontiers in human neuroscience* 10 (2016): 539.
[4] Dasari, Deepika, Guofa Shou, and Lei Ding. "ICA-derived EEG correlates to mental fatigue, effort, and workload in a realistically simulated air traffic control task." Frontiers in neuroscience 11 (2017): 252708.
[5] Li, Qinbiao, et al. "Recognising situation awareness associated with different workloads using EEG and eye-tracking features in air traffic control tasks." *Knowledge-Based Systems* 260 (2023): 110179.
[6] Lin, Li-Yu, James Goppert, and Inseok Hwang. "Log-linear Dynamic Inversion Control with Provable Safety Guarantees in Lie Groups." IEEE Transactions on Automatic Control (2024).
[7] Lin, Li-Yu, James Goppert, and Inseok Hwang. "Application of log-linear dynamic inversion control to a multi-rotor." Workshop on Geometric Representations, ICRA IEEE. 2023.

Autonomous Safe Landing Control for UAV

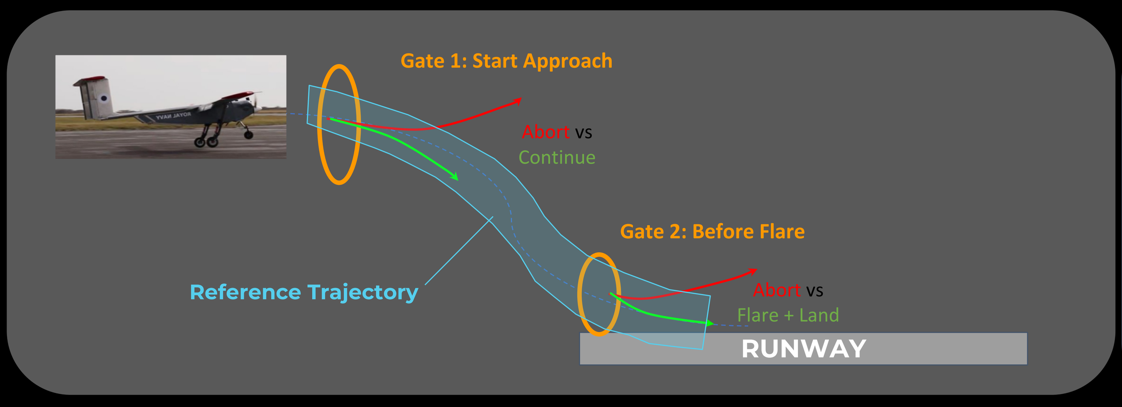
Background

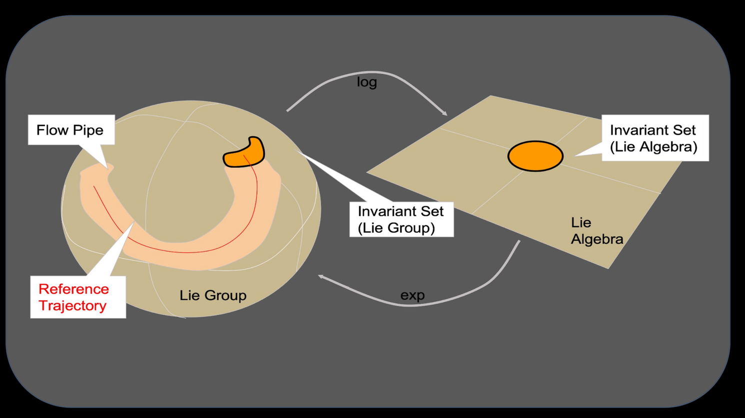
This project focuses on the safety verification of autonomous uncrewed aerial vehicles (UAVs), specifically those that are fixed-wing. We aim to produce safety-bounded operations during landing phase of a flight under external disturbances (i.e. winds and noises) to ensure a land or go-around decisions can be made in favor of the vehicle and its surroundings. Dynamical model of fixed-wing reference vehicle, Windracers' ULTRA, will be considered for the reachability analysis. This approach allow a verification of AI/ML models used to assist UAV operations

Research Needs & Motivations

For most flights, the autonomous landing operations are known to be one of the most dangerous phase of flight especially with wind gusts or other external disturbances. Moreover, it is often observed that present-day autopilot softwares may activate multiple unnecessary go-arounds which ultimately reduce efficiency in UAV operations. Therefore, an effective and robust control algorithm for autonomous landing is crucial.

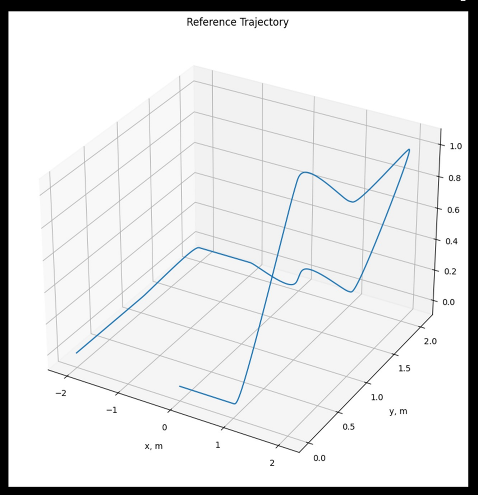
Research Approach & Results



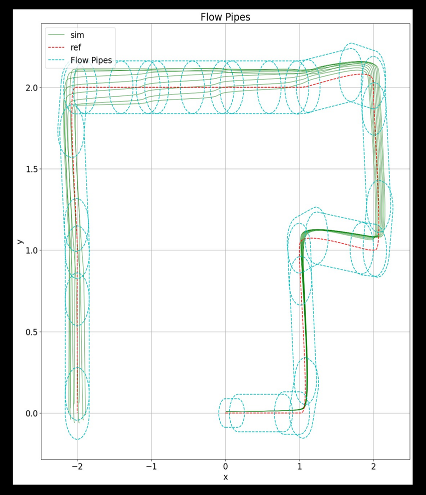


To achieve a safety verification for the vehicle approach, descent, and land, a robust controller is designed to leverage the unique property of Lie Group to guarantee flow pipe corridors for the dynamical model. Here, a verification method allows the flow pipe to either validate the reachability analysis for a safe, collision-free landing or trigger a go-around maneuver.

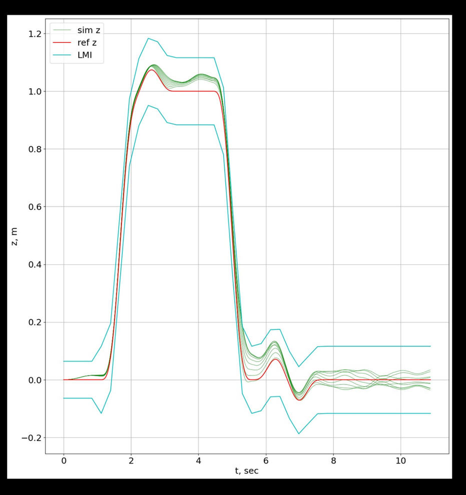
Lyapunov Lie Group Flow Pipe [6,7]
- Verify the safety of the mission before vehicle takeoff under some uncertainties (e.g., disturbances, noises)
- Calculate the invariant set for the system with bounded disturbances
  - Generate flow pipe with invariant set to show the safety bound



Reference trajectory generated by polynomial-based trajectory planning



x-y flow pipes application



Time history plot with invariant bound for z-axis