An Integrated Fault Detection & Isolation (FDI) and Fault Tolerant Control (FTC) Design for an Aircraft Model

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Talk Ingredients

- Brief overview of research projects at the University of Ferrara (Ferrara, Italy)
- The problem of fault diagnosis and fault tolerant control for aircraft systems
- Simulation results
- Conclusion and further works

Projects and Research Topics

- ✓ Turbocharged Diesel Engine Modelling for Nonlinear Controller Design (2007 – 2009)
- ✓ Computerised Decision Support Systems for Oral Anticoagulant Treatment (OAT) Dose Management (2005 - 2007)
- ➢ Development of Fault Tolerant NGC (Navigation, Guidance & Control) Algorithms for CUAV (Civil Unmanned Aerial Vehicle) Patrolling & Rescue Missions in Harsh Environment (2004 – 2008, 2009 – 2012)

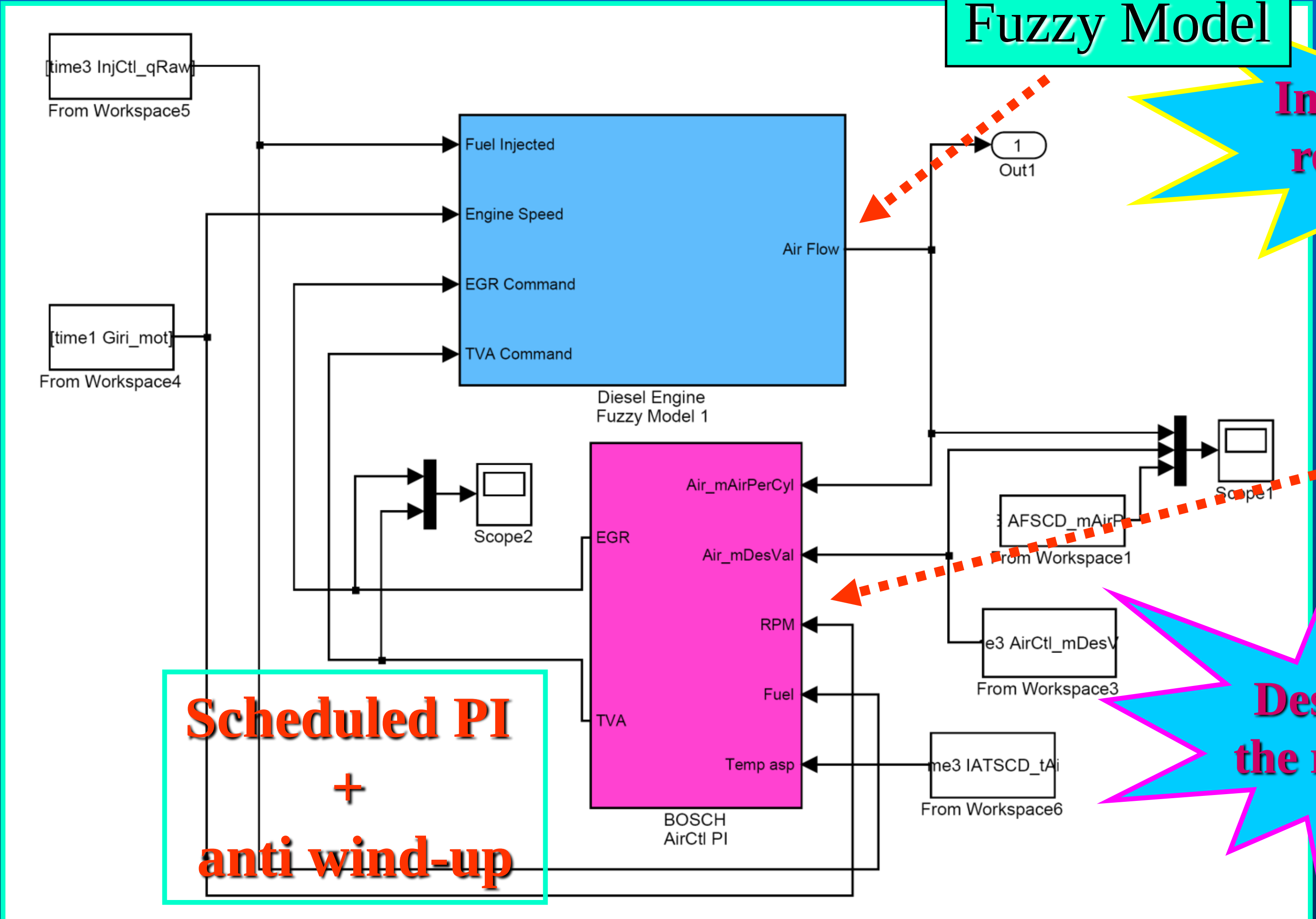
Projects and Research Topics

- ✓ Ongoing (2018 -)
  - Mobile robots & SLAM - Simultanous Localization And Mapping
  - Image based visual servoing of robot manipulators - application to autonomous drones (underwater vehicles)
- ✓ Ongoing (2009 -)
  - Renewable energy conversion systems
  - Wind turbines and hydroelectric plants
  - Advanced control (adaptive, data-driven, model-based)
  - Fault diagnosis and fault tolerant control
  - Sustainable solutions

Turbocharged Diesel Engine Modelling for Nonlinear Controller Design

- Design of a control scheme for commercial diesel engines (boats, ships, farm tractors, ...)
  - Diesel engine modelling
    - black-box: fuzzy modelling
    - grey-box: analytical approach
  - Control system strategy
- Electronic Control Unit (ECU)
  - Control scheme on-board real implementation
  - Automatic software (GUI) for model identification & controller calibration/fine tuning

Final Tool (Simulink®)



Fuzzy Model

Instead of the real process!

Controller BOSCH

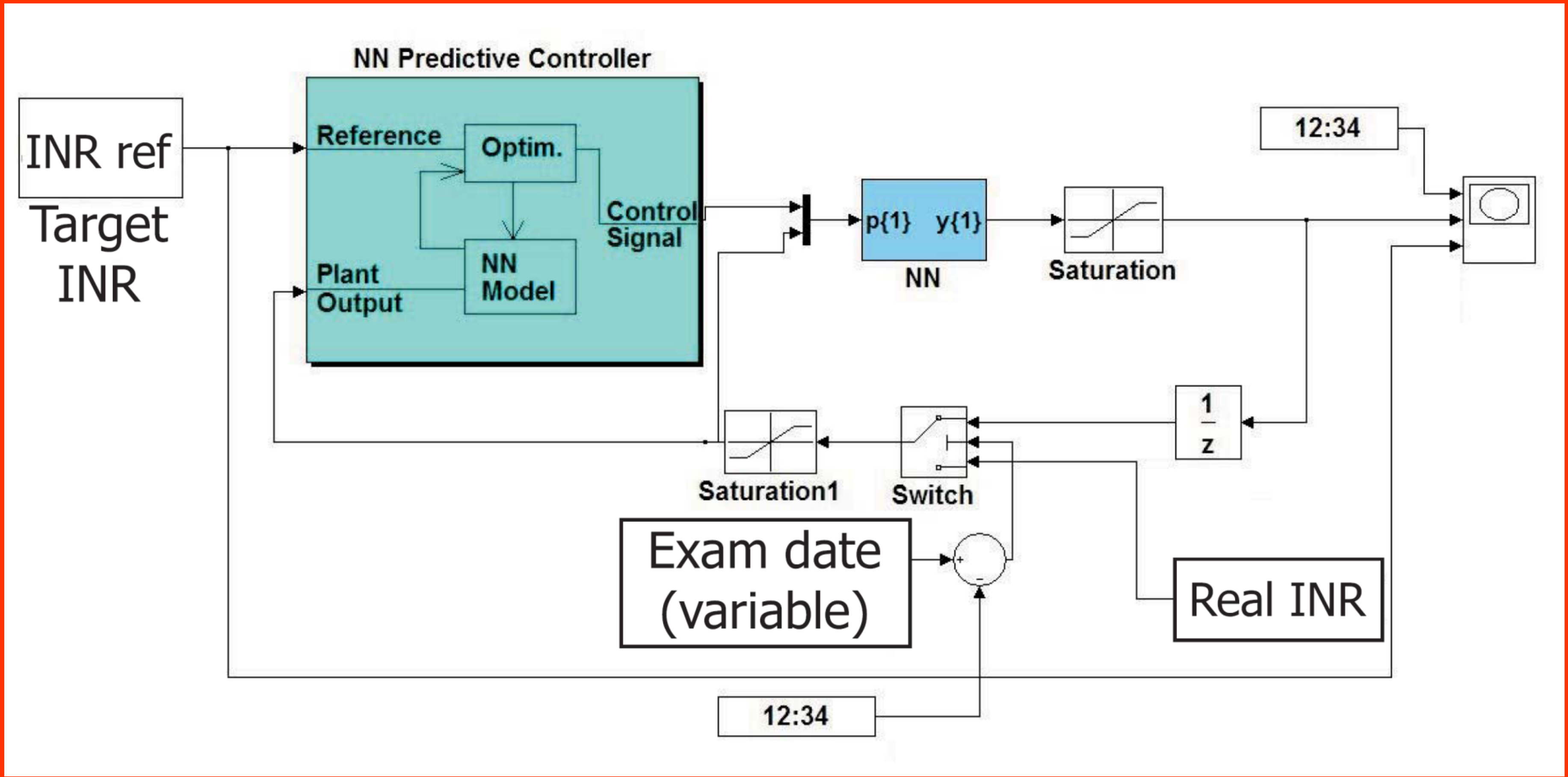
Designed for the real engine

Scheduled PI
+
anti wind-up

Computerised Decision Support Systems for Oral Anticoagulant Treatment Dose Management

- Decision support in anticoagulation drug therapy
  - Used to learn the prescribing behaviour of expert physicians/clinicians or to learn the outcomes associated with such decisions
- Anticoagulant drug therapy inhibits or delays coagulation of the blood
  - INR (International Normalised Ratio): international standardised method of reporting a patient's prothrombin time (the time it takes for the patient's blood to clot)
  - Drug therapy prescription based on statistical analysis (*i.e.* model-free approach)

Final Tool: NN PC (Simulink®)



Development of Fault Tolerant NGC (Navigation, Guidance & Control) Algorithms for CUAV (Civil Unmanned Aerial Vehicle) Patrolling & Rescue Missions in Harsh Environment

An Integrated Fault Detection & Isolation (FDI) and Fault Tolerant Control (FTC) Design for an Aircraft Model

Project Points

- Guidance, navigation and control (GNC) algorithm testing for trajectory tracking
- **Fault Detection and Diagnosis (FDD) + Fault Tolerant control (FTC) algorithms**
- Civil Unmanned Aerial Vehicle (CUAV) demonstrator development (ultra-light aircraft)

Project Details

- Increased payload (60-70 kg versus 3-4 kg)
- Pilot available on-board (longer flying distance)
- Take off from any aerial space & from small civil airports
- Ultra-light aircraft may not requite strict aeronautic regulations, homologation, maintenance, ...
- Real fault testing, generated on-board with electronic & electro-mechanic devices (*e.g.* clutches, ...)
- National Instruments PXI and FPGA (vs. CompactRIO)

FDI/FDD/FTC Main Topics

- Brief sketch on fault tolerant control schemes
  - Passive Fault Tolerant Control Schemes (PFTCS) vs. Active Fault Tolerant Control Schemes (AFTCS)
- AFTCS: from Fault Detection and Isolation (FDI) to Fault Detection and Diagnosis (FDD)
- A novel AFTCS scheme developed by means of an FDD module based on NonLinear Geometric Approach Adaptive Filter (NLGA-AF)

Main Topics

- The FDD module and the Guidance Control System (GCS) are independently designed
- Case study
  - Test of the AFTCS by means of a PA-30 flight simulator with wind
  - Piper PA-30 similar to the ultra-light CUAV
- Standard Guidance and Control System (GCS)
- Actuator faults

PFTCS and AFTCS

- **Passive Fault Tolerant Control Scheme (PFTCS)**
  - Controllers are fixed and designed to be robust against a class of assumed faults
  - Fault estimate (or detection) or controller reconfiguration not needed, but only limited fault-tolerant capabilities
- **Active Fault Tolerant Control Scheme (AFTCS)**
  - AFTCS reacts to the system faults actively by reconfiguring control actions so that the stability and acceptable performance of the entire system can be maintained
- **Pictorial examples...**

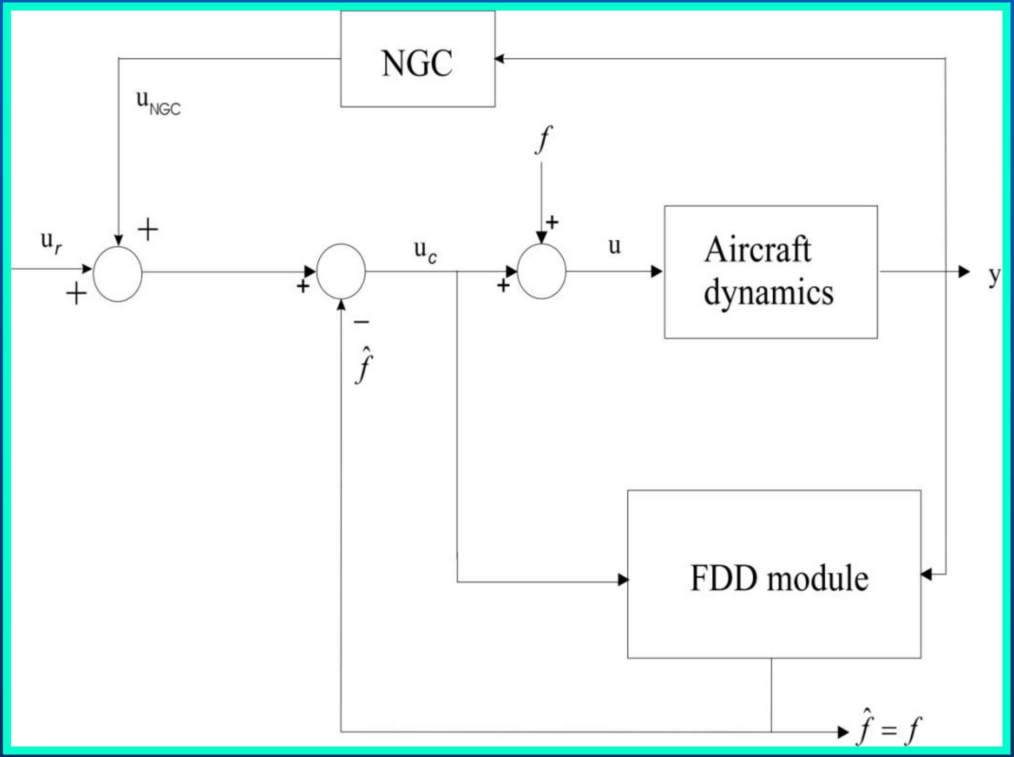
PFTCS and AFTCS (Cont'd)

PFTCS **vs.** **AFTCS**

Robust w.r.t worse-case scenario

Control action reconfiguration and adaptation

AFTCS via a *Novel* FDD



- ✓ The FDD (new) estimates the actual fault
- ✓ The NGC module provides the exact tracking of the reference signal
- ➢ A logic-based switching controller not required!
- ➢ Fault conditions do not modify the system structure, thus guaranteeing the global stability

FDD Module

- FDD via NonLinear Geometric Approach (NLGA) Adaptive Filters (NLGA-AF)
  - Disturbance decoupled filters with the NLGA
  - NLGA determines an equivalent representation of the aircraft model highlighting a subsystem affected by the fault and decoupled from disturbances and other faults
- Adaptive Filter based on the least-squares algorithm with forgetting factor

FDD Module (Cont'd)

- Actuator faults modelled as step functions
  - Convergence of the fault estimate to the actual fault size has been proved in a related paper (Castaldi et al., "Design of residual generators and adaptive filters for the FDI of aircraft model sensors". *Control Engineering Practice*, 2009).
- The novelty of the proposed AFTCS lies in the second feedback of the estimated fault signal, which is obtained by the adaptive filters designed via the NLGA

Aircraft Mathematical Description

- **The simulation model consists of:**
  - ✓ Aircraft 6DoF flight dynamics
  - ✓ Model of engine & servo actuators
  - ✓ Dryden Atmosphere Turbulence & Wind Gust descriptions
  - ✓ Case study : AFTCS applied to standard GCS

- **Standard Nomenclature**

V, a, q_w, q, H, n_e	TAS, angle of attack, pitch rate, elevation angle, altitude, engine shaft angular rate
b, p_w, r_w, f, y	angle of sideslip, roll rate, yaw rate, bank angle, heading angle
$d_e, d_a, d_r; d_{th}$	elevator, aileron, rudder deflection angle; throttle aperture percentage
F_x, F_y, F_z	total force components along body axes
M_x, M_y, M_z	total moment components along body axes

6 DoF Aircraft Dynamics

$$\dot V = F_x \frac{\cos\alpha\cos\beta}{m} + F_y \frac{\sin\beta}{m} + F_z \frac{\sin\alpha\cos\beta}{m}$$

$$\dot\alpha = \frac{-F_x\sin\alpha + F_z\cos\alpha}{mV\cos\beta} + Q - \left(P\cos\alpha + R\sin\alpha\right)\tan\beta$$

$$\dot\beta = \frac{-F_x\cos\alpha\sin\beta + F_y\cos\beta - F_z\sin\alpha\sin\beta}{mV} + P\sin\alpha + -R\cos\alpha$$

$$\dot P = \frac{M_x I_z + M_z I_{xz} + PQ\,I_{xz}\left(I_x - I_y + I_z\right)}{I_x I_z - I_{xz}^2} + \frac{QR\left(I_y I_z - I_{xz}^2 - I_z^2\right)}{I_x I_z - I_{xz}^2}$$

$$\dot Q = \frac{M_y + PR\left(I_z - I_x\right) - P^2 I_{xz} + R^2 I_{xz}}{I_y}$$

$$\dot R = \frac{M_x I_{xz} + M_z I_x + PQ\left(I_x^2 - I_x I_y + I_{xz}^2\right)}{I_x I_z - I_{xz}^2} + \frac{QR\,I_{xz}\left(-I_x + I_y - I_z\right)}{I_x I_z - I_{xz}^2}$$

$$\dot\phi = P + Q\sin\phi\tan\theta + R\cos\phi\tan\theta$$

$$\dot\theta = Q\cos\phi - R\sin\phi$$

$$\dot\psi = \frac{Q\sin\phi + R\cos\phi}{\cos\theta}$$

$$\dot H = V\cos\alpha\cos\beta\sin\theta - V\cos\theta\left(\sin\beta\sin\phi + \sin\alpha\cos\beta\cos\phi\right)$$

The simulation 6 DoF model is simplified to obtain the synthesis model

PA-30 Engine Model

$$\dot{n} = \frac{BP(H)\cdot(1-\eta_{pr})}{I_{pr}n} - \frac{J_{v_1}}{I_{pr}}n - \frac{J_{v_2}}{I_{pr}}n^2 - \frac{J_{v_3}}{I_{pr}}n^3$$

h_{pr}, I_{pr} Þ propeller efficiency and inertia moment

$J_{v_1}, J_{v_2}, J_{v_3}$ Þ polynomial coefficients of the engine shaft viscous friction

$BP(H) = BP_0 \frac{r(H)}{r_0}\sqrt{\frac{T(H)}{T_0}}$ with $BP_0 = d_{th}\cdot P_c(n)$

$BP(H), BP_0 \Rightarrow$ brake power of a single engine

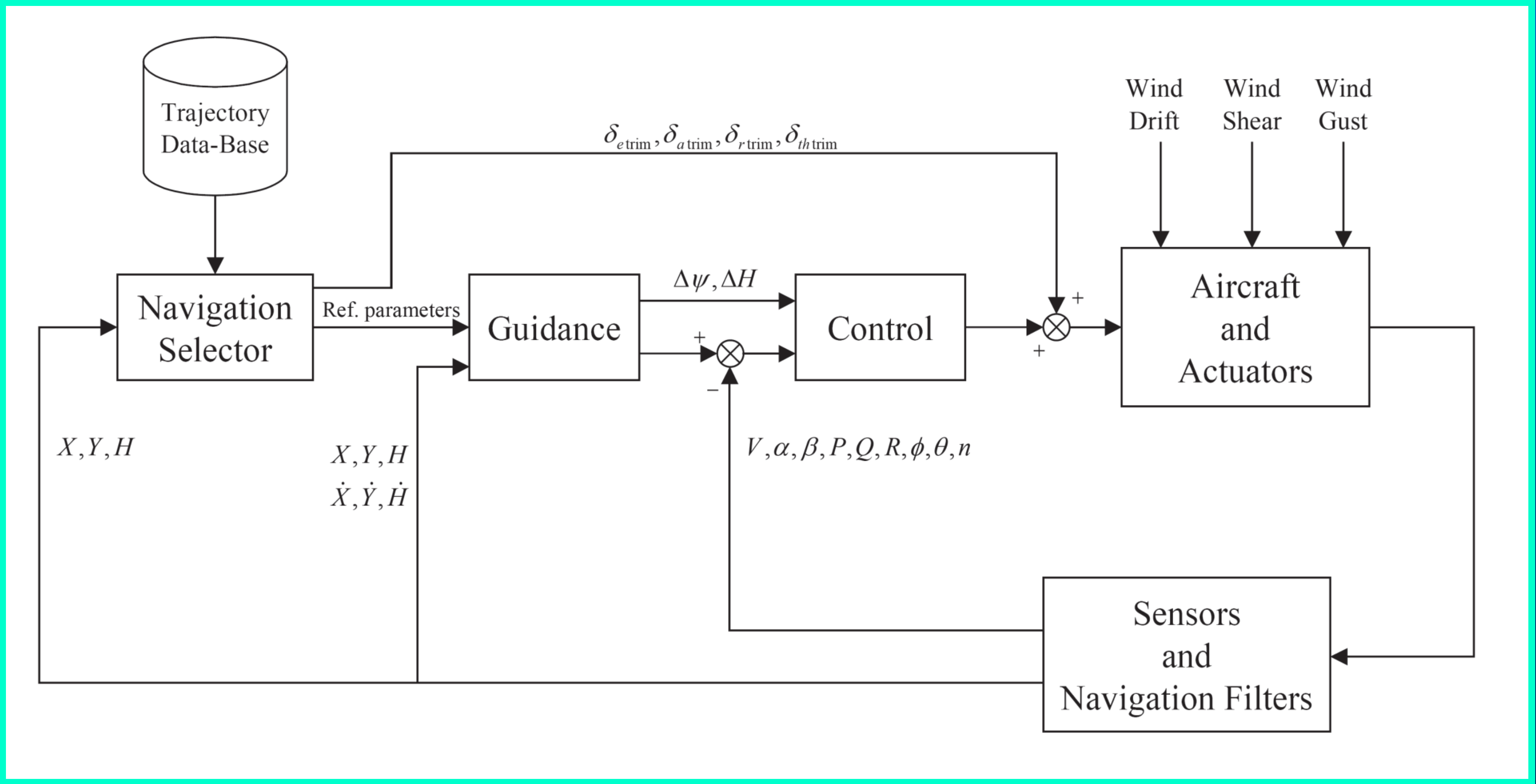
$\rho(H), \rho_0 \Rightarrow$ air density

$T(H), T_0 \Rightarrow$ air temperature

$P_c(n) \Rightarrow$ engine power behavior with respect to n at full throttle

Overall thrust intensity $T_h = \dfrac{2\cdot BP(H)\cdot\eta_{pr}}{V\cos\alpha\cos\beta}$

AFTCS with Standard GCS



NLGA Method

- Coordinate change in the state space and in the output space
  - Observable subsystem affected by the fault and not affected by disturbances and other faults to be decoupled
  - Adaptive Filter (NLGA-AF) designed for the observable subsystem
- NLGA is based on an input affine NonLinear model:

$$\begin{cases} \dot{x} &= n(x) + g(x)u + l(x)f + p(x)d \\ y &= h(x) \end{cases}$$

If $P =$ distribution spanned by $p(x)$

1. Determine the largest observability codistribution contained in $P^{\perp}$ (i.e. Ω^{*})
2. If $l(x) \notin \left(\Omega^{*}\right)^{\perp}$ continue to next steps, otherwise the fault is not detectable
3. In a new (local) coordinate the model can be expressed as: (*see next slide*)

New (Local) State/Output Coordinates

$$\begin{cases} \dot{\overline{x}}_1 = n_1(\overline{x}_1, \overline{x}_2) + g_1(\overline{x}_1, \overline{x}_2)u + \ell_1(\overline{x}_1, \overline{x}_2, \overline{x}_3)f \\ \dot{\overline{x}}_2 = n_2(\overline{x}_1, \overline{x}_2, \overline{x}_3) + g_2(\overline{x}_1, \overline{x}_2, \overline{x}_3)u + \\ \qquad + \ell_2(\overline{x}_1, \overline{x}_2, \overline{x}_3)f + p_2(\overline{x}_1, \overline{x}_2, \overline{x}_3)d \\ \dot{\overline{x}}_3 = n_3(\overline{x}_1, \overline{x}_2, \overline{x}_3) + g_3(\overline{x}_1, \overline{x}_2, \overline{x}_3)u + \\ \qquad + \ell_3(\overline{x}_1, \overline{x}_2, \overline{x}_3)f + p_3(\overline{x}_1, \overline{x}_2, \overline{x}_3)d \\ y_1 = h(\overline{x}_1) \\ y_2 = \overline{x}_2 \end{cases}$$

- The non measured state $\overline{x}_3$ does not exist in our case
- $\overline{x}_1$ **- subsystem can be singled out**

$$\begin{cases} \dot{\overline{x}}_1 = n_1(\overline{x}_1, \overline{y}_2) + g_1(\overline{x}_1, \overline{y}_2)u + \ell_1(\overline{x}_1, \overline{y}_2, \overline{x}_3)f \\ \overline{y}_1 = h(\overline{x}_1) \end{cases}$$

System affected by the fault and decoupled from the disturbance

This subsystsem is exploited for the design of the fault f estimate, i.e. $\hat{f}(t)$

NLGA-AF Design

- **Simulation Model is NOT input affine ⇒ approximations:**
  - simplified aerodynamics (main terms series expansion)
  - simplified engine model (linearisation w.r.t. the angular rate)
  - longitudinal and lateral dynamics 2^{nd} order coupling neglected
  - x–body axis turbulence/wind-gusts component neglected
  - rudder effect on β dynamics neglected

- M. Bonfè, P. Castaldi, W. Geri, and S. Simani, "Fault Detection and Isolation for On–Board Sensors of a General Aviation Aircraft," *International Journal of Adaptive Control and Signal Processing*, vol. 20, pp. 381–408, October 2006.
- M. Benini, M. Bonfè, P. Castaldi, W. Geri, and S. Simani, "Design and Analysis of Robust Fault Diagnosis Schemes for a Simulated Aircraft Model," *Journal of Control Science and Engineering*, vol. 2008, pp. 1–18, 2008.
- M. Bonfè, P. Castaldi, W. Geri, and S. Simani, "Nonlinear Actuator Fault Detection and Isolation for a General Aviation Aircraft," *Space Technology – Space Engineering, Telecommunication, Systems Engineering and Control*, vol. 27, pp. 107–113, December

Synthesis Nonlinear Model

$$
\begin{cases}
\dot{V} = -\dfrac{\left(C_{D0} + C_{D\alpha}\alpha + C_{D\alpha_2}\alpha^2\right)}{m}V^2 + n + g\left(\sin\alpha\cos\theta\cos\phi - \cos\alpha\sin\theta\right) + n + \\
\quad + \dfrac{\cos\alpha}{m}\dfrac{t_p}{V}\left(t_0 + t_1 n_e\right)\delta_{th} + w_v \sin\alpha \\
\dot{\alpha} = -\dfrac{\left(C_{L0} + C_{L\alpha}\alpha\right)}{m}V + n + \dfrac{g}{V}\left(\cos\alpha\cos\theta\cos\phi + \sin\alpha\sin\theta\right) + q_\omega + \\
\quad + n + -\dfrac{\sin\alpha}{m}\dfrac{t_p}{V^2}\left(t_0 + t_1 n_e\right)\delta_{th} + \dfrac{\cos\alpha}{V}w_v \\
\dot{\beta} = \dfrac{\left(C_{D0} + C_{D\alpha}\alpha + C_{D\alpha_2}\alpha^2\right)\sin\beta + C_{Y\beta}\beta\cos\beta}{m}V + n + g\dfrac{\cos\theta\sin\phi}{V} + p_\omega\sin\alpha - r_\omega\cos\alpha + n + \\
\quad - \dfrac{\cos\alpha\sin\beta}{m}\dfrac{t_p}{V^2}\left(t_0 + t_1 n_e\right)\delta_{th} + \dfrac{1}{V}w_\ell \\
\dot{p}_\omega = \dfrac{\left(C_{l\beta}\beta + C_{lp}\,p_\omega\right)}{I_x}V^2 + \dfrac{\left(I_y - I_z\right)}{I_x}q_\omega r_\omega + \dfrac{C_{\delta_a}}{I_x}V^2\delta_a \\
\dot{q}_\omega = \dfrac{\left(C_{m0} + C_{m\alpha}\alpha + C_{mq}\,q_\omega\right)}{I_y}V^2 + \dfrac{\left(I_z - I_x\right)}{I_y}p_\omega r_\omega + n + \dfrac{C_{\delta_e}}{I_y}V^2\delta_e + \dfrac{t_d}{I_y}\dfrac{t_p}{V}\left(t_0 + t_1 n_e\right)\delta_{th} \\
\dot{r}_\omega = \dfrac{\left(C_{n\beta}\beta + C_{nr}\,r_\omega\right)}{I_z}V^2 + \dfrac{\left(I_x - I_y\right)}{I_z}p_\omega q_\omega + \dfrac{C_{\delta_r}}{I_z}V^2\delta_r \\
\dot{\phi} = p_\omega + \left(q_\omega\sin\phi + r_\omega\cos\phi\right)\tan\theta \\
\dot{\theta} = q_\omega\cos\phi - r_\omega\sin\phi \\
\dot{\psi} = \dfrac{\left(q_\omega\sin\phi + r_\omega\cos\phi\right)}{\cos\theta} \\
\dot{n}_e = t_n n_e^3 + \dfrac{t_f}{n_e}\left(t_0 + t_1 n_e\right)\delta_{th}
\end{cases}
$$

The simulation 6 DoF model was simplified to obtain the synthesis model

FDD Assumptions

- **The proposed FDD scheme can be applied only if the fault detectability condition holds and the following new constraints are satisfied:**
- The $\overline{x}_1$–subsystem is independent from the $\overline{x}_3$ state components
- The fault is a step function of the time
- There exists a proper scalar component $\overline{x}_{1s}$ of the state vector $\overline{x}_1$ such that the corresponding scalar component of the output vector is $y_{1s} = x_{1s}$ and the following relation holds:

$$\dot{\overline{y}}_{1s}(t) = M_1(t) \cdot f + M_2(t); \quad M_1(t) \neq 0, \forall t \geq 0$$

FDD Assumptions (Cont'd)

- The structure of $M_1(t)$ and $M_2(t)$ is obtained by means of the NLGA design. Moreover, they can be computed and measured for each time instant
- ✓ In the case considered here, the previous assumptions are satisfied!

Ref: Castaldi, P., Geri, W., Bonfè, M., Simani, S and Benini, M. Design of residual generators and adaptive filters for the FDI of aircraft model sensors. *Control Engineering Practice, 2009*

FDD Solution

- Design an adaptive filter for the system model, in order to perform an estimation $\hat{f}$, which asymptotically converges to the magnitude of the fault f

Solution: the proposed adaptive filter (least-squares)

$$\begin{cases} \dot{\breve{M}}_1 = -\lambda \breve{M}_1 + M_1, & \breve{M}_1(0) = 0 \\ \dot{\breve{M}}_2 = -\lambda \breve{M}_2 + M_2, & \breve{M}_2(0) = 0 \\ \dot{\breve{\bar{y}}}_{1s} = -\lambda \breve{\bar{y}}_{1s} + \bar{y}_{1s}, & \breve{\bar{y}}_{1s}(0) = 0 \end{cases}$$

Data low-pass filtering

$$\begin{cases} \hat{\bar{y}}_{1s} = \breve{M}_1 \hat{f} + \breve{M}_2 + \lambda \breve{\bar{y}}_{1s} \\ \epsilon = \dfrac{1}{N^2}\left(\bar{y}_{1s} - \hat{\bar{y}}_{1s}\right) \end{cases}$$

output estimation

normalized estimation error

$$\begin{cases} \dot{P} = \beta P - \dfrac{1}{N^2} P^2 \breve{M}_1^2, & P(0) = P_0 > 0 \\ \dot{\hat{f}} = P \epsilon \breve{M}_1, & \hat{f}(0) = 0 \end{cases}$$

adaptation law

$\lambda > 0;\ \beta \geq 0;\ N^2 = 1 + \breve{M}_1^2$ Bandwidth; forgetting factor ; normalization factor

Computation Example

$$\begin{cases} \dot{x} = n(x) + g(x)c + l(x)f + p(x)d \\ y = h(x) = I_{10}x \end{cases}$$

$$x = \begin{bmatrix} V & \alpha & \beta & p & q & r & \phi & \theta & \psi & n \end{bmatrix}^T$$

$$c = \begin{bmatrix} \delta_e & \delta_a & \delta_r & \delta_{th} \end{bmatrix}^T$$

$$f = \begin{bmatrix} f_{\delta_e} & f_{\delta_a} & f_{\delta_r} & f_{\delta_{th}} \end{bmatrix}^T$$

$$d = \begin{bmatrix} w_v & w_l \end{bmatrix}^T$$

Computation Example (Cont'd)

$$n(x) = \begin{bmatrix} -\dfrac{\left(C_{d0} + C_{d\alpha}\alpha + C_{d\alpha_2}\alpha^2\right)}{m}V^2 + g\left(\sin\alpha\cos\theta\cos\phi - \cos\alpha\sin\theta\right) \\ -\dfrac{\left(C_{L0} + C_{L\alpha}\alpha\right)}{m}V + \dfrac{g}{V}\left(\cos\alpha\cos\theta\cos\phi + \sin\alpha\sin\theta\right) + q \\ \dfrac{\left(C_{d0} + C_{d\alpha}\alpha + C_{d\alpha_2}\alpha^2\right)\sin\beta + \left(C_{y\beta}\beta\right)\cos\beta}{m}V + g\dfrac{\cos\theta\sin\phi}{V} + p\sin\alpha - r\cos\alpha \\ \dfrac{\left(C_{l\beta}\beta + C_{lp}p\right)}{I_x}V^2 + \dfrac{\left(I_y - I_z\right)}{I_x}qr \\ \dfrac{\left(C_{m0} + C_{m\alpha}\alpha + C_{mq}q\right)}{I_y}V^2 + \dfrac{\left(I_z - I_x\right)}{I_y}pr \\ \dfrac{\left(C_{n\beta}\beta + C_{nr}r\right)}{I_z}V^2 + \dfrac{\left(I_x - I_y\right)}{I_z}pq \\ p + \left(q\sin\phi + r\cos\phi\right)\tan\theta \\ q\cos\phi - r\sin\phi \\ \dfrac{\left(q\sin\phi + r\cos\phi\right)}{\cos\theta} \\ t_n n^3 \end{bmatrix}$$

Computation Example (Cont'd)

$$g(x) = \begin{bmatrix} g_1(x) & g_2(x) & g_3(x) & g_4(x) \end{bmatrix}$$

$$g(x) = \begin{bmatrix} g_1(x) & g_2(x) & g_3(x) & g_4(x) \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & \frac{\cos\alpha}{m}\frac{t_p}{V}(t_0+t_1 n) \\ 0 & 0 & 0 & -\frac{\sin\alpha}{m}\frac{t_p}{V^2}(t_0+t_1 n) \\ 0 & 0 & 0 & -\frac{\cos\alpha\sin\beta}{m}\frac{t_p}{V^2}(t_0+t_1 n) \\ 0 & \frac{C_{\delta_a}}{I_x}V^2 & 0 & 0 \\ \frac{C_{\delta_e}}{I_y}V^2 & 0 & 0 & \frac{d_t}{I_y}\frac{t_p}{V}(t_0+t_1 n) \\ 0 & 0 & \frac{C_{\delta_r}}{I_z}V^2 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{t_f}{n}(t_0+t_1 n) \end{bmatrix}$$

Fault via $g_3(x)$

$g_1(x)$, $g_2(x)$ and $g_4(x)$ regard the faults to be decoupled

Wind disturbance

$$p(x) = p_d(x) = \begin{bmatrix} \sin\alpha & 0 \\ \frac{\cos\alpha}{V} & 0 \\ 0 & \frac{1}{V} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Computation Example (Cont'd)

Rudder actuator fault

$$l(x) = g_3(x) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \dfrac{C_{\delta_r}}{I_z} V^2 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$p(x) = \begin{bmatrix} p_d(x) & g_1(x) & g_2(x) & g_4(x) \end{bmatrix} =$$

$$\begin{bmatrix} \sin\alpha & 0 & 0 & 0 & \dfrac{\cos\alpha}{m}\dfrac{t_p}{V}(t_0 + t_1 n) \\ \dfrac{\cos\alpha}{V} & 0 & 0 & 0 & -\dfrac{\sin\alpha}{m}\dfrac{t_p}{V^2}(t_0 + t_1 n) \\ 0 & \dfrac{1}{V} & 0 & 0 & -\dfrac{\cos\alpha\sin\beta}{m}\dfrac{t_p}{V^2}(t_0 + t_1 n) \\ 0 & 0 & 0 & \dfrac{C_{\delta_a}}{I_x}V^2 & 0 \\ 0 & 0 & \dfrac{C_{\delta_e}}{I_y}V^2 & 0 & \dfrac{d_t}{I_y}\dfrac{t_p}{V}(t_0 + t_1 n) \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \dfrac{t_f}{n}(t_0 + t_1 n) \end{bmatrix}$$

Computation Example (Cont'd)

$$S_0 = \overline{P} = cl(P) = cl\left(\begin{bmatrix} V\sin\alpha & 0 & 0 & 0 & \frac{\cos\alpha}{m}t_pV \\ \cos\alpha & 0 & 0 & 0 & -\frac{\sin\alpha}{m}t_p \\ 0 & 1 & 0 & 0 & -\frac{\cos\alpha\sin\beta}{m}t_p \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & \frac{d_t}{I_y}t_pV \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{t_fV^2}{n} \end{bmatrix}\right)$$

Recalling that

$\ker\{dh\} = \varnothing \;\Rightarrow$

$\Sigma_*^P = \overline{P}$

Computation Example (Cont'd)

Computation of

$$\left(\Sigma_*^P\right)^\perp = \left(\overline{P}\right)^\perp$$

$$\left(\overline{P}\right)^\perp = \left(\left[\begin{array}{ccccc|c} V\sin\alpha & 0 & 0 & 0 & \frac{\cos\alpha}{m}t_pV & 0 \\ \cos\alpha & 0 & 0 & 0 & -\frac{\sin\alpha}{m}t_p & 0 \\ 0 & 1 & 0 & 0 & -\frac{\cos\alpha\sin\beta}{m}t_p & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & \frac{d_t}{I_y}t_pV & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{t_fV^2}{n} & 1 \end{array}\right]\right)^\perp = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Computation Example (Cont'd)

As $span\{dh\} = I_{10} \Rightarrow \Omega^* = \left(\Sigma_*^P\right)^\perp = \left(\overline{P}\right)^\perp \Rightarrow \left(\Omega^*\right)^\perp = \Sigma_*^P = \overline{P}$

The fault is detectable if $l(x) \notin \left(\Omega^*\right)^\perp = \Sigma_*^P = \overline{P}$

This condition holds as $l(x) = g_3(x) = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \dfrac{C_{\delta_r}}{I_z} V^2 & 0 & 0 & 0 & 0 \end{bmatrix}^T$

whilst $\overline{P}$ has all zeros in the 6^{th} row

Computation Example (Cont'd)

$$\psi(y(x)) = \begin{pmatrix} \psi_1(x) \\ \mathrm{H}_2 x \end{pmatrix} = \begin{pmatrix} \begin{bmatrix} r \\ \phi \\ \theta \\ \psi \end{bmatrix} \\ \begin{bmatrix} V \\ \alpha \\ \beta \\ p \\ q \\ n \end{bmatrix} \end{pmatrix}$$

x_1-subsystem

$$\mathbf{x}_1 = \begin{bmatrix} r \\ \phi \\ \theta \\ \psi \end{bmatrix}$$

$$\dot{\mathbf{x}}_1 = \begin{bmatrix} \dot{r} \\ \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}$$

Computation Example (Cont'd)

Only x_{11} is directly affected by the fault, because the other variables do not depend on that input. Thus, in order to design the residual generator it is necessary to compute:

$$\dot{\mathbf{x}}_1 = \dot{r} = \frac{\left(C_{n\beta}\beta + C_{nr}r\right)}{I_z}V^2 + \frac{\left(I_x - I_y\right)}{I_z}pq + \frac{C_{\delta_r}}{I_z}V^2\delta_r$$

Assuming that all the state variables can be measured, the residual generator is:

$$\begin{cases} \dot{\xi} = \dfrac{\left(C_{n\beta}\beta + C_{nr}r\right)}{I_z}V^2 + \dfrac{\left(I_x - I_y\right)}{I_z}pq + \dfrac{C_{\delta_r}}{I_z}V^2\delta_r + K_{\delta_r}\left(r - \xi\right) \\ r_{\delta_r} = \left(r - \xi\right) \end{cases}$$

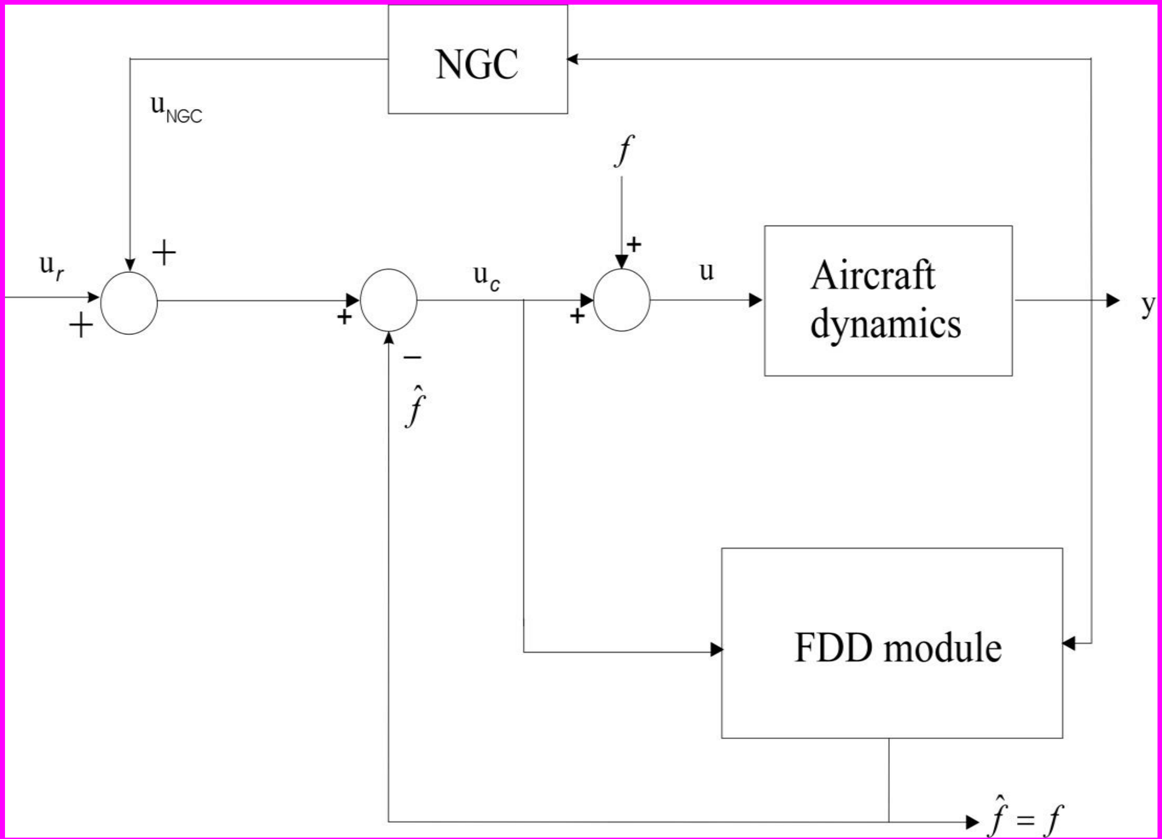
Aircraft Actuator NLGA-AF

- Example - fault on the rudder actuator

Fault on rudder

$$\bar{x}_{1s} = \bar{x}_{11} = r_\omega \quad \Rightarrow \quad \begin{cases} \dot{\bar{y}}_{1s,r} = M_{1r} \cdot f_{\delta_r} + M_{2r} \\ M_{1r} = \dfrac{C_{\delta_r}}{I_z} V^2 \\ M_{2r} = \dfrac{\left(C_{n\beta}\beta + C_{nr} r_\omega\right)}{I_z} V^2 + \dfrac{\left(I_x - I_y\right)}{I_z} p_\omega q_\omega + \\ \qquad + \dfrac{C_{\delta_r}}{I_z} V^2 \delta_r \end{cases}$$

AFTCS Scheme



u_r : reference input (*e.g*. the reference trajectory)
u : actuated input
u_c : controlled input
u_{NGC}: feedback signal from the NGC system

NGC: Navigation, Guidance and Control system;

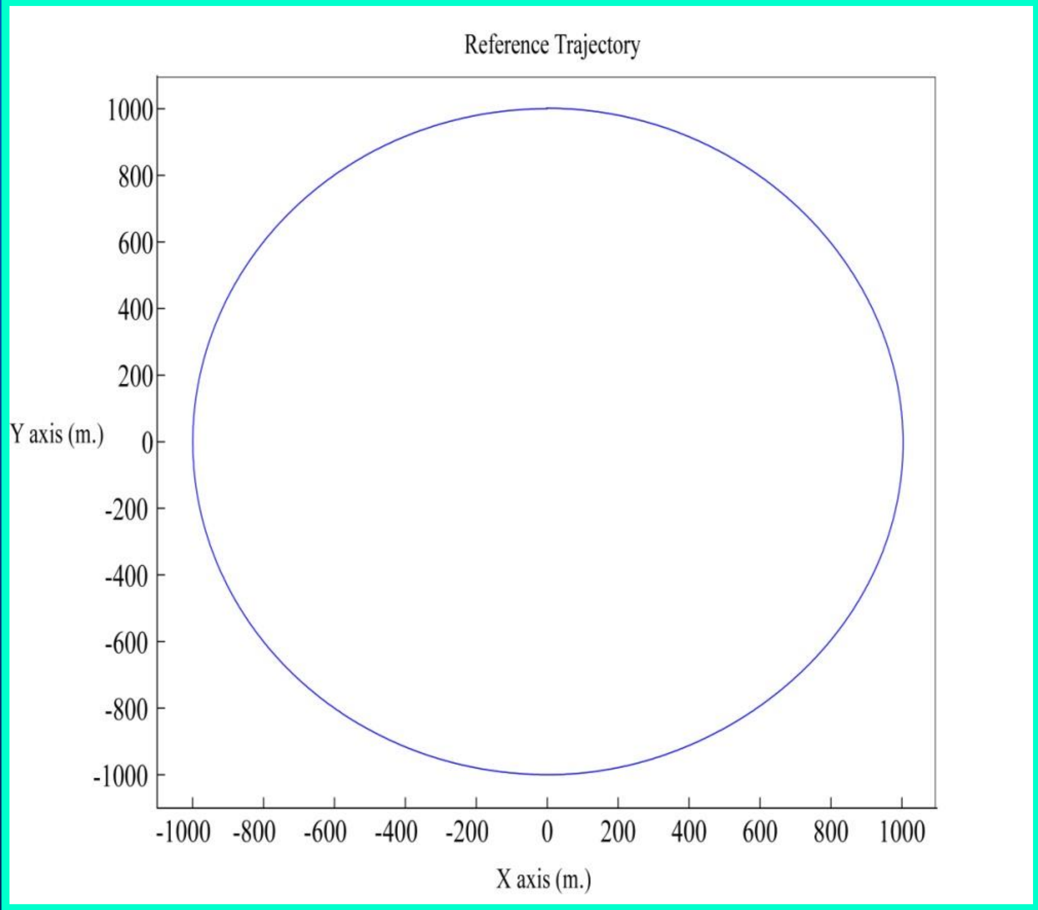
y : controlled output (e.g. the aircraft trajectory)

f : actuator fault

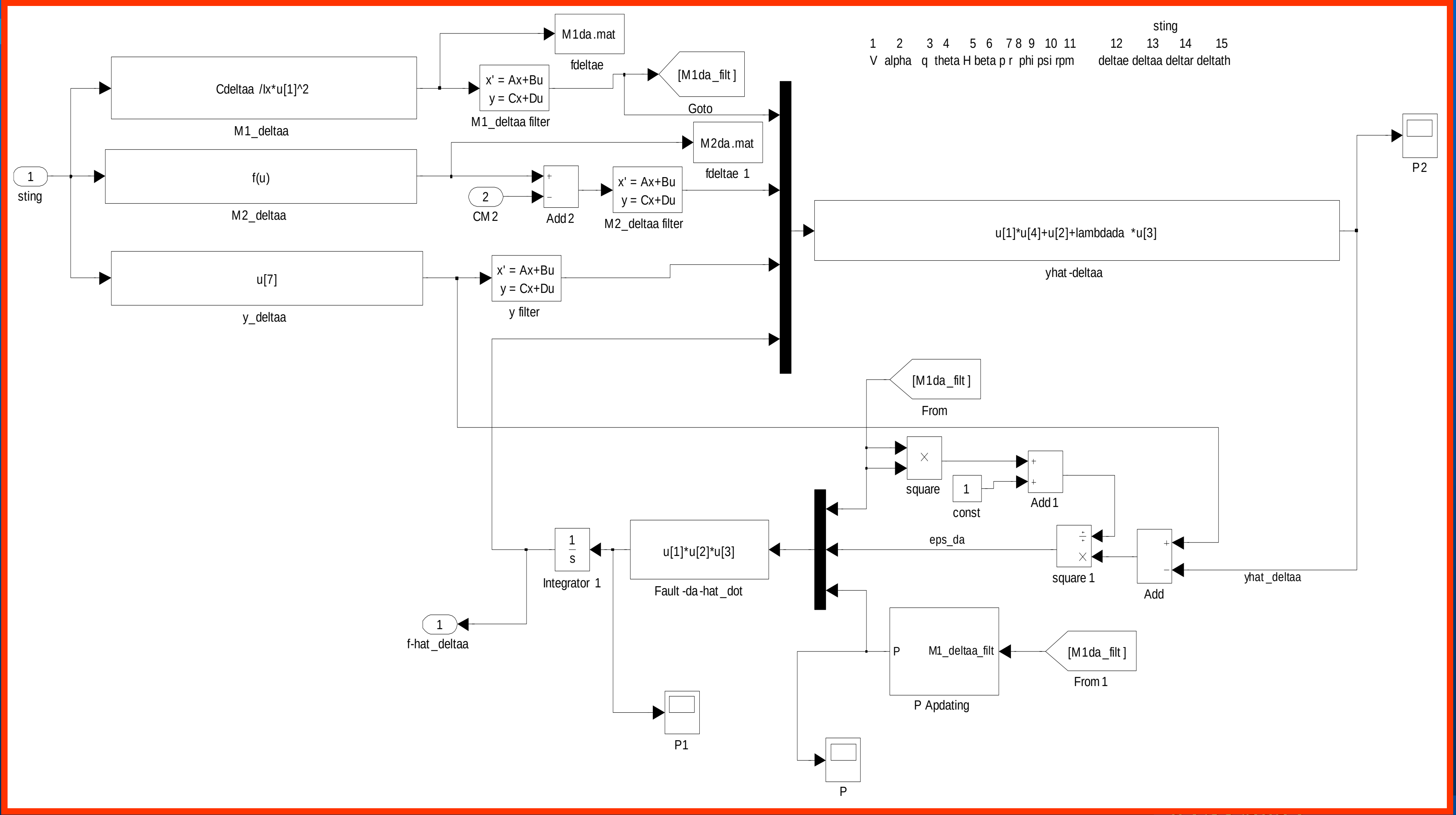
$\hat{f}$: estimated actuator fault.

Simulation Example

- Coordinated turn (circular trajectory)
- Tight coupled longitudinal and lateral-directional dynamics
- Radius of curvature of 1000 m.
- True air speed of 52.36 m/s (120s. to cover the whole circular trajectory)
- Altitude of 330m.
- **Rudder actuator fault of 3° commencing at t=60 s.**

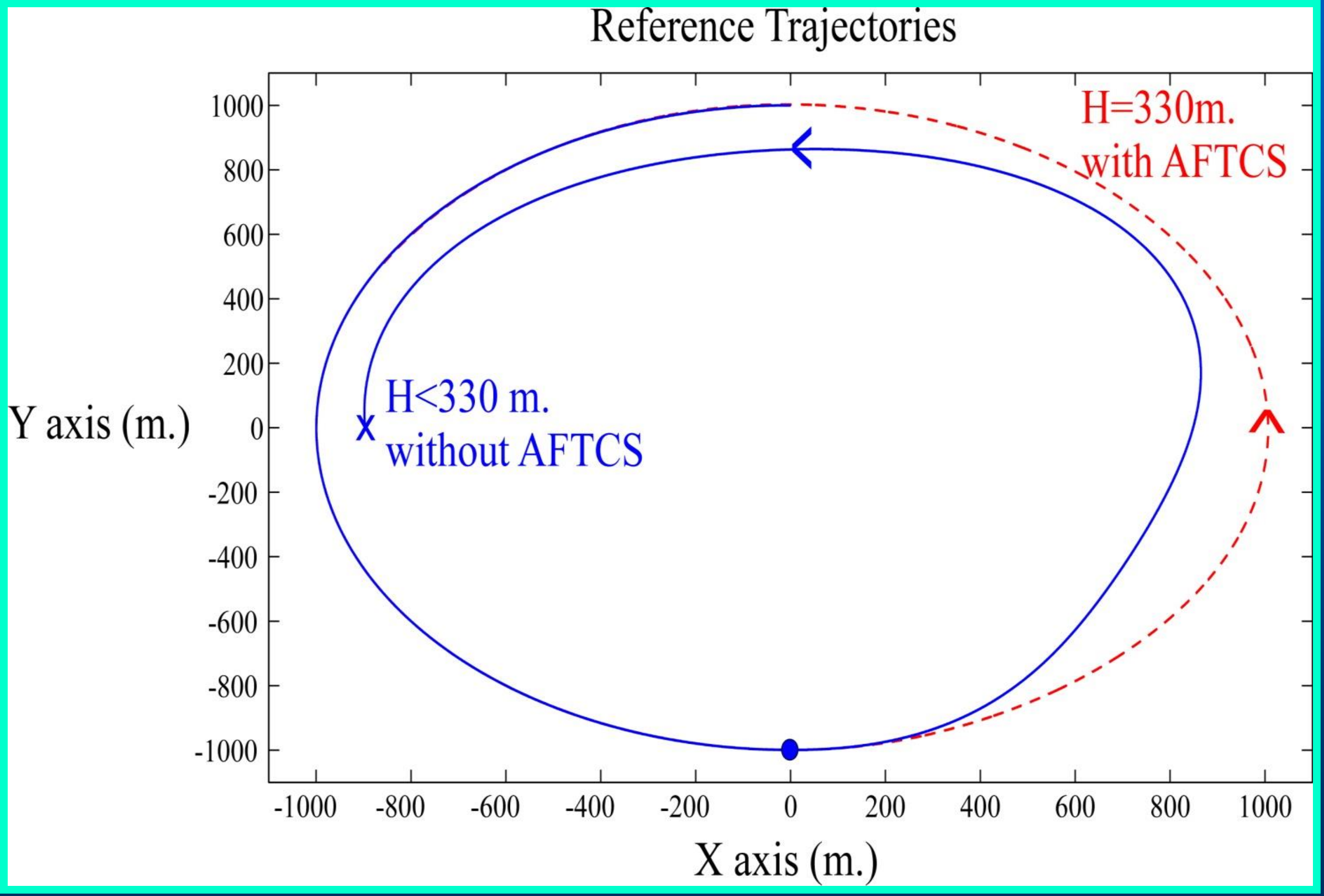


NLGA-AF Simulink® Model



Simulated System...

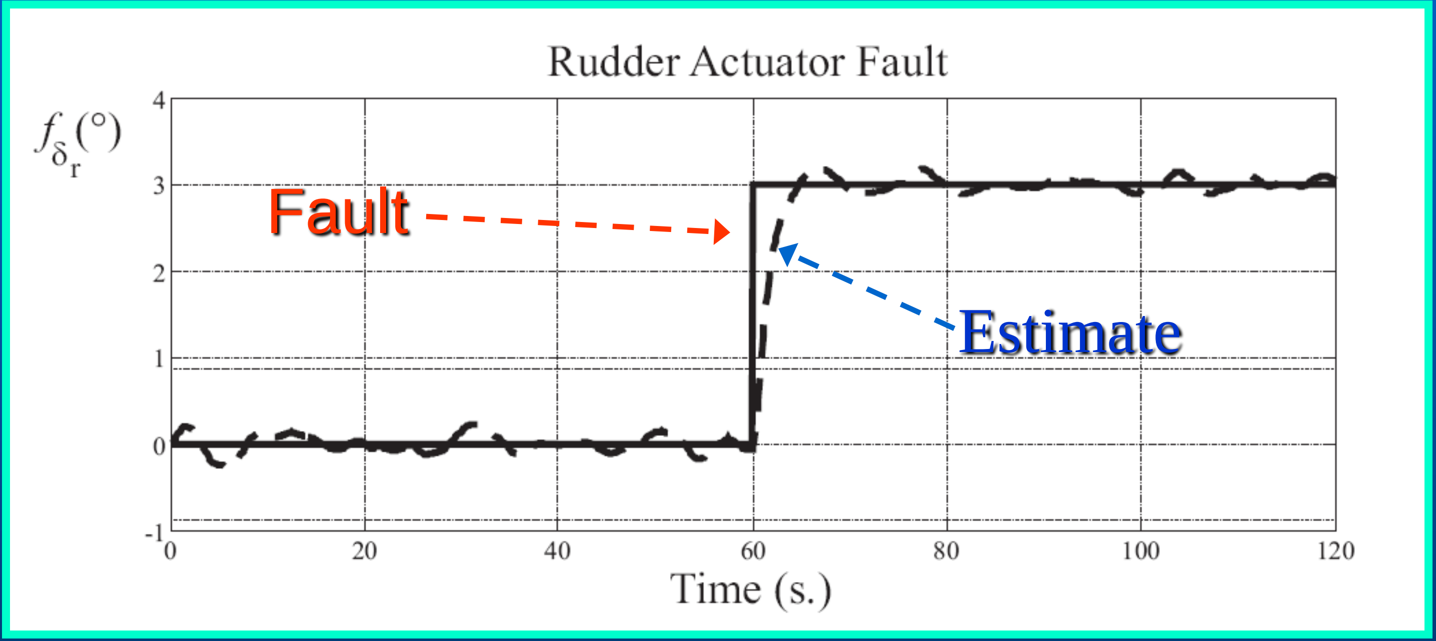
Simulated Fault Conditions



Red : with AFTCS

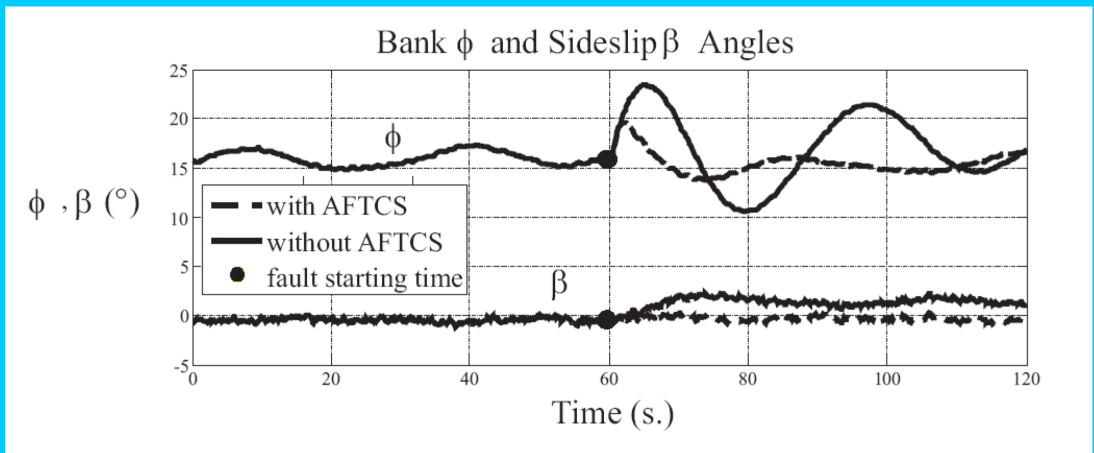
Blue: without AFTCS

Simulation Results

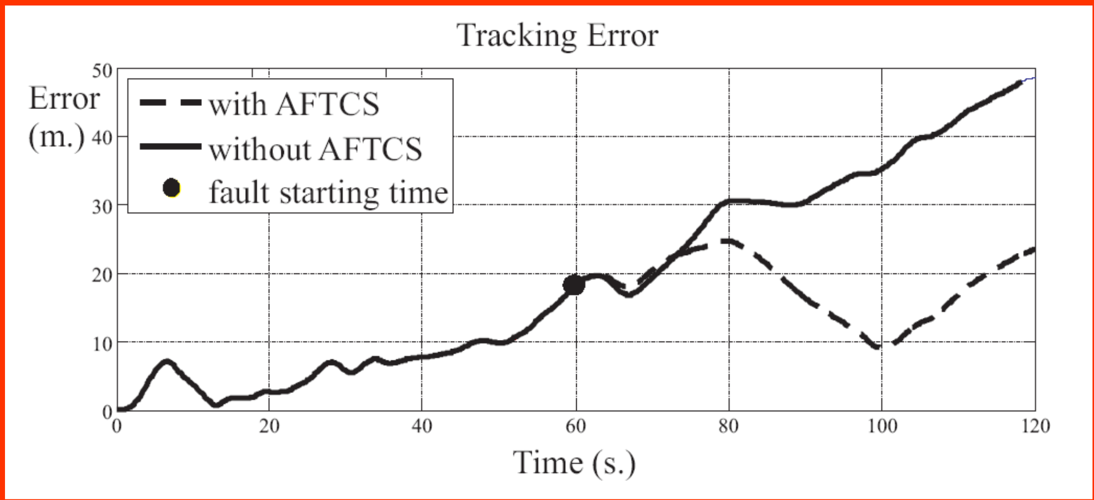


Actuator fault $f_{\delta r}$ and its real–time estimate $\hat{f}$

Simulation Results (Cont'd)



Bank φ and sideslip β angles with and without fault recovery



Tracking error with and without fault recovery

Movie Time…

Conclusion

- ✓ Development of an active fault-tolerant control scheme
  - integration of our NLGA FDD with the design of a controller reconfiguration system
- ✓ FDD relying on adaptive filters designed via the NLGA design
- ✓ Novelty of the proposed fault tolerant scheme
  - use of the fault signals estimated by these adaptive filters and exploited in AFTCS
- ✓ Tested on the PA-30 aircraft simulator with coupled dynamics, actuator faults, turbulence, and modelling errors

Further Investigations

- ❖ Analytical proof of the stability of the complete fault tolerant scheme
- ❖ Evaluation and validation of the effectiveness of the suggested approach applied to a "technological demonstrator" of a Civil Unmanned Aerial Vehicle (CUAV)
- ❖ Implementation of realistic fault conditions on the technological demonstrator

Technological Demonstrator

Thank you for listening!