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IFAC-PapersOnLine 49-17 (2016) 432–437

Combined Geometric and Neural Network Approach to Generic Fault Diagnosis in Satellite Actuators and Sensors

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Abstract: This paper presents a novel scheme for diagnosis of faults affecting the sensors measuring the satellite attitude, body angular velocity and flywheel spin rates as well as defects related to the control torques provided by satellite reaction wheels. A nonlinear geometric design is used to avoid that aerodynamic disturbance torques have unwanted influence on the residuals exploited for fault detection and isolation. Radial basis function neural networks are used to obtain fault estimation filters that do not need a priori information about the fault internal models. Simulation results are based on a detailed nonlinear satellite model with embedded disturbance description. The results document the efficacy of the proposed diagnosis scheme.

Keywords: Fault diagnosis, geometric approaches, neural networks, actuators, sensors, satellite control applications.

1. INTRODUCTION

The increasing operational requirements for onboard autonomy in satellite control systems require structural methods that support the design of complete and reliable Fault Detection and Diagnosis (FDD) systems providing fundamental information about the system health status jointly with accurate fault estimates. Significant research in FDD has been done in the last decades (Isermann (2011); Blanke et al. (2016)). Numerous model-based methods have been proposed for fault diagnosis (Chen-Patton (1999); Ding (2013)) and for the diagnosis in nonlinear systems (Bokor-Szabó (2009)). In particular, a solution to the Fault Detection and Isolation (FDI) problem for nonlinear systems is presented in De Persis-Isidori (2001) through the NonLinear Geometric Approach (NLGA).

This paper presents a novel diagnosis scheme to assess the health condition and proper functioning of essential sensors and actuators of a satellite Attitude Determination and Control Systems (ADCSs). This work is a substantial improvement of a previous work of the same authors (Baldi et al. (2015)), which considered only faults affecting the attitude control torques and flywheel spin rate sensors. In contrast, this paper considers also possible faults affecting the satellite attitude and angular velocity sensors.

The procedure for actuator and sensor fault modelling presented in Mattone-De Luca (2006) is exploited to define a nonlinear model affine in all the actuator and sensor fault inputs and suitable for the NLGA application.

The performances of the proposed FDD system have been evaluated when applied to a detailed nonlinear satellite simulator. In particular, the exogenous disturbance terms represented by the aerodynamic and gravitational disturbance torques are considered. As the gravitational disturbance model is almost perfectly known, the FDD robustness is achieved by exploiting an *explicit disturbance decoupling* based on the NLGA, applied only to the aerodynamic force term (Baldi et al. (2015)). In fact, this term represents the main source of uncertainty in the satellite dynamic model, mainly due to the lack of knowledge of the accurate values of air density and satellite drag coefficient. The scalar residual filters composing the FDI module of the model-based FDD system are designed via the NLGA to obtain diagnostic signals that are independent of the knowledge of the aerodynamic disturbance parameters. The fault isolation is achieved by means of a residual cross-check and a proper decision logic, assuming a single fault occurring at any time. The adaptive filters of the Fault Estimation (FE) module are designed via Radial Basis Function Neural Networks (RBF NN)s (Chen-Chen (1995); Castaldi et al. (2014)) and activated once a fault has been correctly detected and isolated.

The use of a RBF NN allows to design *generalised fault estimation filters* that do not need a priori information about the type of the occurred fault and that are capable of accurately estimating a generic fault without needing to define any specific fault internal model. Moreover, the NLGA allows to obtain a precise FDI and accurate fault estimates, independent of the knowledge of the aerodynamic

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10.1016/j.ifacol.2016.09.074

disturbance parameters, and thus without any isolation and estimation errors due to parameter uncertainties. Simulation results are given in case of both actuator and sensor faults, validating the ability of the proposed scheme to deal with faults of different types, provide a precise fault detection, isolation and accurate fault estimates.

2. SATELLITE AND ACTUATOR MODELS

The satellite is considered as a rigid body, whose attitude is represented by using the quaternion notation. The satellite mathematical model is given by the dynamic and kinematic equations of (1) and (2) (Wie (2008)):

$$\dot{\omega} = -\mathbf{I}_s^{-1}\mathbf{S}(\omega)(\mathbf{I}_s\omega + \mathbf{T}_{rw}\mathbf{h}_{rw}) + \mathbf{I}_s^{-1}(\mathbf{T}_{rw}\mathbf{M} + \mathbf{M}_{gg} + \mathbf{M}_{aero}) \quad (1)$$

$$\dot{\mathbf{q}} = \frac{1}{2}\mathbf{\Omega}\mathbf{q} \quad (2)$$

with the skew-symmetric matrices

$$\mathbf{S}(\omega) = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}, \mathbf{\Omega}(\omega) = \begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix} \quad (3)$$

and where $\omega = [\omega_1, \omega_2, \omega_3]^T$ is the vector of the roll, pitch and yaw body rates, $\mathbf{q} = [q_1, q_2, q_3, q_4]^T$ is the quaternion vector and $\mathbf{h}_{rw} = [h_{rw1}, h_{rw2}, h_{rw3}, h_{rw4}]^T$ is the vector of the flywheel angular momenta. The principal inertia body-fixed frame is considered, with I_{xx}, I_{yy}, and I_{zz} on the main diagonal of the satellite inertia matrix $\mathbf{I}_s$.
The considered Attitude Control System (ACS) consists of a fixed array of four reaction wheels in a tetrahedral configuration defined by the matrix $\mathbf{T}_{rw}$. The elements of the input vector $\mathbf{M} = [M_1, M_2, M_3, M_4]^T$ correspond to the attitude control torques of the reaction wheels.
Equation (1) explicitly includes the gravitational and aerodynamic disturbance torque models $\mathbf{M}_{gg}$ and $\mathbf{M}_{aero}$ about the centre of mass and dependant on the satellite attitude. These disturbances typically represent the most important external disturbance torques affecting Low Earth Orbit (LEO) satellites (Wie (2008)). The design of the FDI system exploits an explicit decoupling only of the aerodynamic torque since the gravitational disturbance has a model which is *almost perfectly known*, and thus it does not need to be decoupled. The gravity gradient torque $\mathbf{M}_{gg}$ is

$$\mathbf{M}_{gg} = \frac{3\mu}{R^3}(\hat{v}_{nadir} \times I_s\hat{v}_{nadir}) \quad (4)$$

where the parameters μ and R represent the gravitational constant and the orbit radius respectively, and $\hat{v}_{nadir}$ is the unit vector towards nadir expressed in body-frame coordinates. The aerodynamic torque $\mathbf{M}_{aero}$ is

$$\mathbf{M}_{aero} = \frac{1}{2}\rho S_p V^2 C_D(\hat{v}_V \times \mathbf{r}_{cp}) \quad (5)$$

where ρ is the atmospheric density, V is the relative velocity of the satellite, S_p is the reference area affected by the aerodynamic flux, and C_D is the drag coefficient. $\mathbf{r_{cp}} = \left[r_{x_{cp}}, r_{y_{cp}}, r_{z_{cp}}\right]^T$ is the vector joining the centre of mass and the aerodynamic centre of pressure and $\hat{v}_V$ is the unit velocity vector expressed in body-frame coordinates. It is worth noting that, mainly due to the presence of the unknown terms ρ and C_D in (5), the input $\mathbf{M}_{aero}$ in (1) represents the main source of uncertainty.
The dynamic equations of the reaction wheel models are

$$\dot{\omega}_{rw} = J_{rw}{}^{-1}\dot{\mathbf{h}}_{rw} = -J_{rw}{}^{-1}(\mathbf{M} + b\,\omega_{rw} + c\, sgn(\omega_{rw})) \quad (6)$$

where J_{rw} denotes the flywheel inertia, $\mathbf{h}_{rw} = J_{rw}\omega_{rw}$ is the vector of the flywheel angular momenta, $\omega_{rw} = [\omega_{rw_1}, \omega_{rw_2}, \omega_{rw_3}, \omega_{rw_4}]^T$ is the vector of the flywheel spin rates and b, c are the viscous and Coulomb friction coefficients, respectively (Carrara et al. (2012)).
The overall system model is given by (1), (2) and (6). Thus, the overall state vector can be represented by $x = [\omega_1, \omega_2, \omega_3, q_1, q_2, q_3, q_4, \omega_{rw_1}, \omega_{rw_2}, \omega_{rw_3}, \omega_{rw_4}]^T$ and all the state variables are assumed to be measurable. Moreover, two different attitude sensors are assumed to be available. The attitude measurements are represented by two different quaternion vectors which are calculated on the basis of the information provided by two physical attitude sensors (*e.g.* star trackers). This hardware redundancy is necessary for the complete fault isolability and comes as outcome of the application of a detectability and isolability study to the proposed fault scenarios.

3. FAULT DETECTION AND ISOLATION

3.1 Actuator and Sensor Fault Modelling

Possible faults affecting the actuated attitude control torques, flywheel spin rate, satellite attitude and angular velocity measurements are considered and it is assumed that at most one fault affects the system at any time.
Since (1) and (6) are affine in the control inputs, the i-th physical actuator fault can be modelled by the following fault input where $M_{c,i}$ is the commanded control input:

$$F_{M\,i} = f_{M\,i} = M_i - M_{c,i} \qquad (i = 1, ..., 4) \quad (7)$$

The occurrence of sensor faults can be taken into account by defining the faults as the differences between the real values ω_{rw_j}, ω_l, q_m and measured values $\omega_{rw_{y,j}}$, $\omega_{y,l}$, $q_{y,m}$:

$$\begin{aligned} F_{\omega_{rw_j}} &= \omega_{rw_{y,j}} - \omega_{rw_j} && (j = 1, ..., 4) \\ F_{\omega_l} &= \omega_{y,l} - \omega_l && (l = 1, ..., 3) \\ F_{q_m} &= q_{y,m} - q_m && (m = 1, ..., 4) \end{aligned} \quad (8)$$

However, this modelling would lead to the appearance of fault terms in the output equations, or more in general to models nonlinear in the sensor fault inputs.
A different modelling procedure for sensor faults was proposed by Mattone-De Luca (2006) to obtain a dynamic model suitable for the FDI design with a structure affine in all the fault inputs as considered by the NLGA.
Essentially, it consists in introducing a suitable set of $\nu \geq 1$ *mathematical* fault inputs f_k $(k = 1, ..., \nu)$ in place of each *physical* sensor fault F, including also a fault input associated to the time derivative of the fault F. Whenever a physical sensor fault $F \neq 0$ occurs, all the associated mathematical fault inputs f_k will become generically nonzero, although with completely different time behaviors and, in general, without a direct physical interpretation. Hence, it will be sufficient to recognise the occurrence of *any* (one or more) of the associated mathematical fault inputs. For a comprehensive detailed application of this modelling procedure, refer to Mattone-De Luca (2006).