Model-based Sensor Fault Detection for an Autonomous Solar-powered Aircraft

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CONTENTS

Introduction

- Fault detection and diagnosis (FDD) is a significant task in the automatic control of complex systems;
- Safety-critical systems require fault detection frameworks to guarantee reliability and availability;
- Applications: from commercial aircrafts to vibration monitoring of mechanical systems;

Motivation

Main Motivation

- Development of a suitable IMU fault detection, diagnosis, and reconfiguration (FDD) approach to be further applied to the Elektra 2 Solar Aircraft;

Elektra 2 Solar: Autonomous Solar-powered aircraft

MOTIVATION

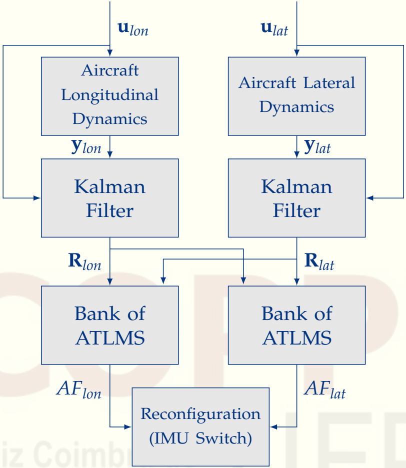
Elektra 2 Solar Specs

- Electric Motor: 23 kW
- Propeller speed for cruise: 1250 rpm
- Wingspan: 24.8 m
- Wing Area: 27 m^2
- Solar Cells: 26.5 m^2
- Maximum Weight: 400 kg
- Maximum Payload: 120 kg

- Max. glide ratio: ≈1:40

Proposed Fault Detection Approach

- **Residual Generator:** Kalman Filters
- **Decision Function:** Sequential Probability Ratio Test (SPRT)
- Longitudinal and Lateral Alarm Flags
- **Residual Sensitivity**



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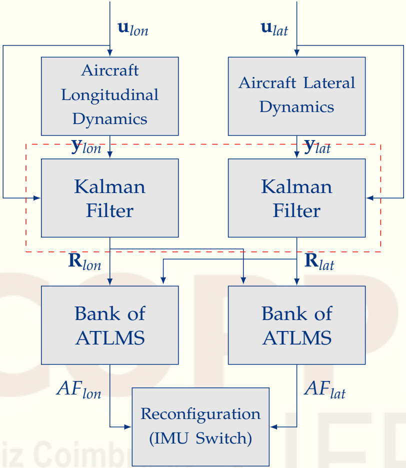

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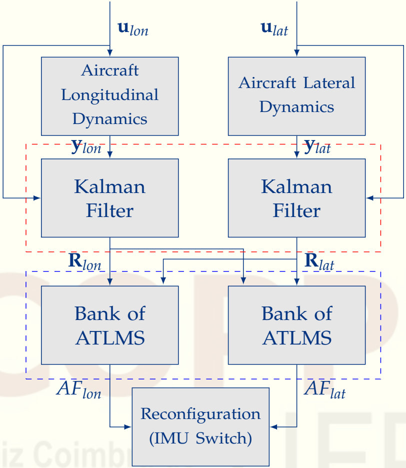


Decoupled Aircraft Dynamics

$$\begin{bmatrix} \dot{\mathbf{x}}_{lon} \\ \dot{\mathbf{x}}_{lat} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{lon} & 0 \\ 0 & \mathbf{A}_{lat} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{lon} \\ \mathbf{x}_{lat} \end{bmatrix} + \begin{bmatrix} \mathbf{B}_{lon} & 0 \\ 0 & \mathbf{B}_{lat} \end{bmatrix} \begin{bmatrix} \mathbf{u}_{lon} \\ \mathbf{u}_{lat} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \mathbf{y}_{lon} \\ \mathbf{y}_{lat} \end{bmatrix} = \begin{bmatrix} \mathbf{C}_{lon} & 0 \\ 0 & \mathbf{C}_{lat} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{lon} \\ \mathbf{x}_{lat} \end{bmatrix} \tag{2}$$

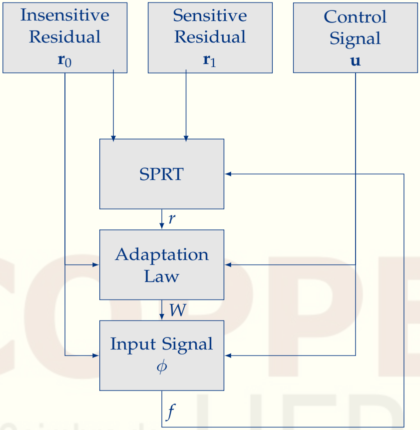
Longitudinal Dynamics	**Lateral Dynamics**
$\mathbf{x}_{lon} = \begin{bmatrix} u & w & q & \theta & alt & \tau \end{bmatrix}^T$	$\mathbf{x}_{lat} = \begin{bmatrix} v & p & r & \phi & \psi \end{bmatrix}^T$
$\mathbf{u}_{lon} = \begin{bmatrix} \delta_e & \delta_t \end{bmatrix}^T$	$\mathbf{u}_{lat} = \begin{bmatrix} \delta_a & \delta_r \end{bmatrix}^T$
$y_{m_{lon}} = \begin{bmatrix} V_a & \alpha & q & \theta & alt \end{bmatrix}^T$	$y_{m_{lat}} = \begin{bmatrix} \beta & p & r & \phi & \psi \end{bmatrix}^T$

$$V_a = \sqrt{u^2 + v^2 + w^2} \quad \alpha = tan^{-1}\left(\frac{w}{u}\right) \quad \beta = sin^{-1}\left(\frac{v}{V_a}\right)$$

Proposed Fault Detection Approach

ATLMS Main Idea

- Adaptability of the LMS to reinitialize the SPRT
- **SPRT for each data sample**:
  - In favor of $\mathcal{H}_0$: normal mode
  - In favor of $\mathcal{H}_1$: faulty mode
  - Not enough information
- **Adaptive threshold behavior:** Different directions under different hypothesis
- **Alarm flag activation**: adaptive threshold crossing the insensitive residual r_0



ATLMS Parameter Tuning

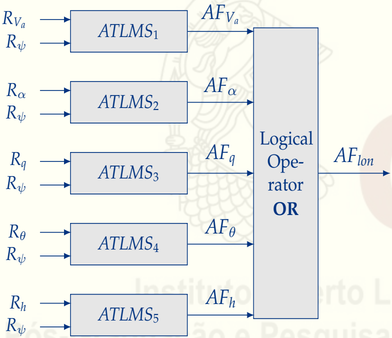
- *Safety Offset*:
  - Prevents undesired false alarms due to the dynamics of the insensitive residual;
- *Sensitivity Rate*:
  - Describes the sensitivity of the adaptive threshold due to changes in the trend of the residuals as determined by the SPRT.
- *Convergence Rate*:
  - Originally from the LMS algorithm
  - Responsible for the adaptation stability and convergence speed of the ATLMS.

Proposed Fault Detection Approach

Bank of ATLMS for **Longitudinal** Dynamics

Sensitive Res.: R_{Va} R_{α} R_q R_{θ} R_h

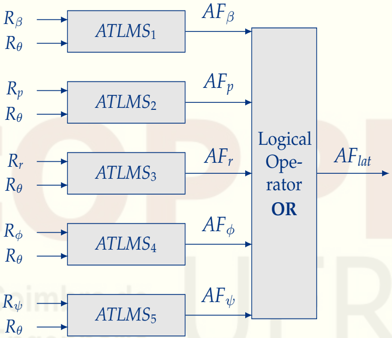
Insensitive Residual: R_{ψ}



Bank of ATLMS for **Lateral** Dynamics

Sensitive Res.: R_{β} R_p R_r R_{ϕ} R_{ψ}

Insensitive Residual: R_{θ}



Simulation Methodology and Assumptions

- Occurrence of single, **additive faults** in primary IMU;
- Backup IMU as well as **other aircraft sensors do not fail**;
- **Reconfiguration procedure:** switch from primary IMU to backup IMU once a fault is detected.
- Simulation time: 100 s
- All faults are introduced at 50 s.

Proposed Faults

- *Abrupt Fault*: modelled as a step-wise function. It represents bias in the monitored signal;
- *Incipient Fault*: modelled by ramp signals. It represents drift of the monitored signal;
- *Extra Noise Fault*: modelled by an abrupt change of the signal standard deviation.

Fault	Measurement	Amplitude
Incipient	θ	0.2 rad/s
Extra Noise	q	$\mathcal{N}(\bar{\mu} = 0, \sigma = 0.01)$
Abrupt	ϕ	0.2 rad

Fault-Free Scenario

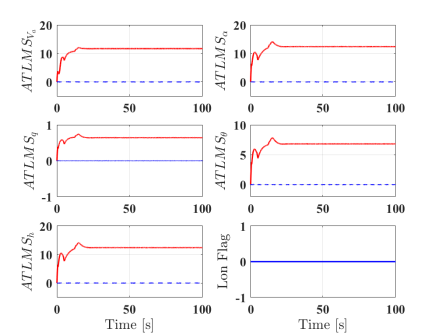
Longitudinal Residuals

$$R_{lon} = \begin{bmatrix} R_{V_a} & R_\alpha & R_q & R_\theta & R_h \end{bmatrix}^T$$

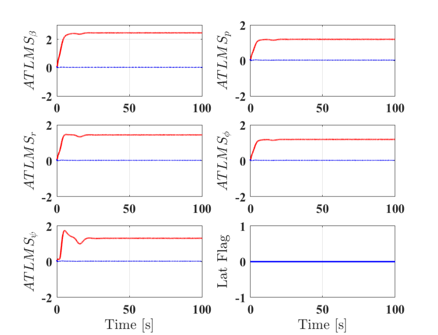
Lateral Residuals

$$R_{lat} = \begin{bmatrix} R_\beta & R_p & R_r & R_\phi & R_\psi \end{bmatrix}^T$$

Longitudinal Adaptive Thresholds



Lateral Adaptive Thresholds



Drift Fault in Pitch Angle θ

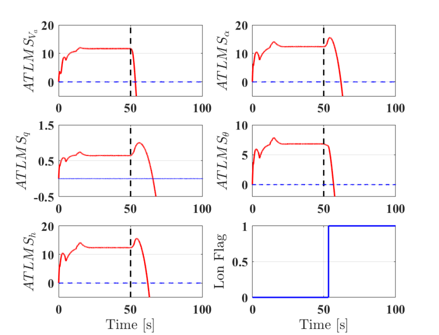
Longitudinal Residuals

$$R_{lon} = \begin{bmatrix} R_{V_a} & R_\alpha & R_q & R_\theta & R_h \end{bmatrix}^T$$

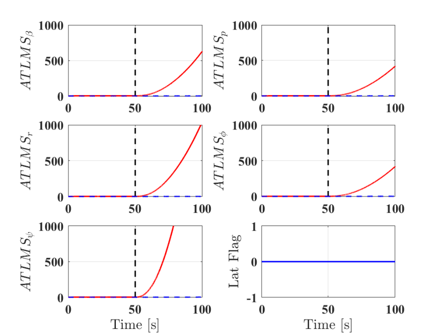
Lateral Residuals

$$R_{lat} = \begin{bmatrix} R_\beta & R_p & R_r & R_\phi & R_\psi \end{bmatrix}^T$$

Longitudinal Adaptive Thresholds



Lateral Adaptive Thresholds

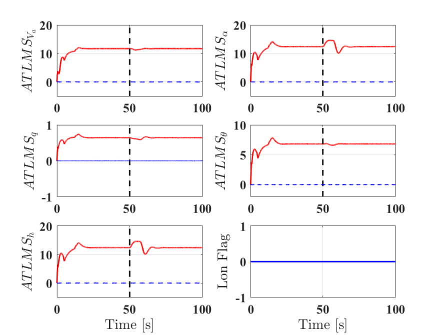


Abrupt Fault in Roll Angle ϕ

Longitudinal Residuals

$$R_{lon} = \begin{bmatrix} R_{V_a} & R_\alpha & R_q & R_\theta & R_h \end{bmatrix}^T$$

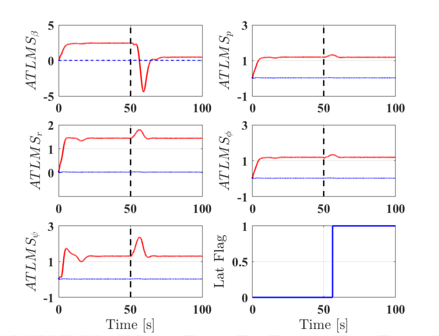
Longitudinal Adaptive Thresholds



Lateral Residuals

$$R_{lat} = \begin{bmatrix} R_\beta & R_p & R_r & R_\phi & R_\psi \end{bmatrix}^T$$

Lateral Adaptive Thresholds



EXTRA NOISE FAULT IN PITCH RATE q

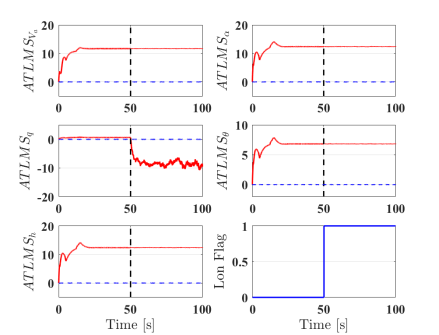
Longitudinal Residuals

$$R_{lon} = \begin{bmatrix} R_{V_a} & R_\alpha & R_q & R_\theta & R_h \end{bmatrix}^T$$

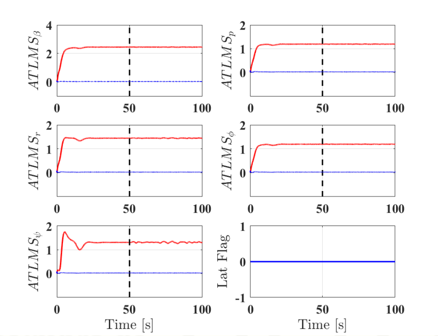
Lateral Residuals

$$R_{lat} = \begin{bmatrix} R_\beta & R_p & R_r & R_\phi & R_\psi \end{bmatrix}^T$$

Longitudinal Adaptive Thresholds



Lateral Adaptive Thresholds



Conclusion

Proposed Fault Detection Approach

- Adaptive Threshold:
  - Possibility of tuning of well-known parameters;
  - Distinguish between changes in flight conditions and fault occurrence;
- Satisfactory detection results of abrupt, drift-like and extra noise faults;
- Requires extraction of suitable linear models;

Future Steps

- Validation of proposed fault detection approach with real flight data.
- Development of strategies for ATLMS parameter tuning;
- Development of strategies for fault isolation and identification;

Contact

Thank you!

Vielen Danke!

Tack så mycket!

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