Inflight Wind Velocity and Aerodynamic Coefficient Estimation for fixed Wing UAVs and Applications to Icing Detection

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Outline

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Motivation

Why do we need Wind velocity estimation?

- Allows Angle of Attack, Airspeed and Sideslip calculation
- Useful for path planning and following as well as landing

Problems:

- Small UAVs have no sensors to measure angle of attack
- Aerodynamic coefficients often unknown

Wind Velocity Estimation

- Kinematic Model (Pitot-static Tube)
  - non parametric
- Aerodynamic Model (Accelerometer)
  - parametric
Kinematic Model

- Wind triangle

\[ \mathbf{v}_r^b = \mathbf{v}^b - R_n^b \mathbf{v}_w^n \]

- Angle of Attack

\[ \alpha = \tan^{-1} \left( \frac{w_r^b}{u_r^b} \right) \]

- Sideslip angle

\[ \beta = \sin^{-1} \left( \frac{v_r^b}{\| \mathbf{v}_r \|} \right) \]

- Airspeed

\[ V_a = \| \mathbf{v}_r \| \]
Kinematic Model

- Pitot-static tube measures $\tilde{V}_a$ if tube wide enough and airspeed small

$$\tilde{V}_a = \frac{V_a}{\gamma} + \eta$$

- The relative airspeed vector:

$$\mathbf{v}_r^b = V_a \begin{bmatrix} \cos \alpha \cos \beta \\ \sin \beta \\ \sin \alpha \cos \beta \end{bmatrix}$$

if $\cos(\beta) \approx 1$

$$\begin{bmatrix} u^b \\ w^b \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{R}_n^b \mathbf{v}_w^n + V_a \begin{bmatrix} \cos \alpha \\ \sin \alpha \end{bmatrix}$$
Aerodynamic Model

- General model for specific force in z-direction

\[ f_z = \frac{\rho S}{2m} V_a^2 (-C_L(\alpha) \cos(\alpha) - C_D(\alpha) \sin(\alpha)) \]

- Coefficients

\[
C_L(\alpha) = C_{L,0} + \alpha C_{L,\alpha} \\
C_D(\alpha) = C_{D,0} + \alpha C_{D,\alpha}
\]

- Since \( \alpha \) is small in normal flying conditions:

\[
f_z = -KV_a^2 (C_{L,0} + \alpha C_{L,\alpha})
\]
Wind Model

- Frequency separation in steady and turbulent wind velocity components

\[ \mathbf{v}_{w,k}^n = \mathbf{v}_{s,k}^n + \mathbf{v}_{t,k}^n \]

- Steady wind velocity model

\[ \Delta \mathbf{v}_{s,k}^n \approx 0 \]

- Turbulent wind velocity model

Dryden model [5]:

\[ \Delta \mathbf{v}_{t,k}^n = -\Delta T \mathbf{V}_{a,k} \left( \begin{array}{c} \frac{u_t^n}{L_u} \\ \frac{v_t^n}{L_v} \\ \frac{w_t^n}{L_w} \end{array} \right)_k + \left( \begin{array}{c} \sigma_u \sqrt{2 \Delta T \frac{V_a}{L_u} \eta_u} \\ \sigma_v \sqrt{2 \Delta T \frac{V_a}{L_v} \eta_v} \\ \sigma_w \sqrt{2 \Delta T \frac{V_a}{L_w} \eta_w} \end{array} \right)_k \]
State-Space Model

- States
  \[ x = [u^n_t \ v^n_t \ w^n_t]^T \]

- Parameters
  \[ p = [u^n_s \ v^n_s \ w^n_s \ K C_{L_0} \ K C_{L_\alpha} \ \gamma]^T \]

- Inputs
  \[ \tilde{u} = [\tilde{u}^b \ \tilde{v}^b \ \tilde{w}^b \ \mathbf{R}_n^b \ \mathbf{h}]^T \]

- Outputs
  \[ z = [\tilde{f}_z \ \tilde{V}_a^m \ \tilde{u}^b \ \tilde{w}^b] \]
State-Space Model

- State transition function

\[ f(x, u, p) = -\bar{V}\alpha \left( \begin{array}{c} \frac{u_t}{L_u} \\ \frac{v_t}{L_v} \\ \frac{w_t}{L_w} \end{array} \right) \]

- Noise transition function

\[ w(x_k, u_k, \eta_{v_t, k}, p) = \left( \begin{array}{c} \sigma_u \sqrt{2\Delta T \frac{\bar{V}\alpha}{L_u}} \eta_{u_t} \\ \sigma_v \sqrt{2\Delta T \frac{\bar{V}\alpha}{L_v}} \eta_{v_t} \\ \sigma_w \sqrt{2\Delta T \frac{\bar{V}\alpha}{L_w}} \eta_{w_t} \end{array} \right) \]

- Measurement function

\[ h(x_k, u_k, p) = \left[ \begin{array}{c} -KV\alpha^2 (C_{L_0} + C_{L\alpha} \alpha) \\ V\alpha / \gamma \\ d_1 R^n b (v^n_s + v^n_t) + V\alpha \cos(\alpha) \\ d_3 R^n b (v^n_s + v^n_t) + V\alpha \sin(\alpha) \end{array} \right] \]
Estimation Setup

- **Sensors:**
  - GNSS
  - IMU
  - Pitot-static tube
- **AHRS** for orientation matrix estimation
- **TMO** for ground velocity estimation
- **Wind velocity and coefficient estimator:**
  - Moving Horizon Estimator
  - Direct Collocation Method
  - UKF for arrival cost approximation
- Implementation in Matlab + Casadi

Wind velocity

+ Aerodynamic parameter estimation

\[ C_{L,0}, C_{L,\alpha} \]

\[ v_r^b, v_w^n \]

\[ R_n^b, \bar{f} \]

\[ \bar{v}^b \]

\[ \bar{u}_r^m \]
Moving Horizon Estimation

- Objective Function

\[
\min_{x_{k-L}, \ldots, x_k, w_{k-L}, \ldots, w_k, \theta_{k-L}, 0, \ldots, \theta_{k,d}} \left( \sum_{p} \frac{1}{\hat{P}_{k-L}} \right)^{-1} \left( x_{k-L} - \hat{x}_{k-L} \right)^2 + \sum_{j=k-L}^{k} \left\| y_j - h(x_j, u_j, p) \right\|^2_{R(q)-1} + \sum_{j=k-L}^{k-1} \left\| \eta_j \right\|^2_{W^{-1}}
\]

\[
\eta_j = \begin{bmatrix} \eta_{v,j} & \eta_{u,j} & \eta_{z,j} \end{bmatrix}
\]

- Arrival Cost:
  - Summarises the information before the current window
  - Tuning factor \( c \)
  - Approximation necessary:

  **Unscented Kalman Filter:**
  - Avoids linearisation
  - Allows representation of input noise
  - Easy to implement
Flight Tests
Flight Profile

Position North

Position East

Andreas Wenz - MHE for Wind Vel. and Aerodyn. Coeff. Estimation
$RMSE_{\text{pixhawk}} = 0.96^\circ$, $RMSE_{\text{navstack}} = 0.81^\circ$
\[ \text{RMSE}_{\text{pixhawk}} = 4.25^\circ, \text{RMSE}_{\text{navstack}} = 3.85^\circ \]
Wind Estimation Error

![Wind Estimation Error Graphs](image)

- **x-direction**
  - Blue: Estimation Error Navstack
  - Red: Estimation Error Pixhawk

- **y-direction**
  - Blue: Estimation Error Navstack
  - Red: Estimation Error Pixhawk
Wind Estimation Error

z-direction
Conclusions

- MHE provides accurate estimation of AoA, Coefficients and Wind velocities
- Attitude changes during take off sufficient for persistence of excitation
- No prior knowledge about the UAV needed
- Realtime capable (0.072 s/sample < 0.2 s)

**Future / Current Work:**

- Wind adaptive path planning/ following
- Icing detection
Icing Detection
Motivation

Inflight icing is a global phenomenon

Effects of Inflight Icing on UAVs

- Control Surfaces
- Engine
- Pitot-static Tube
- Wings
Icing Detection Architecture

- T/H Sensor
- Environment
- Wind, Ice
- Trigger
- Autopilot
- Control
- Measurements
- Aero. Coeff. Estimation
- T/H Sensor
- Trigger
- Measurements
Effects of Airfoil Icing

- Lower stall angle
- Lower maximal lift force
- Flatter rise in lift coefficient

Effects on Lift Coefficient:

\[ \text{Re} = 2 \times 10^5 \]
Drag coefficients in Icing
Future Work: Drag Estimation

Benefits
• More accurate icing detection
• Allows pitot-tube and engine fault detection

Challenges
• More parameters to estimate => Lack of excitation source of errors
• Thrust estimation needed => RPM sensor or RPM estimation
(1) Estimation of Wind Velocities and Aerodynamic Coefficients for UAVs using standard Autopilot Sensors and a Moving Horizon Estimator, Wenz et al., ICUAS 2017

(2) Combining model-free and model-based Angle of Attack estimation for small fixed-wing UAVs using a standard sensor suite, Wenz et al., ICUAS 2016, Arlington

(3) On estimation of wind velocity, angle-of-attack and sideslip angle of small UAVs using standard sensors, Johansen et al., ICUAS 2015, Denver


(6) Small Unmanned Aircraft: Theory and Practice, Beard and McLain 2012

(7) MIL-STD-1797A: Flying Qualities of Piloted Aircraft

Questions?