A UDE-based Controller with Targeted Filtering for the Stabilization of a Fixed-Wing UAV in the Harrier Maneuver

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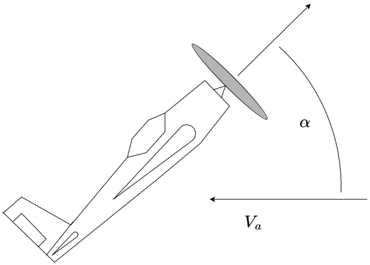
Outline

Background

- Despite long range/endurance, many small UAV applications use multirotor vehicles over fixed-wing vehicles due to better low-speed control
- Solution: expand low speed operating envelope using **aerobatic maneuvers** to allow use of fixed-wings in applications that require both long range and low speed

2. Problem Description

2.1 Low Speed, High Angle-of-Attack Aerobatic Maneuvering



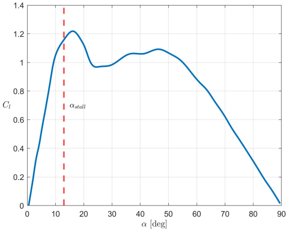


Fig 1: Lift coefficient vs angle-of-attack for a symmetric 2D airfoil.

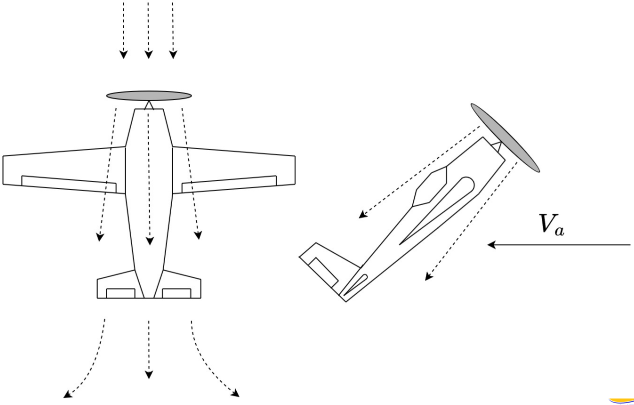
- At lower airspeed, fixed-wing vehicles must increase angle-of-attack to maintain lift and altitude
- Below stall speed, small UAVs can maintain altitude using thrust. However, dynamics are more nonlinear, and control is more challenging

2. Problem Description

2.1 Low Speed, High Angle-of-Attack Aerobatic Maneuvering

Dynamics Challenges

- Nonlinear lift response
- Varying local velocities across the airframe
- Aerodynamic interaction between lifting surfaces
- Time-dependent effects
- Many of these features are difficult to accurately model



2. Problem Description

2.2 Time-Varying Effects During Maneuvering

- Time-varying dynamic effects and disturbances present
- High angle-of-attack results in varying lift, drag due post-stall phenomena on airfoils
- Additional dynamic modes observed at high angle-of-attack

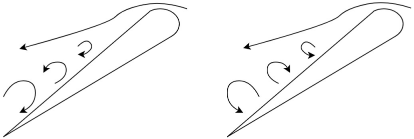


Fig 2: Vortices shed with alternating rotation directions over time, causing a fluctuating lift coefficient.

2. Problem Description

2.2 Time-Varying Effects During Maneuvering

- Typical wind disturbances have more pronounced effect during high angle-of-attack
- Velocity perturbations can cause sudden changes in attitude

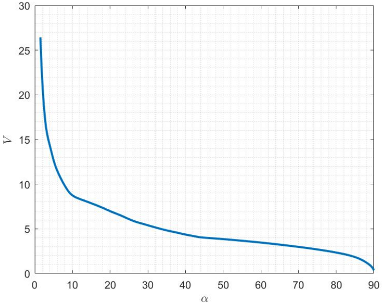


Fig 3: Airspeed velocity to maintain altitude for fixed-wing aerobatic UAV at a specific angle-of-attack.

2. Problem Description

Summary of problem:

- Model uncertainty
- Nonlinearities
- Time-varying effects

Robust control solution to address all of these?

3. Control Solution

3.1 Uncertainty and Disturbance Estimator

Uncertainty and Disturbance Estimator (UDE) capabilities:

- Estimate and compensate for disturbances, given a nominally stabilizable system
- Two DOF freedom in designing nominal controller $\boldsymbol{u}_0$ and disturbance estimator $\hat{\boldsymbol{d}}$
- Lumped disturbance estimation, with frequency based estimation capabilities

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}) + \boldsymbol{d} \qquad (1)$$

$$\boldsymbol{u} = \boldsymbol{u}_0 - \hat{\boldsymbol{d}} \qquad (2)$$

3. Control Solution

3.1 Uncertainty and Disturbance Estimator

Application to this problem:

- Nominal aircraft system typically performs well with linearized models when controlling for fixed-operating points
- Propwash keeps aircraft inboard wing, fuselage, tail in linear aerodynamic response range
- Linear control solution developed with suitable derivation of aircraft longitudinal and lateral linearized model during aerobatic maneuvers

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{d} \qquad (3)$$

$$\boldsymbol{B}\boldsymbol{u} = \boldsymbol{B}\boldsymbol{u}_0 - \hat{\boldsymbol{d}} \qquad (4)$$

$$\boldsymbol{B}\boldsymbol{u} = -\boldsymbol{B}\boldsymbol{K}\boldsymbol{x} - \hat{\boldsymbol{d}} \qquad (5)$$

$$\boldsymbol{A} \in \mathbb{R}^{n\times n}$$

$$\boldsymbol{B} \in \mathbb{R}^{n\times m}$$

3. Control Solution

3.1 Uncertainty and Disturbance Estimator

Design of disturbance estimator:

- Disturbance estimate obtained by filtering system dynamics
- Typical applications design filter in the frequency domain based on disturbance frequency

$$\begin{aligned} G_f(s) &= [g_{ij}] \in \mathbb{C}^{n\times n} \\ g_{ij} &= 0, i \neq j \\ g_{ij} &\neq 0, i = j \end{aligned}$$

$$\begin{aligned} \hat{\boldsymbol{d}} &= g_f * \boldsymbol{d} && (6) \\ \hat{\boldsymbol{D}} &= \boldsymbol{G}_f(s)\boldsymbol{D} && (7) \\ &= \boldsymbol{G}_f(s)\left(s\boldsymbol{X} - \boldsymbol{A}\boldsymbol{X} - \boldsymbol{B}\boldsymbol{U}\right) && (8) \\ &= \left([\boldsymbol{I} - \boldsymbol{G}_f(s)]^{-1}\boldsymbol{G}_f(s)\right) \times \\ &\qquad (s\boldsymbol{X} - \boldsymbol{A}\boldsymbol{X} - \boldsymbol{B}\boldsymbol{U}_0) && (9) \end{aligned}$$

3. Control Solution

3.1 Uncertainty and Disturbance Estimator

Standard filter designs:

- Low-pass filters
- α filter
- General linear filter of order k

$$g_{ij} = \frac{\omega}{s+\omega} = \frac{1}{\tau s + 1} \tag{10}$$

$$g_{ij} = \frac{(1-\alpha)\tau s + 1}{\tau s + 1} \tag{11}$$

$$g_{ij} = \frac{(\tau s + 1)^k - (\tau s)^k}{(\tau s + 1)^k} \tag{12}$$

3. Control Solution

3.2 Targeted UDE Filtering

Motivation:

- Practical limitations on cut-off frequency of low-pass filter
- State derivative information availability for α filter
- Improve filter design using system error dynamics

Error dynamics:

$$\begin{aligned} \boldsymbol{X}(s) &= -[s\boldsymbol{I} - (\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K})]^{-1} \times \\ &\qquad (\boldsymbol{I} - \boldsymbol{G}_f(s))\boldsymbol{D}(s) \\ \boldsymbol{X}(s) &= \boldsymbol{Z}(s)\boldsymbol{D}(s) \qquad (13) \end{aligned}$$

Disturbance estimation error:

$$\begin{aligned} \tilde{\boldsymbol{D}}(s) &= \boldsymbol{D}(s) - \hat{\boldsymbol{D}}(s) \\ &= (\boldsymbol{I} - \boldsymbol{G}_f(s))\boldsymbol{D}(s) \\ \tilde{\boldsymbol{D}}(s) &= \boldsymbol{W}(s)\boldsymbol{D}(s) \qquad (14) \end{aligned}$$

3. Control Solution

3.2 Targeted UDE Filtering

Proposed targeted filter:

- Maximize disturbance attenuation effect at most significant frequency
- Combination of linear filter and bandpass filter

$$g_{ij} = \frac{2\omega_1 s + \omega_1^2}{s^2 + 2\omega_1 s + \omega_1^2} + K\left(\frac{\frac{\omega_2}{Q}\mu + s^2}{s^3 + s^2 + \frac{\omega_2}{Q_2}s + \omega_2^2}\right) \tag{15}$$

3. Control Solution

3.2 Targeted UDE Filtering

Comparison to low-pass filter:

$G_{f_{lp}}(s)$, low-pass filter matrix

$G_{f_n}(s)$, proposed filter matrix

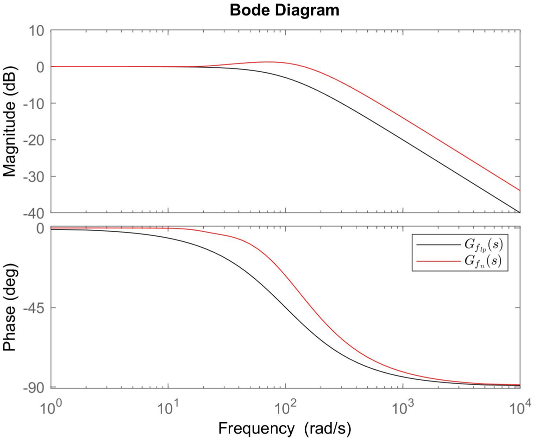
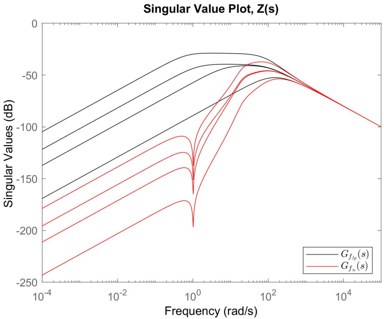


Fig 4: Bode plot of low-pass filter ($\omega = 100$ rad/s, black) frequency response vs proposed filter (red).

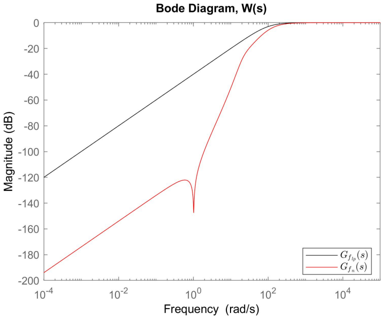
3. Control Solution

3.2 Targeted UDE Filtering

Error dynamics:



Disturbance Estimation Error:



3. Control Solution

3.2 Targeted UDE Filtering

Frequency identification:

- Frequency of disturbance is required to design filter
- With UDE, disturbances are lumped, combined frequency response required
- Frequency content can be obtained by analyzing spectral density of state signals

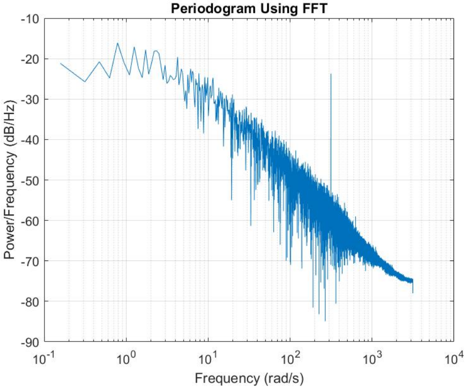


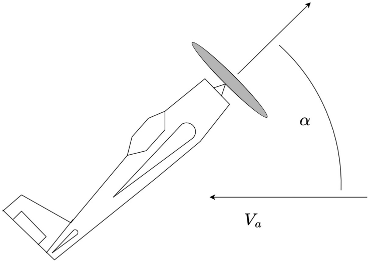
Fig 5: Power spectral density of state variables during harrier aerobatic maneuver.

3. Control Solution

3.3 Simulation Results

Harrier maneuver test case:

- Control law test on harrier maneuver linearized system
- Goal to maintain altitude and pitch angle ($\theta = 45°$), $\theta = \alpha$ with no wind



3. Control Solution

3.3 Simulation Results

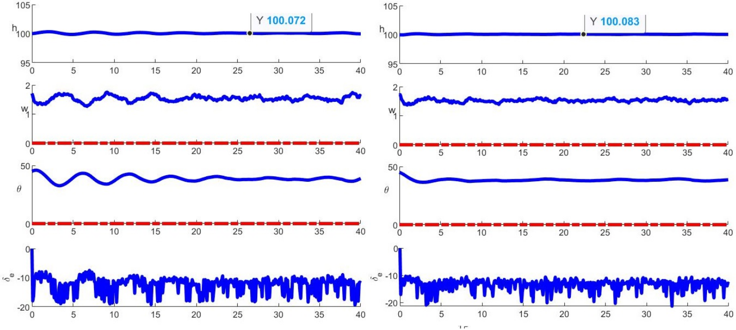


Fig 6: Comparison of altitude tracking problem while maintaining harrier maneuver, with low-pass filter (left) and the novel proposed filter (right).

Conclusion:

- This paper discusses the use of targeted UDE filtering to improve disturbance rejection capabilities, with application to a fixed-wing UAV system performing a harrier maneuver
- Filter design uses disturbance frequency content and system dynamics

Thank you!

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