MULTI-SCALE AERIAL VEHICLE OPERATIONS: MODELS AND TEST FACILITY AT PURDUE

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Overview

- Motivation
- Innovation
- Formulation
- Purdue UAS Test Facility

Motivation

- Large scale cargo operation
- Autonomous aerial vehicles integrations
- Hierarchical operation structure and heterogeneous vehicles management
- System level operation modelling
- Large scale optimization

Innovation

- Logistics Problems:
  - Strategic: hierarchical transportation network generation
  - Tactical: resource/vehicles allocation, fleet management
  - Operational: task assignment, scheduling, routing
- Key Characteristics:
  - Multi-objective, multi-class, multi-player.
  - Real time restriction modelling, data integrating.
  - Problem decomposition for fast solution generation.
  - Sensitivity analysis.
  - Parameter tunning…

Formulation

Noise Optimal Route Planning for Multi Aerial Vehicles

- Problem description:
  - Arrival route planning for aerial vehicles
  - Noise Optimal
  - Collision free
- Approach:
  - Noise Evaluation Model
  - MILP formulation for multi-AV route planning
  - LP formulation for fast solution time

Formulation

Noise Optimal Route Planning for Multi Aerial Vehicles

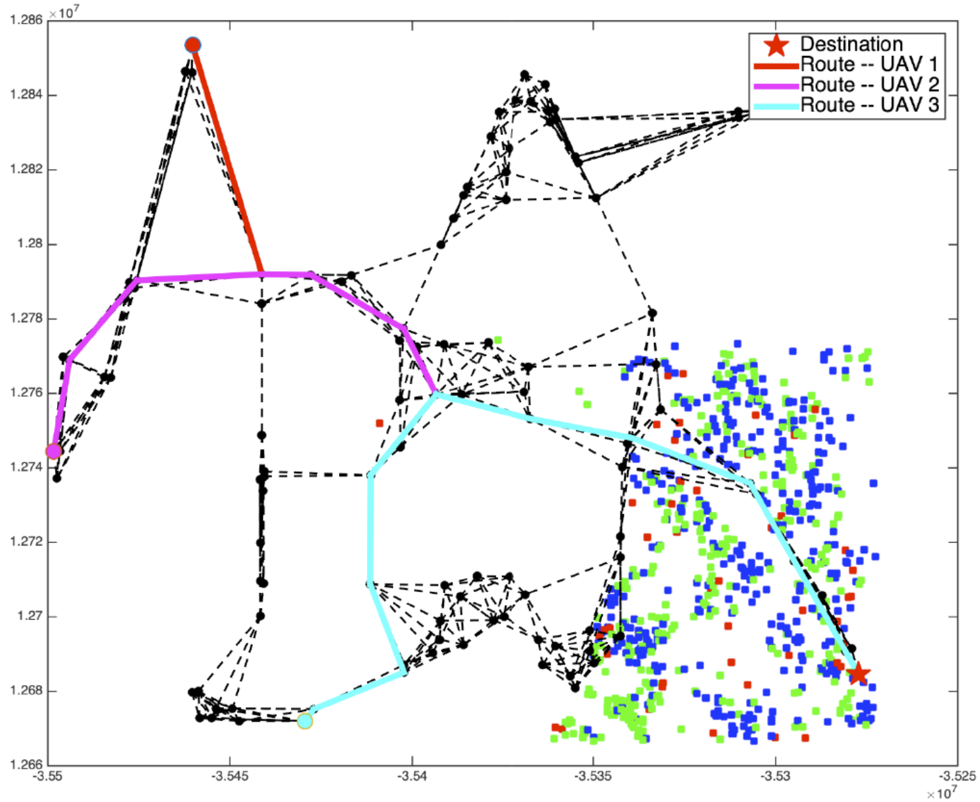
- Optimization model:

$$
\begin{aligned}
\min_{\{x_{i,j}^k(t)\}} \quad & \sum_{t\in\mathcal{T}} \sum_{k\in\mathcal{K}} \sum_{i,j\in\mathcal{N}} c_{i,j} \cdot x_{i,j}^k(t). \\
\text{s.t.} \ & \sum_{j\notin\mathcal{N}_i} x_{i,j}^k(t) = 0, \quad \forall i\in\mathcal{N}, k\in\mathcal{K}, t\in\mathcal{T}, \\
& \sum_{j\in\mathcal{N}_i} x_{j,i}^k(t) = \sum_{s\in\mathcal{N}_i} x_{i,s}^k(t+1), \quad \forall i\in\mathcal{N},\ k\in\mathcal{K},\ t\in\mathcal{T}\setminus\{T\}, \\
& \sum_{j\in\mathcal{N}_{s_k}} x_{s_k,j}^k(0) = 1, \quad \forall k\in\mathcal{K}, \\
& \sum_{i\in\mathcal{N}_d} x_{i,d}^k(T) = 1, \quad \forall k\in\mathcal{K}; \\
& \sum_{i\in\mathcal{N}_d} x_{i,d}^k(t) = x_{d,d}^k(t+1), \quad \forall k\in\mathcal{K},\ t\in\mathcal{T}\setminus\{T\}, \\
& \sum_{k\in\mathcal{K}} \sum_{j\in\mathcal{N}_i} x_{j,i}^k(t) \le 1, \quad \forall i\in\mathcal{N},\ t\in\mathcal{T}
\end{aligned}
$$

- Noise model: $c_{i,j} = \frac{1}{R} \cdot \sum_{n=1}^{N} r_n \cdot L_A(\mathbf{p}_i, \mathbf{p}_j; \mathbf{p}_n^{\text{obs}})$

Formulation

Noise Optimal Route Planning for Multi Aerial Vehicles



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Formulation

Trajectory planning in Uncertain Environment

- Problem description:
  - UAV trajectory planning
  - Probabilistic Geo-fence
  - Geo-fence avoidance
- Approach:
  - Chance constrained modelling of the probabilistic geo-fence
  - Sampling based solution method
  - Iterative optimization for less conservative solution

Formulation

Trajectory planning in Uncertain Environment

- Optimization Model:

$$
\begin{aligned}
\min_{\{\mathbf{u}(t)\}_{t\in\mathcal{T}}} \quad & \sum_{t=0}^{T-1} ||\mathbf{u}(t)||^2, \\
\text{s.t.} \quad & \begin{bmatrix} \mathbf{x}(t+1) \\ \mathbf{v}(t+1) \end{bmatrix} = A \begin{bmatrix} \mathbf{x}(t) \\ \mathbf{v}(t) + B \end{bmatrix} \mathbf{u}(t), \forall t \in \mathcal{T}, \\
& \mathbf{x}(0) = \mathbf{x}^{orig}, \mathbf{x}(T) = \mathbf{x}^{dest} \\
& \mathbf{x}(t) \in \mathcal{K}, \forall t \in \mathcal{T}, \\
& \mathbf{Pr}\Big(\mathbf{x}(t) \notin \mathcal{S}_i^{\mathbf{r}}, \forall i \in \mathcal{I}\Big) \geq \alpha, \forall t \in \mathcal{T},
\end{aligned}
$$

where

$$
\mathcal{S}_i := \left\{ \mathbf{x} \middle| \begin{bmatrix} \cos(\theta_i^k) \\ \sin(\theta_i^k) \end{bmatrix} (\mathbf{x} - \mathbf{p}_i) < r_i^k, \forall k \in \{1, 2, \ldots, K_i\} \right\}
$$

Formulation

Trajectory planning in Uncertain Environment

Algorithm 1 Trajectory Planning via Iterative CC-MIQP

Data: Initialize the set of collision avoidance time-steps as $\mathcal{T}_s = \emptyset$. Solve the CC-MIQP problem (23), and obtain the trajectory.

while *the obtained trajectory is NOT collision-free* **do**

`(S.1)` For each unsafe traverse i, compute traverse time interval $[t_l^i, t_u^i]$;

`(S.2)` Augment the basic CC-MIQP formulation by adding the new time-steps into $\mathcal{T}_s$,

$$\mathcal{T}_s \longleftarrow \mathcal{T}_s \bigcup \{\frac{t_l^i + t_u^i}{2}\}, \ \forall i; \tag{26}$$

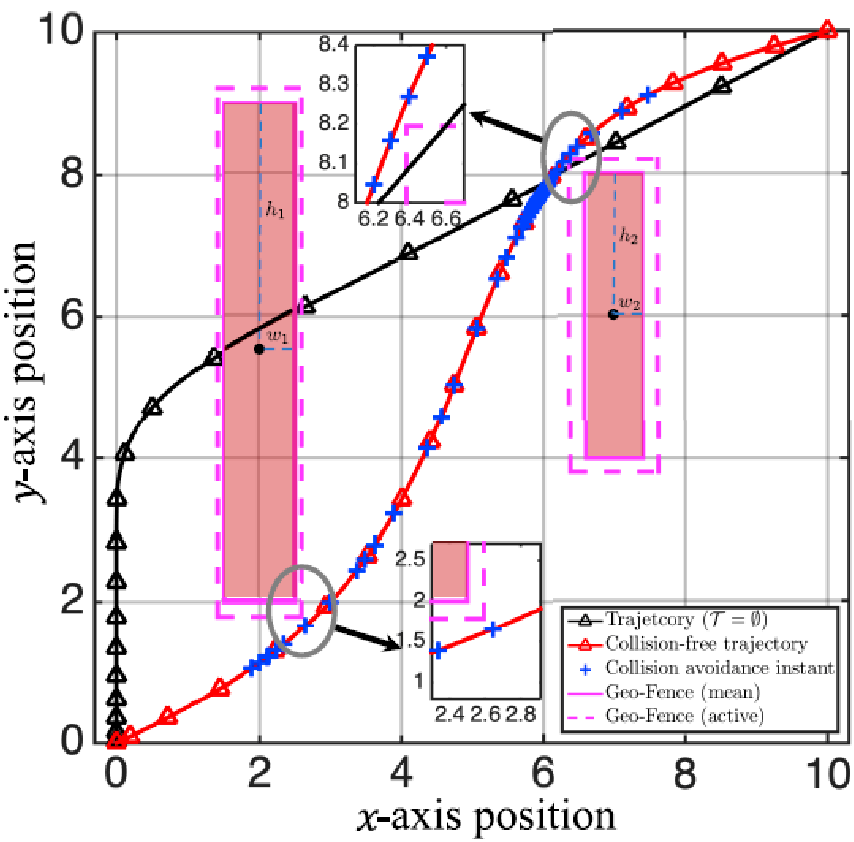
`(S.3)` Solve the augmented CC-MIQP problem by the sampling based solution method, and obtain the new trajectory;

`(S.4)` Detect the unsafe traverses, and continue.

end

Formulation

Trajectory planning in Uncertain Environment



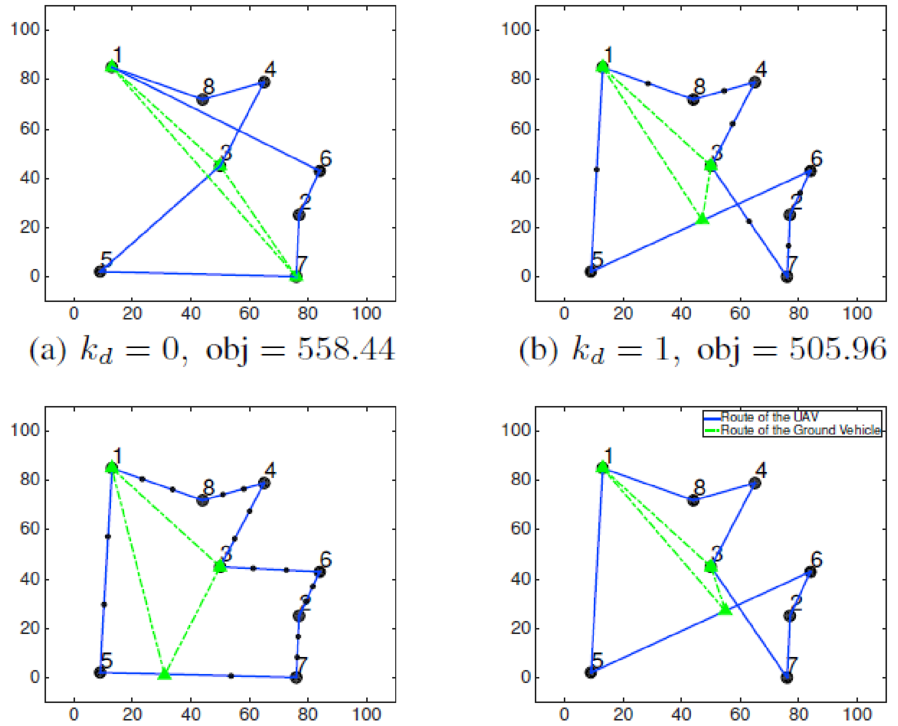
Formulation

Cooperative Air-Ground Vehicle Routing

- Problem description:
  - UAV traverses all targets
  - UAV rendezvous with ground vehicle
  - Targets/rendezvous capacity constraints
  - Speed adjustment
  - Cost minimization for both vehicles
- Approach:
  - Chance constraint modelling for simultaneous arrival at rendezvous point
  - Relaxation on specification of rendezvous point.

Formulation

Cooperative Air-Ground Vehicle Routing



(a) $k_d = 0$, obj $= 558.44$

(b) $k_d = 1$, obj $= 505.96$

(c) $k_d = 2$, obj $= 505.06$

(d) continuous, obj $= 503.15$

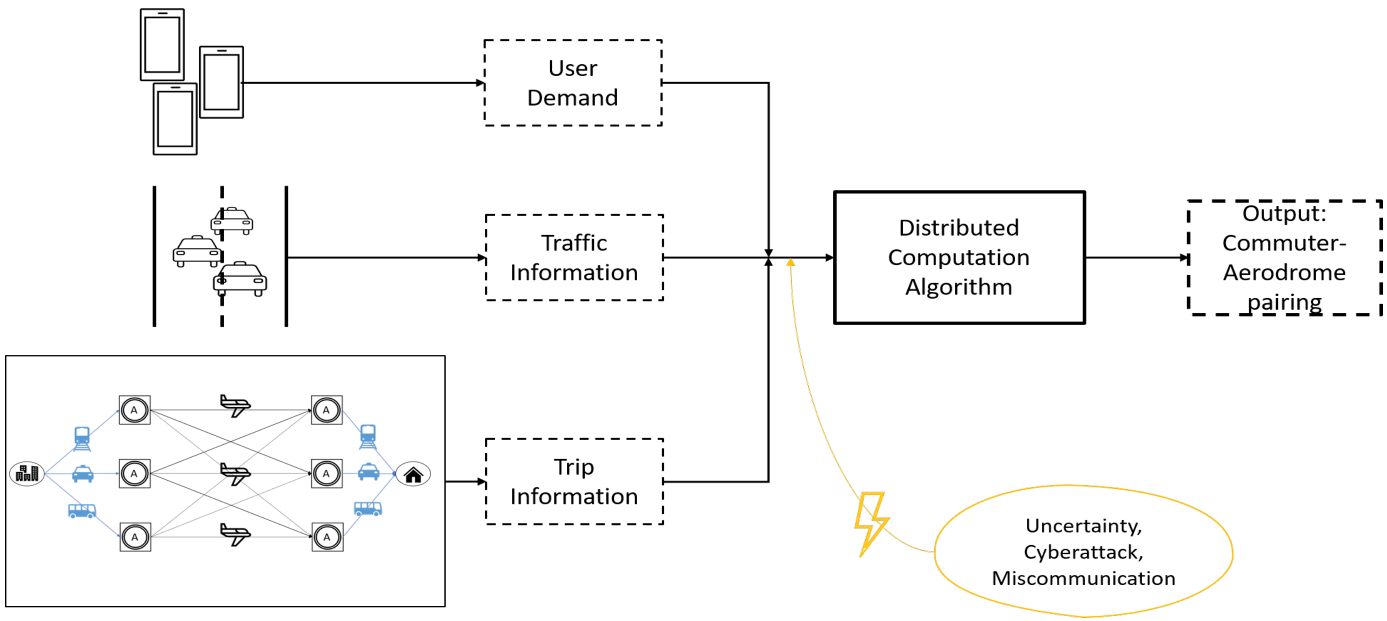
Formulation

Autonomy-enabled Multi-mode Ride-sharing

- Problem description:
  - Trip recommendation system in multi-mode regional transportation
  - Commuter: ground – air – ground
  - Service Provider: aerodrome – shared UAM - aerodrome
  - Least commute time based on real-time data
- Features:
  - Distributed computation framework
  - Robust optimization models
  - Resilient computation algorithms

Formulation

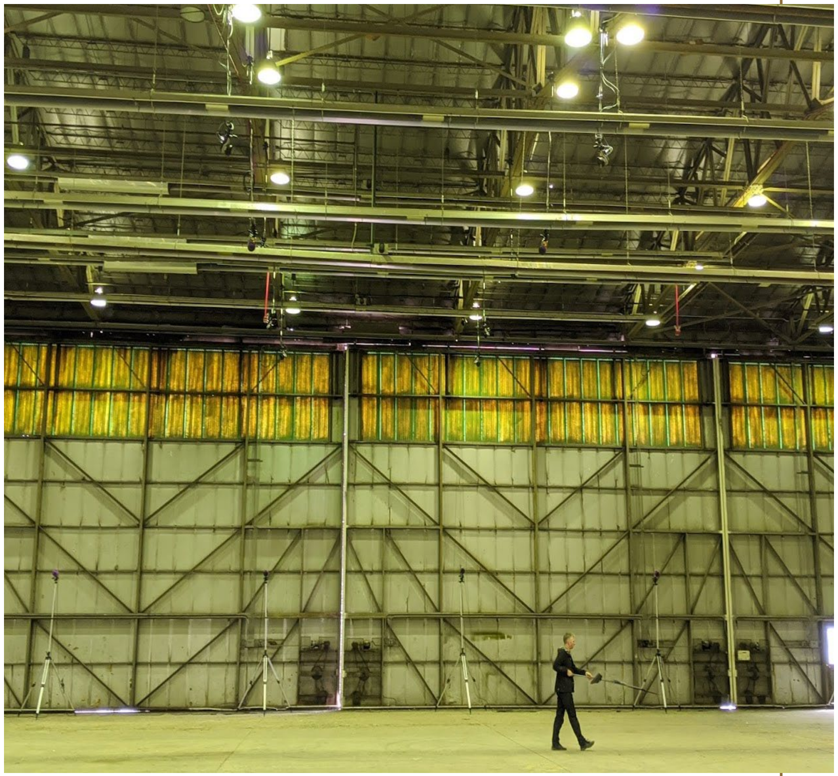
Autonomy-enabled Multi-mode Ride-sharing



Purdue UAS Testbed

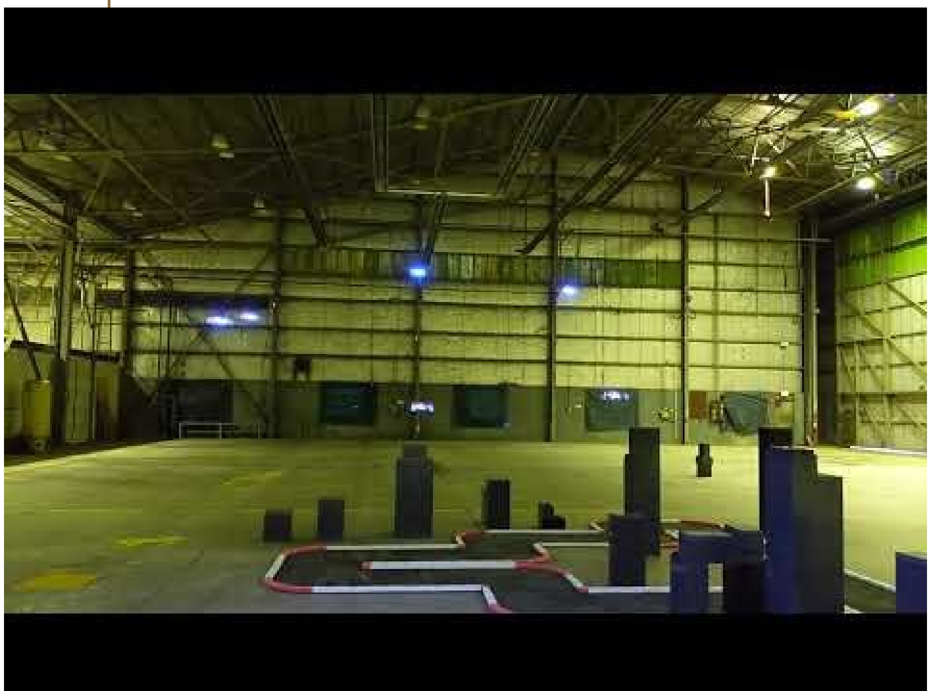
Purdue UAS Testbed

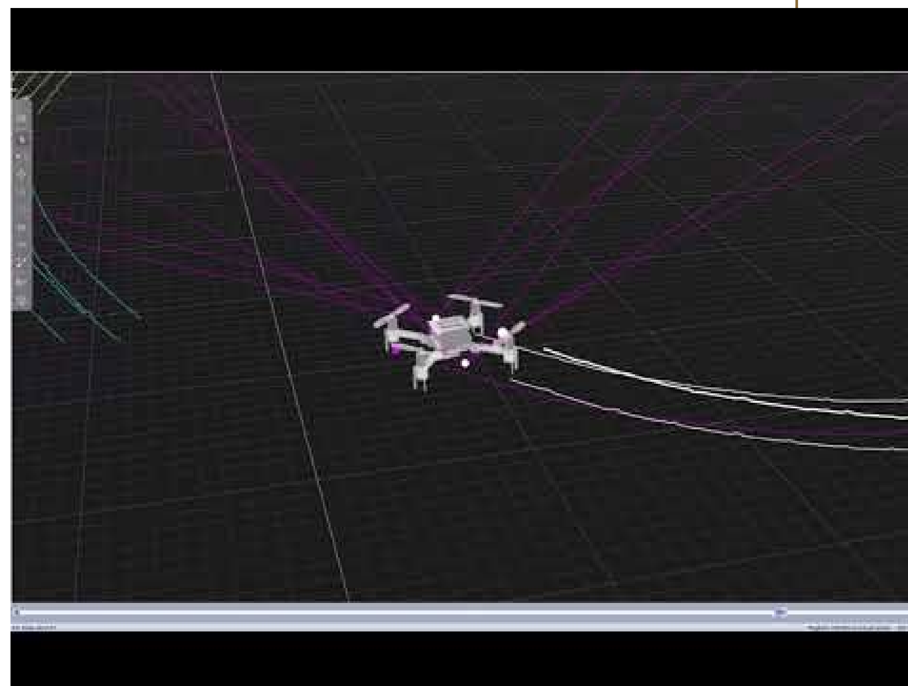
- **World's Largest** indoor motion capture facility, 20,000 sq ft. 30ft ceiling
  - Support for large and fast-moving vehicles such as fixed-wing aircraft
  - Reconfigurations of large environments
- Motion capture tracks rigid bodies with active or passive markers and enables:
  - **Sensor-emulation**, GPS, ultra-sonic, ADS-B, LIDAR, camera,etc
  - **Mixed-reality** environments
  - **Real-time** feedback of position for **closed-loop control**
  - **Ground truth**: Provides mm accurate position and 0.1 deg attitude for typical UAS



PurdueUAS Testbed

Provide Real-time Data for Closed Loop Control of Vehicles

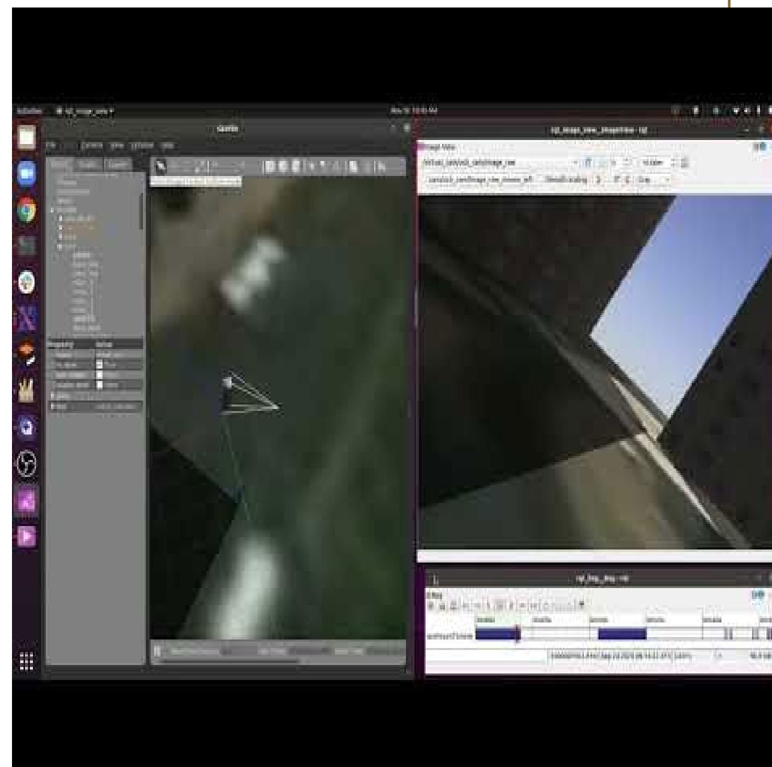




Purdue UAS Testbed

Create Virtual/Augmented/Mixed Reality Environments

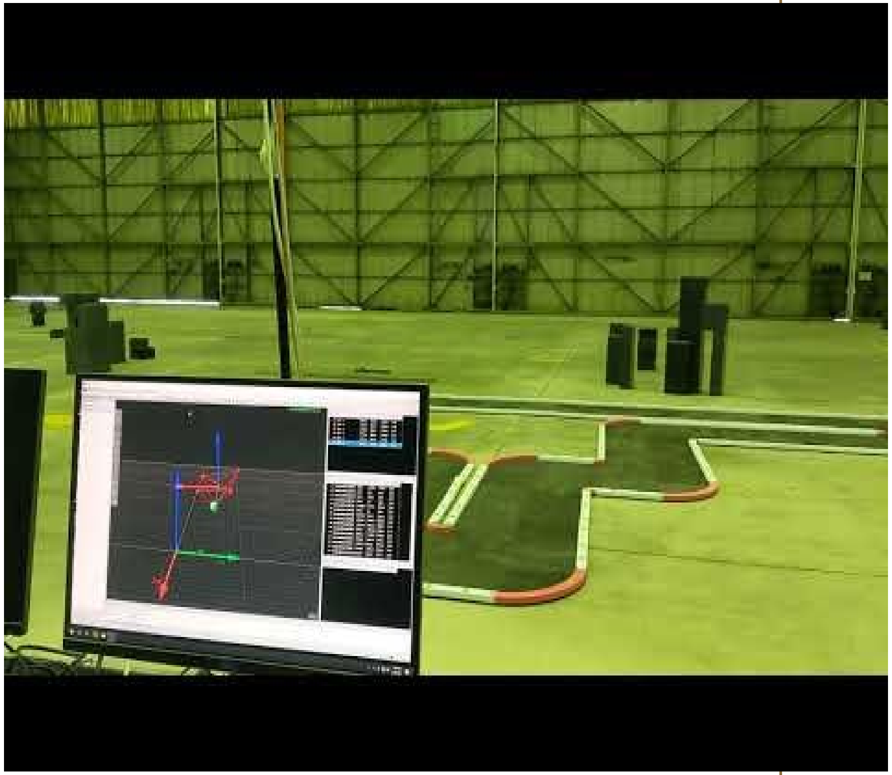
- Processing Steps:
  - Motion Capture Data is Fed to Simulator
  - Simulator Renders Camera Images and other Sensor Information
  - Sensor information is fed back to vehicle via WiFi



Purdue UAS Testbed

Provide Ground Truth Data for Experiments

- This is this most useful, but least glamorous use case
  - Development of autonomy solutions using computer vision, machine-learning, all require a base-line for tuning and development of the algorithm



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THANK YOU