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A direct/functional redundancy scheme for fault detection and isolation on an aircraft

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Abstract

In this paper the problem of detecting and isolating sensor faults on aircraft, in the presence of external disturbances, is considered. A novel *nonlinear* observer based approach is proposed; this approach exploits the so-called *Unknown Input Observer* (UIO) theory and guarantees disturbance decoupling with an H_∞ performance level. The proposed nonlinear observer has been tested and compared with the classical linear UIO scheme via numerical simulations performed on the model of the small commercial aircraft under consideration; this simulation activity has shown the benefits of the novel approach. The proposed methodology is finally exploited to design an algorithm which, on the basis of the hardware and software measurements, decides if and where a fault has occurred, isolates the faulted signal, and outputs the corresponding healthy signal. Tests performed on the flight simulator of the National Aerospace Laboratory in Amsterdam show that this algorithm improves the performance of a classical *duplex* hardware system.

Keywords: Sensor fault detection and isolation; Unknown input observers; Nonlinear observers; H_∞ control; Linear matrices inequalities

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1. Introduction

Sensor failures on aircraft are not uncommon. In order to detect and isolate faults, system redundancy is necessary. Two main categories of redundancies are typically used: *direct redundancy* and *functional redundancy*. Direct redundancy means that multiple independent hardware channels, with a procedure to *vote* the healthy system channels, are used. On the other side, functional redundancy implies the use of mathematical relations to obtain the redundant measurements. Today in flight control system design, especially for the category of small commercial aircraft (SCA), the direct redundancy approach is typically used.

In order to achieve a functional sensors redundancy it is necessary to have at disposal one or more signal reconstruction modules, that is one or more algorithms able to estimate a given variable from the knowledge of the inputs and the outputs of the system under consideration. Several techniques are available in the literature to design state estimators for the solution of Fault Detection and Isolation (FDI) problems [1–3], among which the best assessed are those based on parity spaces [4,5], dedicated observers and Kalman filtering [6], and the Unknown Input Observers (UIOs) [7,8] approach.

A first contribution of the paper is a novel technique, extending the classical linear UIO theory to the nonlinear context, which, provided the availability of a sufficiently reliable nonlinear model of the aircraft, allows to improve the performance of the classical linear approach.

One important feature of the UIO is that it can attain the decoupling between the external disturbances (unknown inputs) acting on the system and the estimation error. However in our problem we have also to cope with neglected *nonlinearities*. These nonlinearities can be taken into account by adding fictitious disturbances to the system; in this way, the number of disturbances affecting the system becomes too high to be decoupled by the application of the usual methodology. Therefore a second contribution of the paper is the use of an H_∞ based

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Nomenclature

g	gravity acceleration constant
l_c	reference length for aerodynamic moments
S	wing reference area
V	true air speed
W	aircraft weight (force)
$\mathbf{g}$	gravity acceleration
$\mathbf{p}_E$	center of gravity position: $[X_E\ Y_E\ Z_E]^{\mathrm{T}}$
$\mathbf{v}_B$	velocity vector in body axes: $[u_B\ v_B\ w_B]^{\mathrm{T}}$
$\mathbf{v}_{Bwind}$	wind velocity vector in body axes: $[u_{Bwind}\ v_{Bwind}\ w_{Bwind}]^{\mathrm{T}}$
$\mathbf{C}_F$	aerodynamic forces coefficients vector (C_D, C_L, C_Y) (drag, lift, side forces in wind axes)
$\mathbf{C}_T$	aerodynamic moments coefficients vector (C_R, C_M, C_N) (roll, pitch, yaw moments in wind axes)
$\mathbf{F}_A$	aerodynamic forces vector
$\mathbf{F}_E$	engine forces vector
$\mathbf{J}$	inertia matrix (wing span (X–Z axes) or mean aerodynamic chord (X axis))
$\mathbf{T}_A$	aerodynamic moments vector
$\mathbf{T}_E$	engine moments vector
$\mathbf{T}_{\omega\dot{\Phi}}$	transformation matrix from body fixed angular rates to Euler angles derivatives
$\mathbf{T}_{BE}$ ($\mathbf{T}_{EB}$)	transformation matrices from earth to body (body to earth) axes
α	angle of attack
β	sideslip angle
ρ	air density
δ_e, δ_r, δ_a	elevator, rudder, ailerons deflection (primary surfaces)
δ_{st}	horizontal stabilizer
δ_T	throttle command
δ_f	flap deflection
δ_{SB}	speed brake command
δ_{SL}	slat command
$\boldsymbol{\omega}$	angular velocity vector in body axes: $[p\ q\ r]^{\mathrm{T}}$ (roll, pitch, yaw rates)
$\boldsymbol{\Phi}$	Euler angles vector $[\phi\ \theta\ \psi]^{\mathrm{T}}$ (roll, pitch, yaw angles)

technique [9] to reduce the effects of the undecoupled disturbances in the H_∞ sense.

The performance of the nonlinear UIO versus the classical linear UIO have been tested via numerical simulations on a model of the SCA under consideration [9]. Finally the nonlinear UIO technique has been exploited to improve, without further replication of expensive sensors, the performance of a classical duplex hardware system.

The paper is organized as follows: In Section 2 the FDI problem we deal with is presented. In Section 3 the novel nonlinear UIO approach is described in details together with the H_∞ procedure to improve the disturbance rejection. In Section 4, via numerical simulations, it is shown that the proposed approach performs better than the classical linear UIO. In Section 5 the mixed hardware/software redundancy scheme to detect and isolate a possible fault and to vote the correct signal is described. Section 6 finally illustrates some experimental results from the NLR Flight simulator.

2. Aircraft model and problem statement

The mathematical model of the SCA under consideration is a classical six degree of freedom aircraft model. The equations of motion in body axes are [10] (see Nomenclature for the list of symbols)

$$\dot{\mathbf{v}}_B = \frac{\mathbf{F}_A + \mathbf{F}_E}{W} g + \mathbf{T}_{BE}(\boldsymbol{\Phi})\mathbf{g} - \boldsymbol{\omega} \times \mathbf{v}_B, \tag{1a}$$

$$\dot{\mathbf{p}}_E = \mathbf{T}_{EB}(\boldsymbol{\Phi})\mathbf{v}_B, \tag{1b}$$

$$\dot{\boldsymbol{\omega}} = -\mathbf{J}^{-1}\boldsymbol{\omega} \times (\mathbf{J}\boldsymbol{\omega}) + \mathbf{J}^{-1}(\mathbf{T}_A + \mathbf{T}_E), \tag{1c}$$

$$\dot{\boldsymbol{\Phi}} = \mathbf{T}_{\omega\dot{\Phi}}(\boldsymbol{\Phi})\boldsymbol{\omega}. \tag{1d}$$

As for the aerodynamic forces and moments, we have

$$\mathbf{F}_A = \frac{1}{2}\rho V^2 S \mathbf{C}_F, \qquad \mathbf{T}_A = \frac{1}{2}\rho V^2 S \mathbf{C}_T l_c, \tag{2}$$

where the force and moment coefficients $\mathbf{C}_F$ and $\mathbf{C}_T$ are nonlinear functions of the system state and of the surfaces deflections.

The most significant external disturbances are sudden wind gusts, atmospheric turbulence [10,11] and sensor noise. In the presence of atmospheric disturbances we have

$$V = \|\mathbf{v}_B - \mathbf{v}_{Bwind}\|, \tag{3a}$$

$$\alpha = \arctan\big[(w_B - w_{Bwind})/(u_B - u_{Bwind})\big], \tag{3b}$$

$$\beta = \arcsin\big[(v_B - v_{Bwind})/V\big]. \tag{3c}$$

$\|\cdot\|$ denoting the Euclidean norm.

In order to write the system equations in a compact form, let us denote by $\mathbf{u} = (\delta_e\ \delta_T\ \delta_a\ \delta_r\ \delta_{st}\ \delta_f\ \delta_{SB}\ \delta_{SL})^{\mathrm{T}}$ the input vector and by $\mathbf{y} = (V\ \alpha\ p\ q\ r\ \phi\ \theta\ \psi)^{\mathrm{T}}$ the measured output vector. To obtain a linear output equation, which will be useful later for the development of our design methodology, we define the state vector as $\mathbf{x} = (V\ V_B\ \alpha\ \beta\ \mathbf{p}_E^{\mathrm{T}}\ \boldsymbol{\omega}^{\mathrm{T}}\ \phi\ \theta\ \psi)^{\mathrm{T}}$, $V_B = \|\mathbf{v}_B\|$ being the true airspeed free of the disturbance effect. Denoting by $\mathbf{w} = [\mathbf{v}_{Bwind}^{\mathrm{T}}\ \dot{\mathbf{v}}_{Bwind}^{\mathrm{T}}]^{\mathrm{T}}$ the wind disturbance, the aircraft equations can be rewritten as

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, \mathbf{w}), \tag{4a}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x}. \tag{4b}$$

In order to be suitable for the implementation on a real aircraft, a sensor FDI technique should be able to detect and isolate faults in the presence of external disturbances, unmodeled dynamics, neglected nonlinearities. An improvement to standard