Advanced Kalman Filter-based Wind Velocity Estimation using Autonomous Aerial Vehicles

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INTRODUCTION

Estimating wind velocity is crucial for environmental monitoring. Ground-based sensors offer precise wind velocity estimations; however, it is costly, and in emergencies such as wildfires, portability becomes essential. Numerous studies have utilized uncrewed aerial vehicles (UAVs) for wind velocity estimation. Quadrotor UAVs are favoured due to their compact size, maneuverability, and cost-effectiveness. Direct and model-based approaches are two main methods in wind velocity estimation. The direct approach requires additional sensors onboard, increasing the payload and cost. The model-based approach relies only on the system model and onboard sensors. Extended Kalman Filters (EKF) accurately estimate states in the presence of process and measurement noise [1]. EKF relies on a linearized nonlinear system model, reducing accuracy in highly nonlinear conditions. The Unscented Kalman Filter (UKF) is used in nonlinear state estimation. However, its applicability in quadrotor UAV-based wind velocity estimation is yet to be fully explored. This study implemented and compared model-based wind velocity estimation with EKF and UKF in a highly nonlinear simulation environment.

METHOD

Design of EKF and UKF wind velocity estimation is done directly on the nonlinear manifold of the special Euclidean group SE(3) with a Geometric Controller [2]. This is to avoid the singularities and complexities inherent to the Euler angles or quaternions. The full state vector includes position, velocity, angular velocity, attitude on SO(3), and wind velocity components. Bias terms are added to the nonlinear truth model to account for unmodeled terms. The observable states, position, angular velocity, and acceleration were corrupted with noise of standard deviations 0.1 m, 0.0094 $rads^{-1}$, 0.0972 ms^{-1} to simulate the Global Positioning System (GPS) and the Inertial Measurement Unit (IMU).

RESULTS AND DISCUSSION

Simulations were run using a 0.005-second step size for a total duration of 15 seconds. The quadrotor UAV was tested in constant and sinusoidal wind fields, while hovering, during a straight-line trajectory and a Lissajous trajectory. Fig. 1 compares the EKF and UKF estimation with the ground truth when the quadrotor UAV is following a Lissajous trajectory under sinusoidal wind disturbances. Table 1 depicts the RMSE values and standard deviations of the wind velocity estimation. As the nonlinearity of the system increases, the accuracy of the EKF compared to the UKF decreases. Overall, the vertical wind velocity component is less accurate. In each cycle, EKF estimation consumes an average of 0.00013 seconds while UKF consumes 0.00220 seconds.

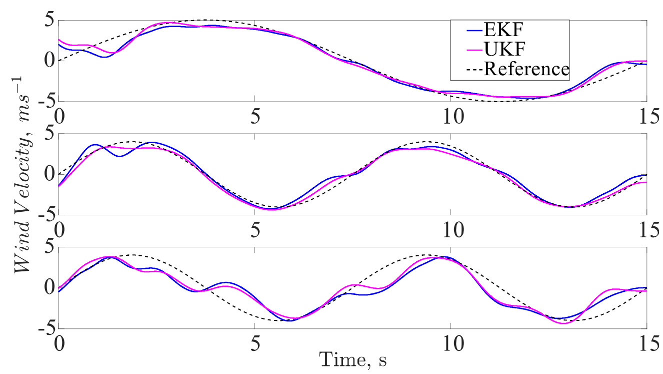

Fig 1 Wind velocity estimation using a quadrotor UAV following a Lissajous trajectory under sinusoidal wind disturbances.

Table 1: RMSE and standard deviations of the estimations

Estimator	Filtered Wind Velocity (mean (std))	Unfiltered Wind Velocity (mean (std))
EKF	0.7004 (± 0.6952) 0.6323 (± 0.6284) 1.3419 (± 1.3227)	2.4565 (± 2.4538) 2.8164 (± 2.8151) 4.0619 (± 4.0575)
UKF	0.6694 (± 0.6695) 0.4964 (± 0.4566) 1.2463 (± 1.2442)	2.3658 (± 2.3658) 2.4698 (± 2.4646) 3.9149 (± 3.9149)

CONCLUSIONS

The UKF achieves higher accuracy, whereas the EKF trades accuracy for faster computation. Consequently, the UKF is the preferred choice for high-precision wind field estimation. The reduced accuracy of vertical wind estimation may result from weak observability due to the dominance of gravity in that direction and limited vertical excitation of the quadrotor UAV. Future research will focus on testing EKF and UKF under realistic wind conditions.

REFERENCES

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