Fault diagnosis for nonlinear aircraft based on control-induced redundancy

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retour sur innovation

Outline

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- FDI algorithm description

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- Robustness

Summary and future work

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Nonlinear Fault Detection and Isolation - related work

Fault Detection and Isolation of actuator faults
for Nonlinear control-affine systems

Differential-geometric approach (De Persis & Isidori)

Transformation of coordinates to design nonlinear residual filters sensitive to faults and decoupled from disturbances.

Differential-algebraic approach (Diop, Bokor, Shumsky...)

Transformation of the system into a set of differential polynomials, functions of inputs, outputs and their successive derivatives. Use elimination theory to extract fault information.

Inversion-based FDI (Edelmayer, Szigeti...)

Left-inverse computation to obtain dynamical model with faults as outputs and original inputs, outputs and their successive derivatives as inputs.

Objectives

Known drawbacks of these nonlinear methods

- Design of coordinate transforms, tuning of inner parameters
- Successive time derivatives of noisy and disturbed measurements
- Integration of dynamical filters

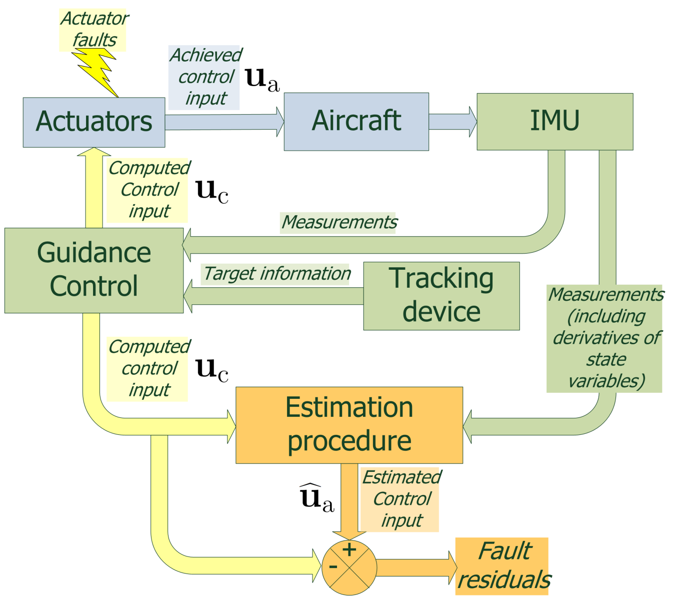
Objectives of present work

- Avoid numerical differentiation of measured variables
- Avoid dynamical integration, to reduce computational cost
- Assess robustness to model and measurement uncertainty

New approach

- Take advantage of systems involving *measured* state derivatives (e.g., autonomous vehicles equipped with IMUs)
- Design a completely nonlinear actuator fault diagnosis method

Principles of the approach



6-DOF aeronautical model

- State vector : $\mathbf{x} = [\zeta, \mathbf{v}_\mathrm{b}, \boldsymbol{\Theta}, \omega]^\mathrm{T}$, ζ position in inertial frame, $\mathbf{v}_\mathrm{b}$ speed in body frame, $\boldsymbol{\Theta}$ orientation, $\boldsymbol{\omega}$ angular velocity
- Input vector : $\mathbf{u} = [\delta_\mathrm{l}, \delta_\mathrm{m}, \delta_\mathrm{n}, \eta]^\mathrm{T}$, rudders $\delta_{(\cdot)}$ and propulsion η
- Measurements : $\mathbf{y} = [\mathbf{a}_\mathrm{b}, \omega]^\mathrm{T}$, acceleration in body frame $\mathbf{a}_\mathrm{b}$

Nonlinear aircraft model

$$\begin{cases} \mathbf{a}_\mathrm{b} = \dot{\mathbf{v}}_\mathrm{b} + \boldsymbol{\omega} \times \mathbf{v}_\mathrm{b} = m^{-1}\left[\mathbf{f}_\mathrm{aero}(\mathbf{x},\mathbf{u}) + \mathbf{f}_\mathrm{g}(\mathbf{x})\right] & \text{force equation} \\ \dot{\boldsymbol{\omega}} = \mathbf{I}^{-1}\left[\mathbf{m}_\mathrm{aero}(\mathbf{x},\mathbf{u}) - (\boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega})\right] & \text{momentum equation} \\ \dot{\zeta} = \mathbf{R}_\mathrm{bi}(\mathbf{x})\,\mathbf{v}_\mathrm{b} & \text{coordinate transform} \\ \dot{\boldsymbol{\Theta}} = \mathbf{R}_\Theta(\mathbf{x})\,\boldsymbol{\omega} & \text{angular dynamics} \end{cases}$$

6-DOF aeronautical model

- State vector : $\mathbf{x} = [\zeta, \mathbf{v}_\mathrm{b}, \mathbf{\Theta}, \omega]^\mathrm{T}$, position in inertial frame ζ, speed in body frame $\mathbf{v}_\mathrm{b}$, orientation $\mathbf{\Theta}$, angular velocity ω
- Input vector : $\mathbf{u} = [\delta_\mathrm{l}, \delta_\mathrm{m}, \delta_\mathrm{n}, \eta]^\mathrm{T}$, rudders $\delta_{(\cdot)}$ and propulsion η
- Measurements : $\mathbf{y} = [\mathbf{a}_\mathrm{b}, \omega]^\mathrm{T}$, acceleration in body frame $\mathbf{a}_\mathrm{b}$

Nonlinear aircraft model

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Starting point: force equation involves control inputs and only measured or estimated state variables and their *measured* derivatives

Preliminary step

- Extract force equation, $\mathbf{a}_\mathrm{b} = m^{-1}\left[\mathbf{f}_\mathrm{aero}(\mathbf{x},\mathbf{u}) + \mathbf{f}_\mathrm{g}(\mathbf{x})\right]$

$$\left\{\begin{aligned} a_\mathrm{bx} &= -\frac{Qs_\mathrm{ref}}{M}\left[c_{\mathrm{x}0} + c_\mathrm{xa}\alpha + c_{\mathrm{x}\delta_\mathrm{m}}\delta_\mathrm{l} + c_{\mathrm{x}\delta_\mathrm{m}}\delta_\mathrm{m} + c_{\mathrm{x}\delta_\mathrm{n}}\delta_\mathrm{n}\right] \\ &\quad + \frac{1}{m}\left[f_\mathrm{min} + (f_\mathrm{max} - f_\mathrm{min})\eta\right] \\ a_\mathrm{by} &= \frac{Qs_\mathrm{ref}}{m}\left[c_{y0} + c_{yb}\beta + c_{y\delta_\mathrm{l}}\delta_\mathrm{l} + c_{y\delta_\mathrm{n}}\delta_\mathrm{n}\right] \\ a_\mathrm{bz} &= \frac{Qs_\mathrm{ref}}{m}\left[c_{z0} + c_{za}\alpha + c_{z\delta_\mathrm{m}}\delta_\mathrm{m}\right] \end{aligned}\right.$$

- Rewrite model (linear in **u** due to small-angle assumption) as

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & 0 & g_{23} & 0 \\ 0 & g_{32} & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_\mathrm{l} \\ \delta_\mathrm{m} \\ \delta_\mathrm{n} \\ \eta \end{bmatrix}$$

where f_i and g_{ij} $(i = 1, 2, 3, j = 1, 2, 3, 4)$ are nonlinear functions of $\mathbf{y}$, derived from above equations

Direct Residual Generation

- Estimate each control input as a function of measurements and other computed control inputs. For example, ,

$$\begin{cases} \widehat{\delta}_{\mathrm{la}} = \frac{f_2 - g_{23}\delta_{\mathrm{nc}}}{g_{21}} \\ \widehat{\delta}_{\mathrm{na}} = \frac{f_2 - g_{21}\delta_{\mathrm{lc}}}{g_{23}} \end{cases}$$

- Compare these estimates to corresponding computed inputs,

$$\begin{cases} r_{21} = \widehat{\delta}_{\mathrm{la}} - \delta_{\mathrm{lc}} = \frac{f_2 - g_{23}\delta_{\mathrm{nc}}}{g_{21}} - \delta_{\mathrm{lc}} \\ r_{23} = \widehat{\delta}_{\mathrm{na}} - \delta_{\mathrm{nc}} = \frac{f_2 - g_{21}\delta_{\mathrm{lc}}}{g_{23}} - \delta_{\mathrm{nc}} \end{cases}$$

- Example of sensitivity to faults. Inject expression of f_2 into residual

$$r_{21} = \frac{g_{21}\delta_{\mathrm{la}} + g_{23}\delta_{\mathrm{na}} - g_{23}\delta_{\mathrm{nc}}}{g_{21}} - \delta_{\mathrm{lc}} = (\delta_{\mathrm{la}} - \delta_{\mathrm{lc}}) + \frac{g_{23}}{g_{21}}(\delta_{\mathrm{na}} - \delta_{\mathrm{nc}})$$

$\rightarrow$ *Sensitivity to faults on δ_{l} and δ_{n} and possible identification on δ_{l}*

Additional Residual Generation

Further combinations between equations

$$\text{Reminder :} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & 0 & g_{23} & 0 \\ 0 & g_{32} & 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{\mathrm{l}} \\ \delta_{\mathrm{m}} \\ \delta_{\mathrm{n}} \\ \eta \end{bmatrix}$$

From 3rd line, $\widehat{\delta}_{\mathrm{ma}} = f_3/g_{32}$ can be used in other residuals, e.g.,

$$r_{11} = \frac{f_1 - g_{12}\delta_{\mathrm{mc}} - g_{13}\delta_{\mathrm{nc}} - g_{14}\eta_{\mathrm{c}}}{g_{11}} - \delta_{\mathrm{lc}}$$

to get

$$\tilde{r}_{11}^{1} = \frac{f_1 - g_{12}\frac{f_3}{g_{32}} - g_{13}\delta_{\mathrm{nc}} - g_{14}\eta_{\mathrm{c}}}{g_{11}} - \delta_{\mathrm{lc}}$$

This residual is now insensitive to faults affecting rudder δ_{m}

Additional Residual Generation

- From line 2, $\widehat{\delta}_{\mathrm{la}}$ and $\widehat{\delta}_{\mathrm{na}}$can be used similarly to get residuals that are insensitive to faults on either δ_{l} or δ_{n}.
- One step further: combine $\widehat{\delta}_{\mathrm{la}}$ and $\widehat{\delta}_{\mathrm{ma}}$ to obtain residuals insensitive to faults on both actuators.
- Same kind of substitution possible with $\widehat{\delta}_{\mathrm{ma}}$ and $\widehat{\delta}_{\mathrm{na}}$.

Fault signature table – 27 residuals max with 8 different signatures

	r_{1i}	r_{21}/r_{23}	r_{32}	$\tilde{r}_{1i}^{1}$	$\tilde{r}_{1i}^{2}$	$\tilde{r}_{1i}^{3}$	$\tilde{r}_{1i}^{4}$	$\tilde{r}_{1i}^{5}$
δ_{l}	1	1	0	1	0	1	0	1
δ_{m}	1	0	1	0	1	1	0	0
δ_{n}	1	1	0	1	1	0	1	0
η	1	0	0	1	1	1	1	1

$(i = 1, 2, 3, 4)$

Full isolation possible, and partial identification

Simulation set-up

3 fault scenarios

1. Loss of 25% propulsion
2. Locking-in-place of δ_{m} then loss of 25% propulsion
3. Loss of 50% propulsion then locking of δ_{m} then locking of δ_{n}

IMU uncertainty

Measurement of q is $\tilde{q} = k_q q + b_q + w_q$

k_q : scale factor, b_q : bias, w_q : Gaussian white noise

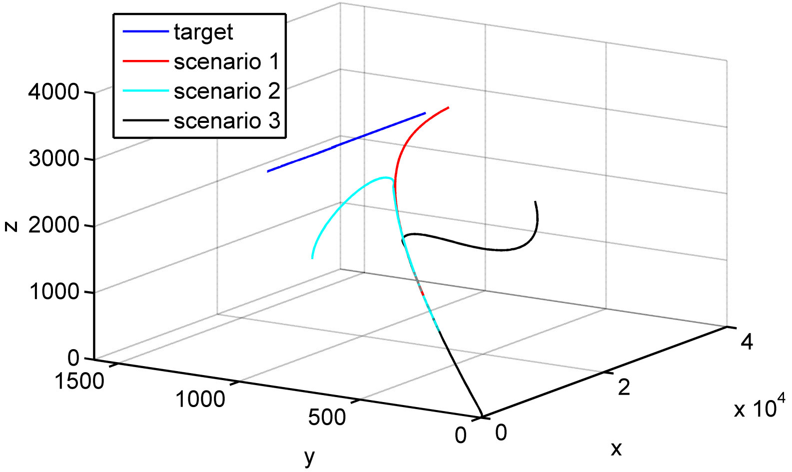
Delay of 2 time steps

Multiplicative model uncertainty

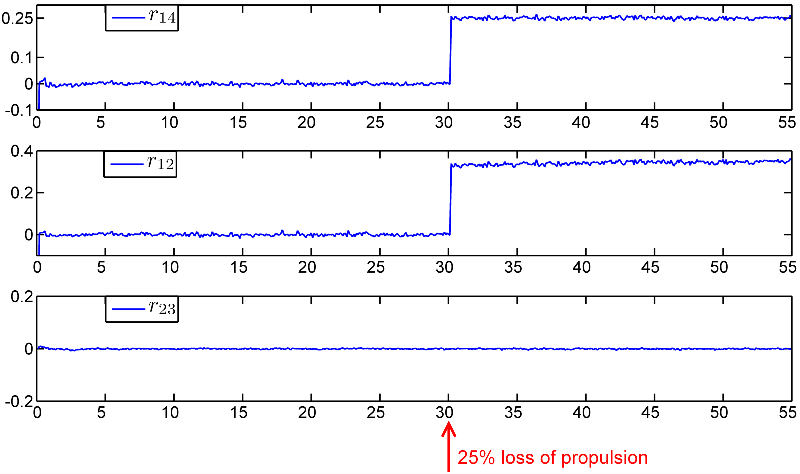
Each aerodynamic coefficient value is randomly chosen as either

$c_{\mathrm{sim}} = 0.95 c_{\mathrm{model}}$ or $c_{\mathrm{sim}} = 1.05 c_{\mathrm{model}}$

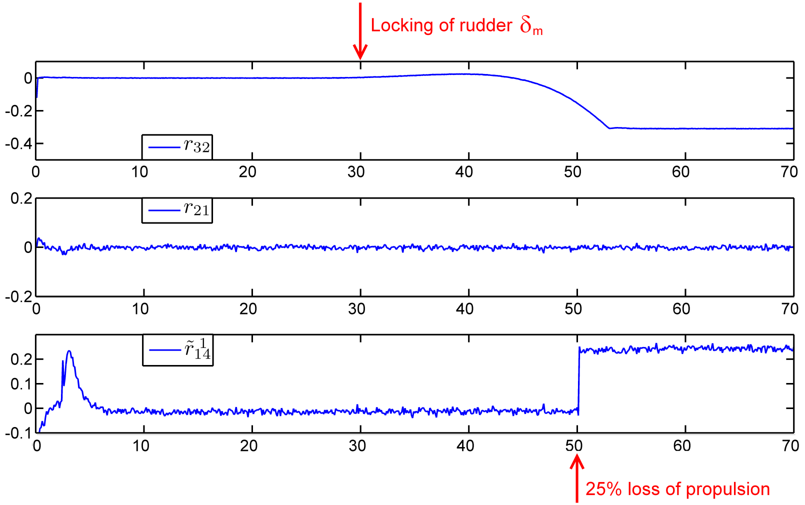
Trajectories



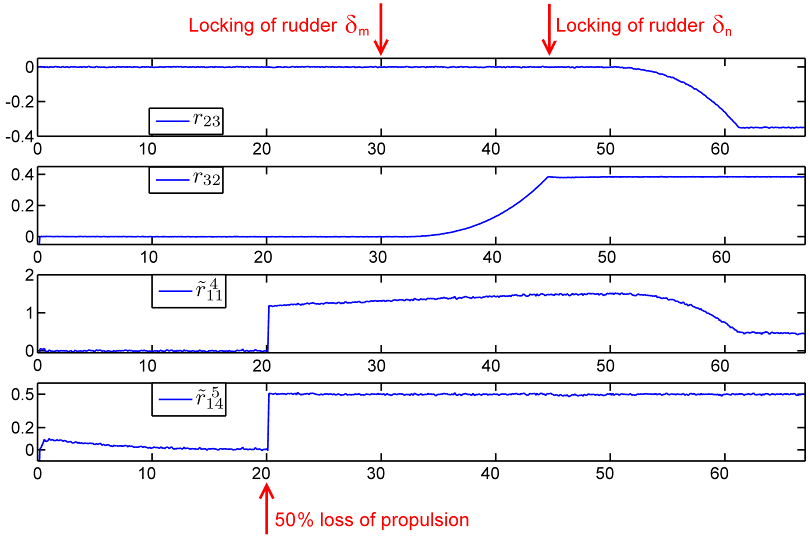
Selection of residuals - Scenario 1



Selection of residuals - Scenario 2



Selection of residuals - Scenario 3



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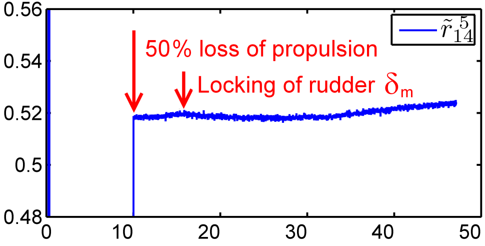
Robustness of the residuals

Model error $g_{12-\mathrm{sim}} = g_{12-\mathrm{model}} + \varepsilon$, ε small and bounded

$$\tilde{r}_{14}^{5} = \frac{1}{g_{14}}\left[\left(g_{11} + \frac{g_{13}g_{21}}{g_{23}}\right)(\delta_{\mathrm{lc}} - \delta_{\mathrm{l}}) + \frac{g_{12}\delta_{\mathrm{m}}}{g_{23}} - \frac{(g_{12} + \varepsilon)\,\delta_{\mathrm{m}}}{g_{23}} + g_{13}\left(\delta_{\mathrm{n}} - \delta_{\mathrm{n}}\right)\right] + (\eta_{\mathrm{c}} - \eta)$$

$$\tilde{r}_{14}^{5} = (\eta_{\mathrm{c}} - \eta) + \frac{g_{11}g_{23} + g_{13}g_{21}}{g_{14}g_{23}}(\delta_{\mathrm{lc}} - \delta_{\mathrm{l}}) + \frac{g_{12}}{g_{23}g_{14}}\varepsilon\delta_{\mathrm{m}}$$



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Summary and future work

Summary

- Nonlinear FDI scheme applied to a realistic aeronautical model
- Multiple faults detectable, isolable and identifiable
- Static residuals : hard-coding possible, no tuning required
- Acceptable robustness to model and measurement uncertainty
- Formal description of the procedure in our NOLCOS 2010 paper + MAPLE implementation providing residuals automatically

Future work

- Loosen sensitivity of the static residuals with a sliding window
- Automatic tuning of FDI approaches for systematic comparison