Probability of Obstacle Collision for UAVs in Presence of Wind

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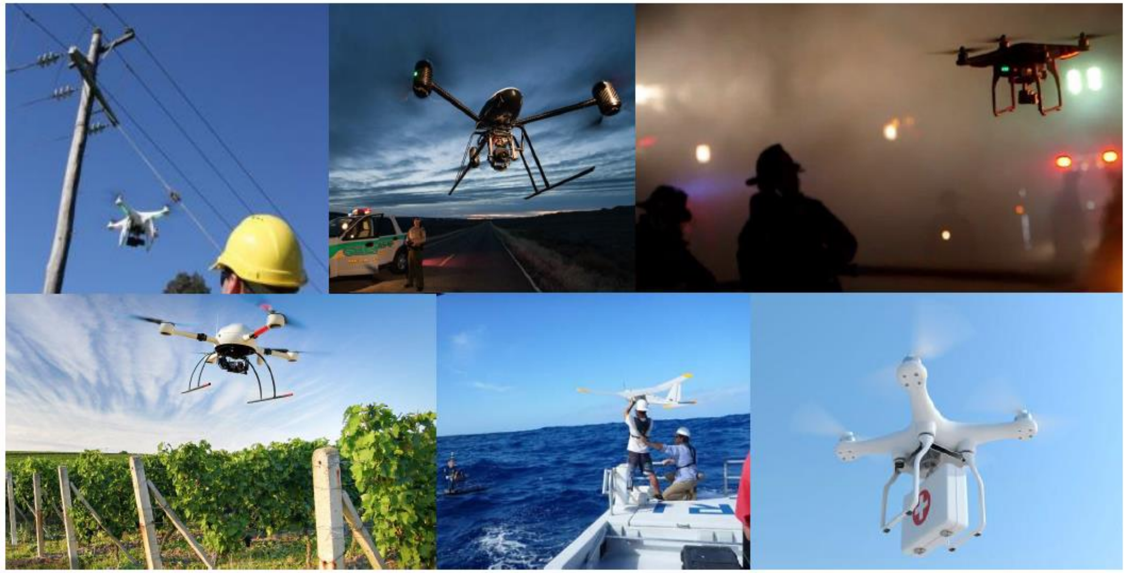
Overview

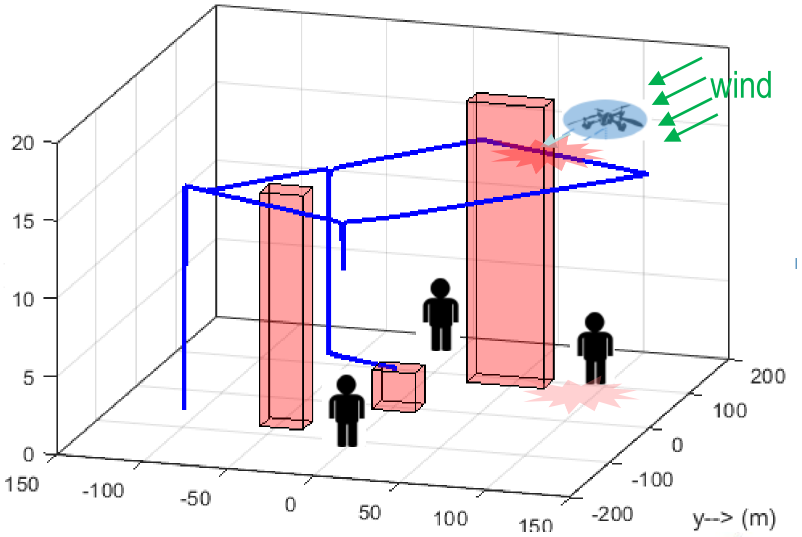
- Motivation: Safety monitoring of UAV flights
- NTSB records: UAV flight incidents caused by wind
- Wind data and models
- 6DOF Trajectory Simulation with Aerodynamic drag
- Probability of Obstacle Collision
- Validation results:
  - Simulated trajectory with empirical wind
  - Experimental trajectory with real wind measurements.
- Conclusion and Future work

Motivation: Safety monitoring of UAV flights

Objective: Under NASA's ARMD initiative , we develop services, functions and risk mitigation capabilities to ensure safe UAV operations.

- Rapid increase of UAV applications in low altitude airspace & above densely populated areas.
- Multiple safety-critical factors: loss-of-communication, degraded navigation unit, **loss-of-control due to sudden wind gusts/ turbulence.**
- Assessment of risk (to people and property on ground) in a resource-constrained environment.





NTSB records: UAV loss-of-control due to wind

- **National Transportation Safety Board (NTSB)***

By investigating accidents related to unmanned aircrafts in the NTSB Case Analysis and Reporting Online (CAROL) tool (https://data.ntsb.gov/carol-main-public/basic-search), 4 UAV incidents were identified out of the 21 reported from the year 2010-2022, caused by unaccounted wind scenarios.

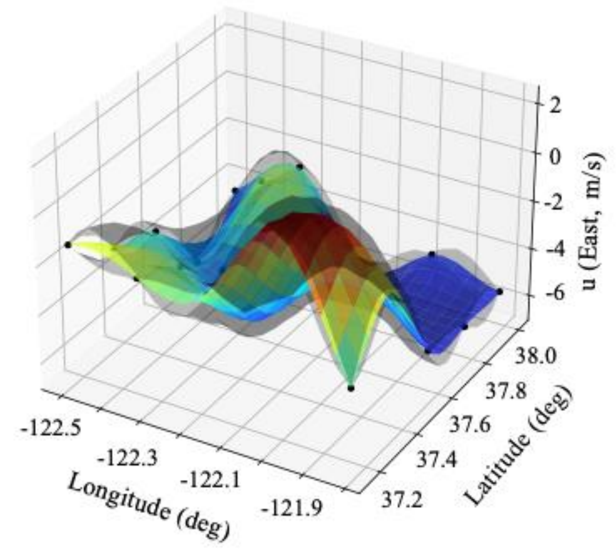
On November 2019, UAS sustained substantial damage when landing during a training flight. The accident was triggered due to the presence **of 7 knots crosswind** that was not accounted for during landing. According to the operator/manufacturer, the student pilot was pilot-flying and the aircraft touched down at 79 knots indicated airspeed (KIAS) **crabbed to the left approximately 5 degrees**, consistent with a 7 knot crosswind component from the left. Upon touchdown, **the aircraft began drifting to the left with the nose wheel off the ground, demanding pitch command higher than recommended and limiting yaw control.** Despite increasing the right rudder, the aircraft continued drifting to the left due to the crosswinds and ended up deviating from the runway before a go-around could be initiated.	On June 2019, UAS sustained substantial damage during a contingency landing for a test flight. The aircraft was a large UAS with 12 electric motors and 12 propellers planned to fly autonomously at the speed of 30 knots. On reviewing the accident flight, the probable cause was identified as the presence of a higher than expected and accounted for **crosswind, around 10 knots of steady wind and 6 knots of gusts which initiated a lateral deviation from the programmed flight profile.** This resulted in the UAV reaching the limits of the geo-fence area **triggering a contingency forced landing** where power was cut down and the **UAV fell on ground with significant damage to the aircraft**. The operators reported that the unaccounted **crosswind resulted in high vibration within the aircraft navigation system** and the contingency logic was unable to return the aircraft to the planned abort zone in a safe manner.	On June 2016, UAS experienced an **in-flight structural failure** on final approach at a designated landing site near Yuma, Arizona. During the final approach, the UAV encountered an **increasing amount of turbulence and wind speeds of up to 10 knots at the surface and 12 to 18 knots,** as measured by the aircraft at flight altitude. The operators post-flight telemetryanalysis showed that the **aircraft experienced significant deviations in pitch, roll, and airspeed, due to the turbulence.** The gusts lofted the aircraft above the glidepath about 5 seconds prior to failure. Due to high wind gusts, up elevon, and low angle of attack, the downward lift (and torsion) on the outer wing panels increased and the loading exceeded its structural limit **resulting in a downward deformation and failure of the right wing.** Finally, the aircraft impacted the ground at a groundspeed of 25 knots suffering significant damages, although no injuries were reported.	On June 2008, UAS **sustained substantial damage when it collided with a stadium light pole** while maneuvering for a pre-programmed landing. From examining the data file after collision, the aircraft showed **several instances of overshooting the programmed trajectory** as it transitioned through waypoints. The abnormal tracking was caused as a result of software and gains parameters being inadequate to compensate for the **high tailwinds at the aircraft's flight altitude** and the aggressive profile of the flight plan.

Wind Data & Models

Steady state wind:

- modelled based on look-ahead forecasts of wind speed and direction from True Weather Solutions Inc. (TWS) at time intervals of 1 hour with a spatial resolution of 1 km.
- Gaussian Process Regression (GPR) [10] is implemented to interpolate the sparse grid of available data points and obtain the wind field along the horizontal u (West-East) and vertical v (South-North) directions.

Corbetta,M.,Jarvis,K.J.,andBanerjee,P.,"UncertaintyPropagationinPre-FlightPredictionofUnmannedAerialVehicle Separation Violations," *IEEE Aerospace Conference 2022*, IEEE, Big Sky, MT, 2022.



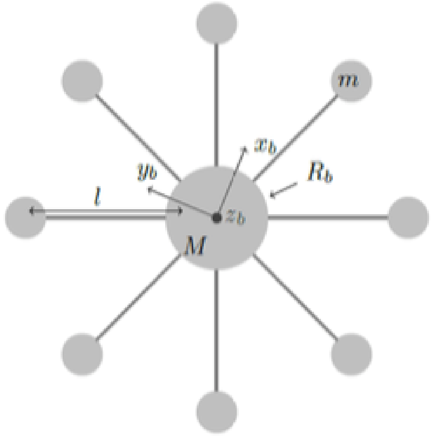
Wind gusts or turbulence:

- Brief and sudden increase in wind speed along a specific direction, the duration of which is usually less than 20 s. Turbulence is an irregular motion of the air resulting from eddies and vertical currents.
- Von Kármán models to generate time series representing wind turbulence, using model parameters representative of low-altitude airspace (below 1000 ft).
- Use measurements from Vaisala wind sensors (ground anemometers).

Moorhouse,D.J.,andWoodcock,R.J.,"BackgroundinformationanduserguideforMIL-F-8785C,militaryspecification-flying qualities of piloted airplanes," Tech. rep., Air Force Wright Aeronautical Labs Wright-Patterson AFB OH, 1982.

UAV Trajectory Prediction with Wind Effect

- 6 DOF airframe dynamic model using Newton-Euler equations, where inertia is described by lumped masses and followed by a linear quadratic integrator (LQI) controller.
- Low fidelity model in order to capture the basic fundamental dynamics of the vehicle without increasing the computational load, making it suitable for in-time predictions of trajectory deviations.



$$\dot{\boldsymbol{x}} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ (s_\theta c_\psi c_\phi + s_\phi s_\psi)\frac{T}{m_t} \\ (s_\theta s_\psi c_\phi - s_\phi s_\psi)\frac{T}{m_t} \\ -g + c_\phi c_\theta \frac{T}{m_t} \\ p + q s_\phi t_\theta + r c_\phi t_\theta \\ q c_\phi - r s_\phi \\ q\frac{s_\phi}{c_\theta} + r\frac{c_\phi}{c_\theta} \\ \left(\frac{I_{y_b y_b} - I_{z_b z_b}}{I_{x_b x_b}} qr + \frac{l}{I_{x_b x_b}}\tau_\phi\right) \\ \left(\frac{I_{z_b z_b} - I_{x_b x_b}}{I_{y_b y_b}} pr + \frac{l}{I_{y_b y_b}}\tau_\theta\right) \\ \left(\frac{I_{x_b x_b} - I_{y_b y_b}}{I_{z_b z_b}} qr + \frac{l}{I_{z_b z_b}}\tau_\psi\right) \end{bmatrix}$$

- Aerodynamic drag embedded in the vehicle dynamic equations: drag forces D_{i_b} added to the acceleration terms of the Newton-Euler equations.

$$D_{i_b} = -\frac{1}{2} C_{D,i_b} A_{i_b} \rho \vec{V}^2_{r,i_b}$$

- LQI control where a linear quadratic regulator (LQR) has been enhanced by an integral term to compensate for constant biases caused due to wind.

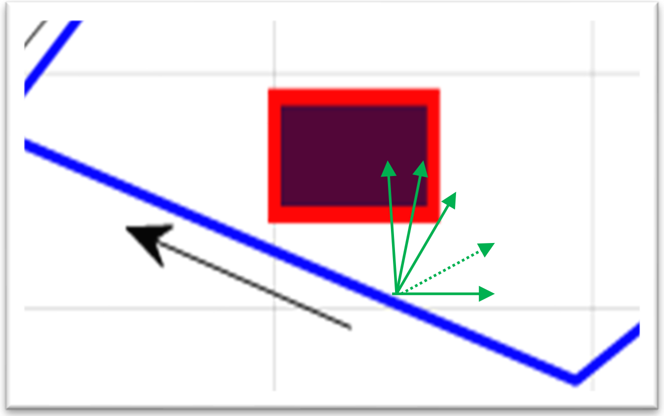
Corbetta, M., Banerjee, P., Okolo, W., Gorospe, G., and Luchinsky, D. G., "Real-time uav trajectory prediction for safety monitoring in low-altitude airspace," *AIAA Aviation 2019 Forum*, 2019, p. 3514.

Probability of Obstacle Collision

Probability of Obstacle Collision ($P_{obs-col}$): as a function of probability of collision with an obstacle such as buildings caused by off-nominal conditions, area of exposure dependent on vehicle size and obstacle measurement noise.

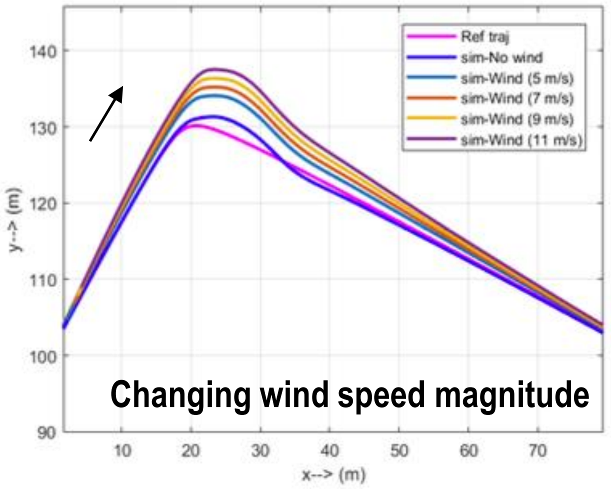
Steps to compute $P_{obs-col}$ with wind information:

1. Wind velocity is estimated at every point on the trajectory based on the wind models.
2. Given the GPR technique or Von Karman turbulence model, each wind estimate has an associated variance.
3. Based on the wind field distribution, n_s samples of wind, and the associated probabilities, are generated.
4. Using the state-space formulation, deviated trajectory positions is calculated for each n_s sample.
5. The trajectory positions that hit or lie within the boundary of any obstacle are identified as collided samples, n_{dev}
6. $P_{obs-col} = \frac{n_{dev}}{n_s}$

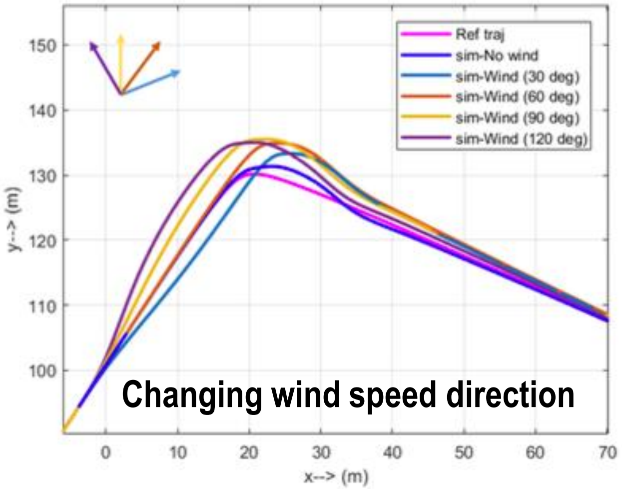


Validation results: Simulation

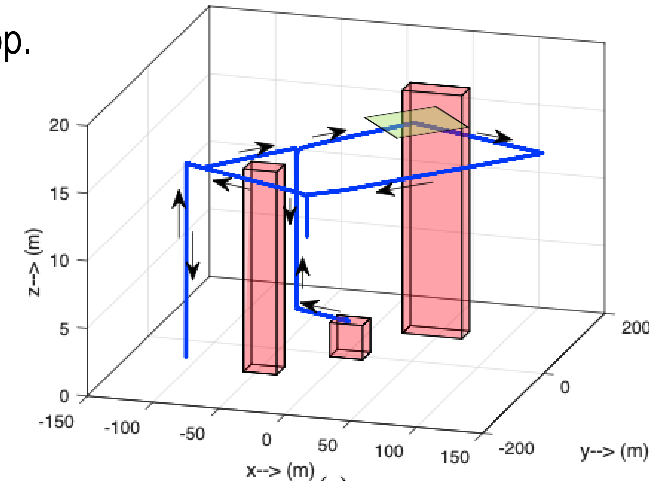
Wind causes higher deviation at the turns (UAV changes its flight direction) due to the controller in the loop.

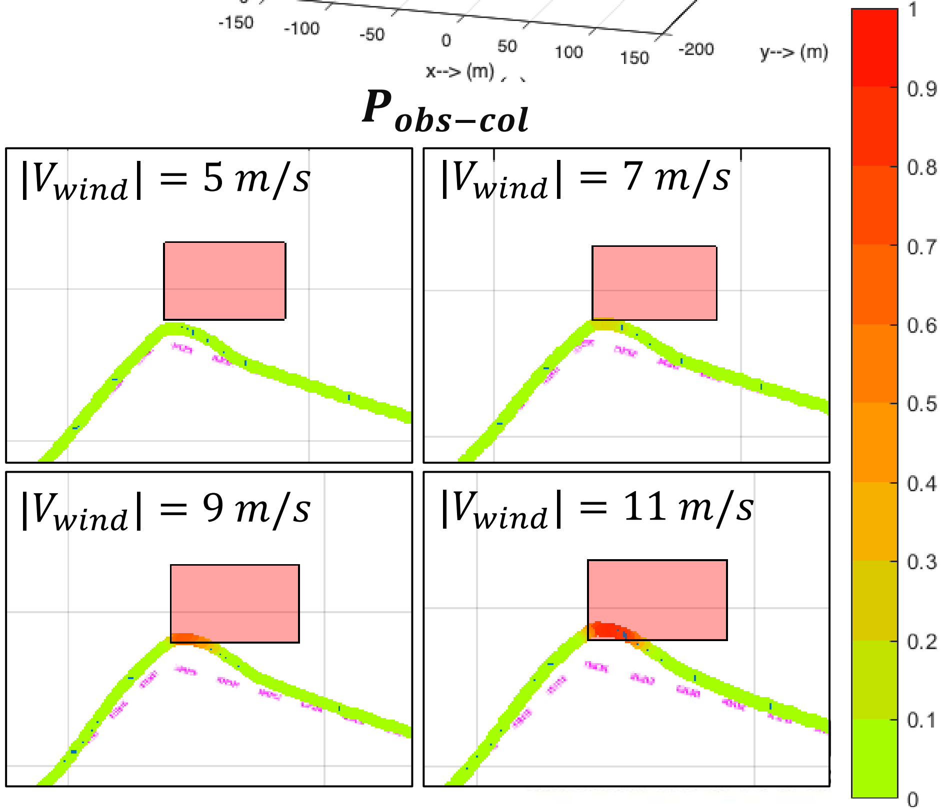


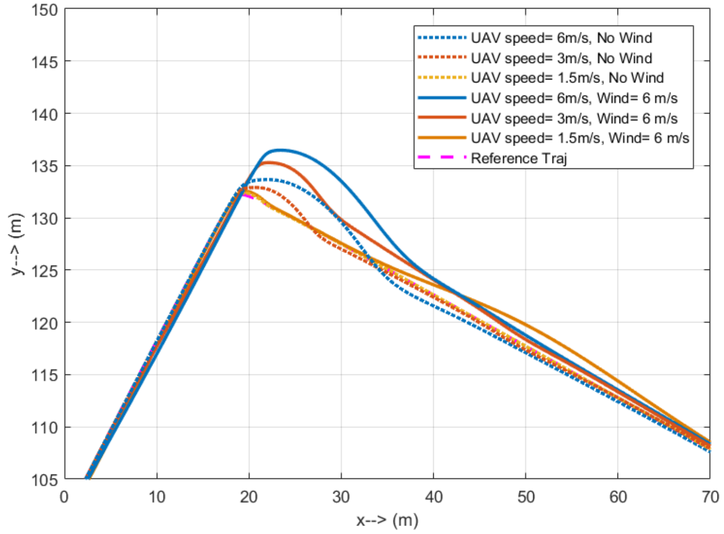
Changing wind speed magnitude



Changing wind speed direction



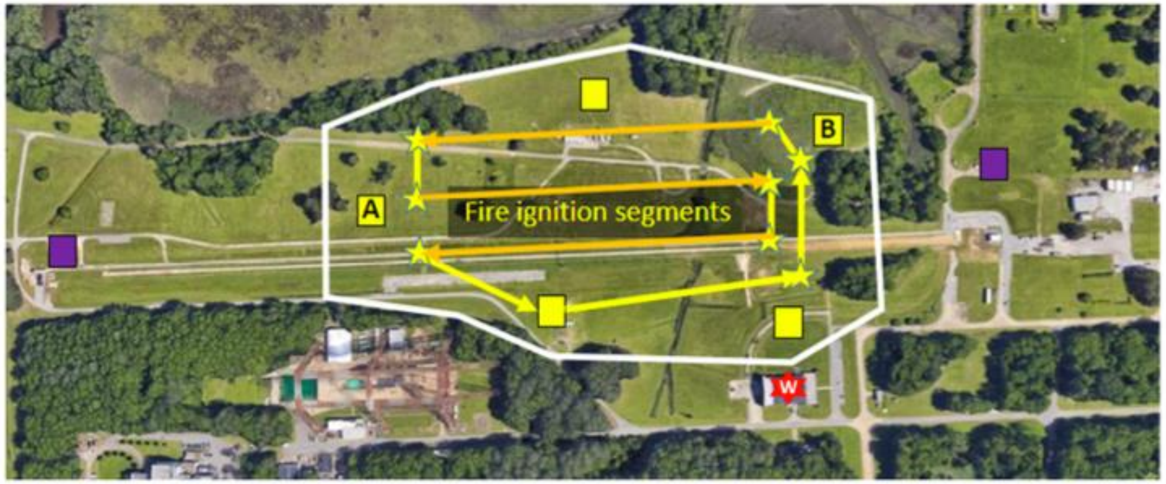


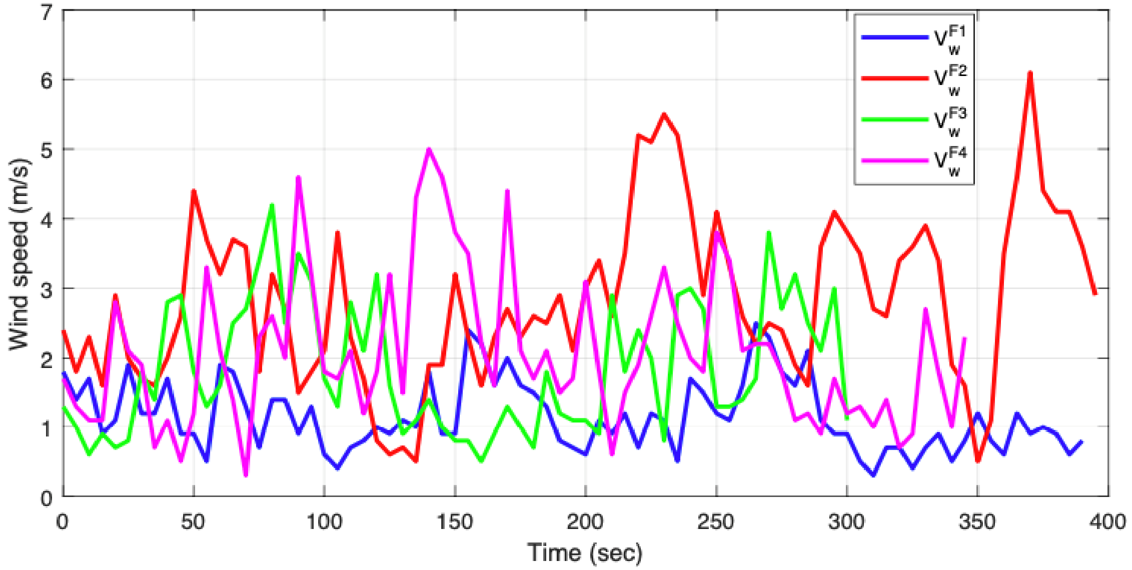


Changing UAV air speed with same wind conditions.

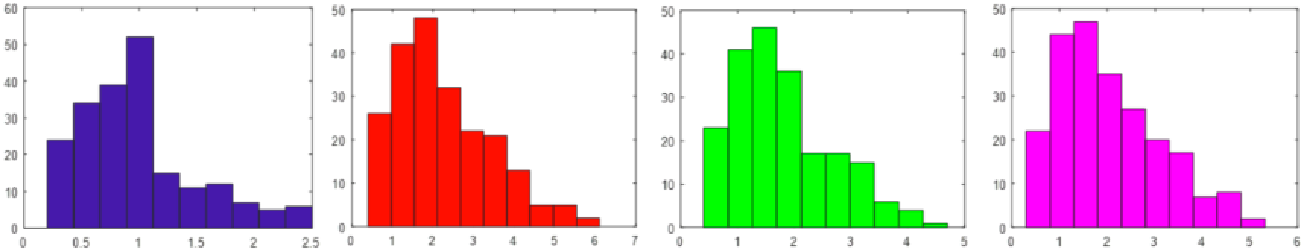
Trajectory deviation is higher when UAV takes a turn at a higher speed. For low speed, controller has more time to compensate for the deviation error and adjust back to the desired location, hence lower deviation.

Validation results: Experiments





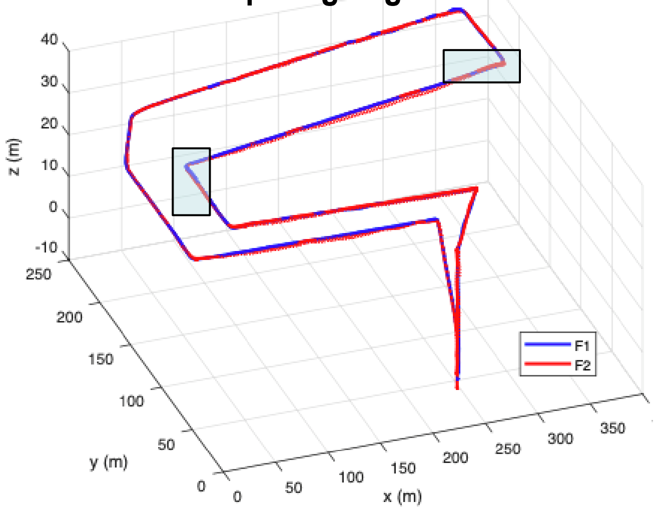
(a)

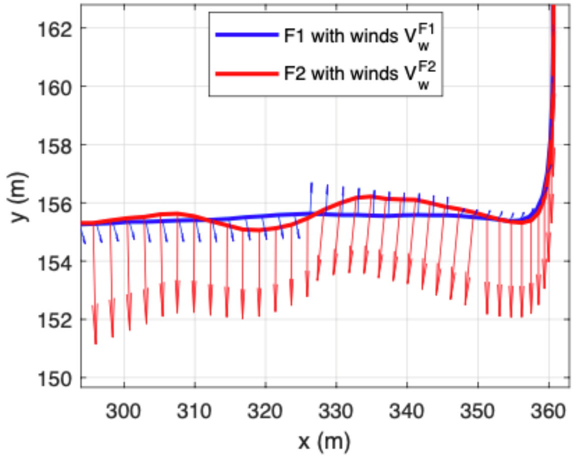


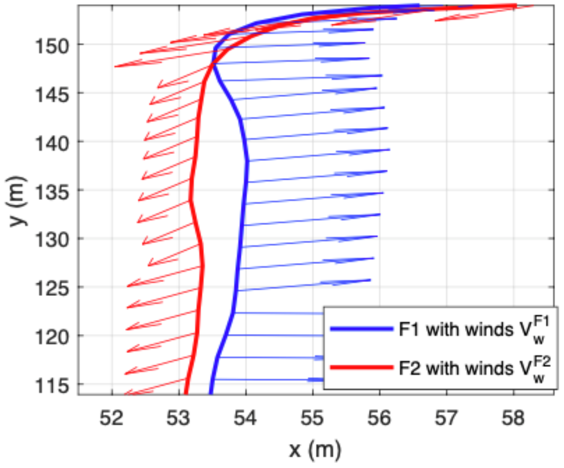
- F1: UAV ground speed at 5 m/s with mostly low winds (maximum wind speed= 2.5 m/s)
- F2: UAV ground speed at 5 m/s with mostly high winds (maximum wind speed= 6 m/s)
- F3: UAV ground speed at 8 m/s with mostly high winds (maximum wind speed= 4.5 m/s)
- F4: UAV ground speed at 8 m/s (and 3 m/s for the last section of flight trajectory) with mostly high winds (maximum wind speed= 5 m/s)

Validation results: Experiments

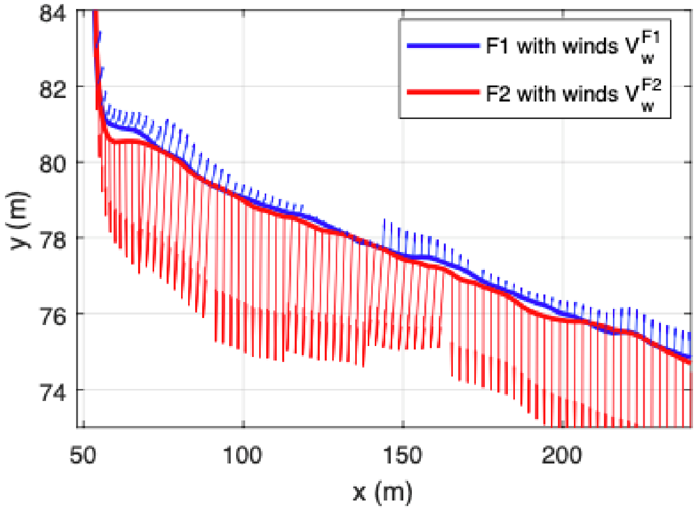
Comparing Flights F1 and F2.



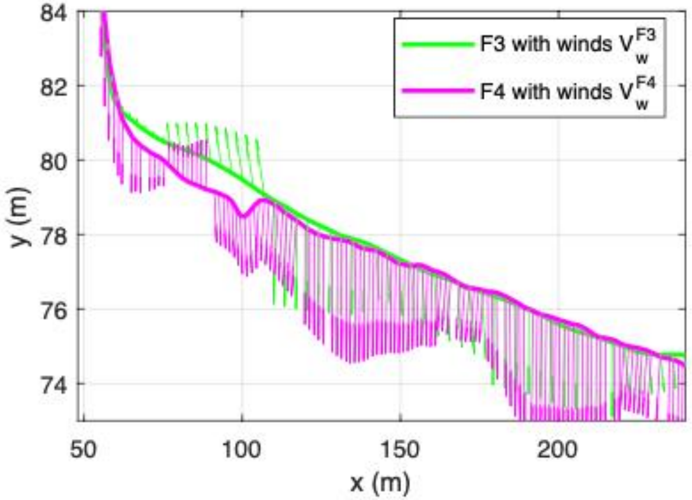




Higher deviations/ oscillation at the turns due to wind.



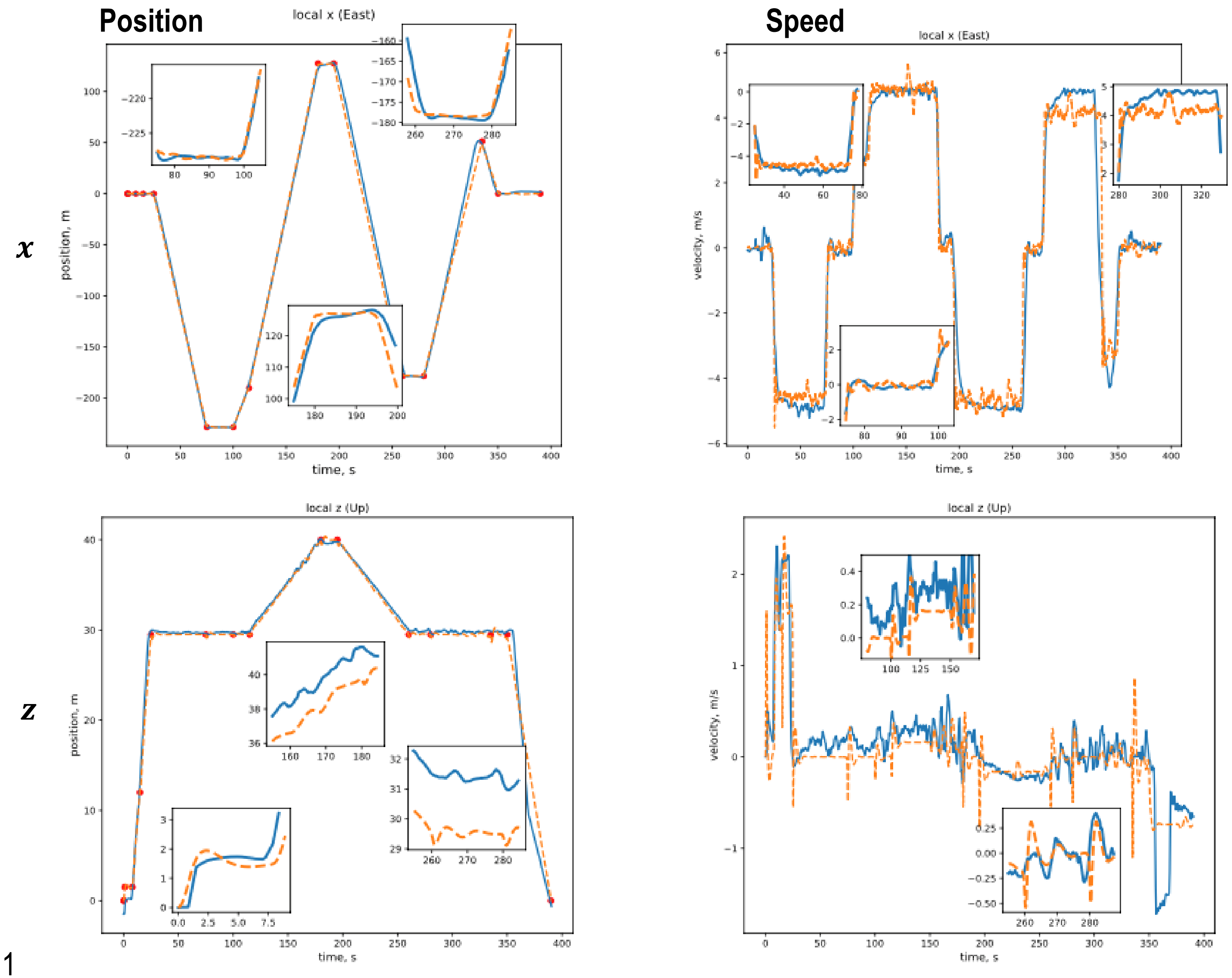
F1 and F2:
UAV airspeed= 5 m/s.



F3 and F4:
UAV airspeed= 8 m/s.

Higher wind-induced deviations when UAV flies at higher speed.

Validation results: Experiments



Telemetry data from flight F1 (blue solid line) and simulation model predictions (orange dashed line).

Conclusion & Future Work

- This paper presents a framework to integrate wind information into the UAV trajectory prediction.
- Methods for incorporating and modelling wind characteristics (steady-state wind and turbulence) from external sources into the UAV aerodynamic simulations have been discussed.
- Effect of wind speed magnitude, direction and UAV airspeed on Probability of Obstacle collision is analyzed using simulated scenarios and demonstrated in experimental flights with real wind measurements.
- Finally, the position and speed profile obtained from experimental telemetry data is compared against simulation model predictions ensuring a good agreement between the both, particularly the fluctuations caused by wind highly align with flight observations.

- Some discrepancies are noted between simulation model predictions and real flight data, owing to lack of complete set of wind measurements, lack of motor and propeller dynamics in the model, simplified assumptions of inertia measurements. These shall be refined in future.
- Surrogate models are being investigated to incorporate more complex wind predictions into powertrain and trajectory model.

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