ACTIVE FAULT TOLERANT GYROMOMENT CONTROL OF THE INFORMATION SATELLITES

Yevgeny Somov
Department for Navigation,
Guidance and Control
Samara State Technical University
Russia
e_somov@mail.ru

Sergey Somov
Department for Navigation,
Guidance and Control
Samara State Technical University
Russia
s_somov@mail.ru

Key words
fault tolerance, spacecraft, attitude control system

Abstract
Methods for modeling and detection of anomalous functioning the automatic control systems and practical methods for active analysis of anomalous situations, are presented. We consider methods for consecutive classification of onboard equipment failures, control loop reconfiguration and present results on analysis of the gyromoment attitude control systems for the information satellites.

1 Introduction

The problem of fault-tolerance and dynamic reliability is actual for wide class of automatically controlled mechanical systems in machine building, power engineering, aerospace industry etc. The failure of any instrument in a control loop changes a system structure in principle and can lead to arising a contingency situation. The basic research on fault diagnosis, fault detection and isolation (FDI) at control systems have received much attention, see general research works (Wu *et al.*, 2000; Patton *et al.*, 2000; James and Dubon, 2000; De Persis and Isidori, 2001; Frank *et al.*, 2001; Liao *et al.*, 2002; Bodson, 2002); (Qu *et al.*, 2003; Venkatasubramanian *et al.*, 2003; Maki *et al.*, 2004); (Isermann, 2005*a*; Isermann, 2005*b*; Henry and Zolghadri, 2005; Zhang *et al.*, 2005; Blanke *et al.*, 2006); (Mattone and De Luca, 2006; Shin and Belcastro, 2006; Rodrigues *et al.*, 2007); (Zhang and Jiang, 2008; Narasimhan *et al.*, 2008; Ding, 2008; Cieslak *et al.*, 2008; Rodrigues *et al.*, 2008); (Wang *et al.*, 2009; Yang *et al.*, 2009) and ones for aerospace engineering (Hajiyev and Caliskan, 2003; Bonfe *et al.*, 2006; Bonfe *et al.*, 2007; Ducard and Geering, 2008; Jiang *et al.*, 2008; Henry, 2008; Bertoni *et al.*, 2009; Bertoni *et al.*, 2010; Falcoz *et al.*, 2010; Cieslak *et al.*, 2010). The main trends on the FDI and reconfiguration problems were analyzed (Frank, 1990):

(i) a model-based approach using the parameter estimation and parity methods;

(ii) a knowledged-based approach including the AI-methods, fuzzy logic and neural networks, having in mind a control aerospace practice.

The model-based approach is now recognized as an important and efficient method (Frank, 1994; Frank *et al.*, 2000), the trends in extending that methodology to nonlinear control systems today are practically realized at space engineering by most modern motto (Kurakin, 1999): from *Artificial Intelligence* to *Natural Tricks.*

During the recent 20 years a lot of research works were carried out in Russia on modeling, dynamic research and designing the spacecraft (SC) attitude control systems (ACS) with high fault-tolerance, survivability and autonomy at the expense of functional redundancy (Matrosov *et al.*, 1997; Somov *et al.*, 1999*a*; Somov and Butyrin, 1999; Somov *et al.*, 1999*b*; Somov, 2002; Matrosov and Somov, 2004; Somov *et al.*, 2009). The dynamic requirements to the ACS for the communication SC are:

- continuous precise 3-axis orientation of the SC body at conditions of possible ACS onboard equipment failures, disturbances on optical devices etc., and also at executing a SC orbit correction;
- possibility of the SC body re-orientation for its orbit correction, as well orientation of the solar array panels and each high-gain receiving-transmitting antennas with respect to the SC body;
- robustness to variations of the SC inertial and rigidity characteristics under minimum mass, size and power expenditures,

and for the remote sensing SC there are the needs:

- to orient the line-of-sight to a predetermined part of the Earth surface with the scan in designated direction;
- to compensate a image motion at the onboard optical telescope focal plane.

Increased requirements to such information satellites (lifetime up to 10 years, exactness of spatial rotation manoeuver with the effective damping of the SC flexible construction oscillations, fault-tolerance, reliability as well as to reasonable mass, size and energy characteristics) has motivated intensive development the gyro moment clusters (GMCs) based on excessive number of reaction wheels (RWs) and gyrodines (GDs) — single-gimbal control moment gyros. For the SC close-loop control a principal meter has been represented by a strap-down inertial navigation system (SINS) based on the fine gyros and optoelectronic sensors, which are intended for correction of the SINS. For increasing the SINS accuracy and reliability a certain redundancy on measuring channels is introduced at any inertial gyroscopic assembly.

In the paper, we consider some problems of active FDI and reconfiguration of the ACS' GMC only.

2 The problem statement

Let be given the nonlinear generalized controlled object $\mathcal{O}$ for a time $t \in \mathrm{T}_{t_0} \equiv [t_0, \infty)$

$$D^{+}\mathrm{x}(t) = \mathcal{F}(\mathrm{x}(t), \mathrm{u}, \mathrm{p}(t,\mathrm{x}), \gamma_{\nu}^{f}(t)),\ \mathrm{x}(t_0) = \mathrm{x}_0; \quad (1)$$

$$\begin{aligned} \mathrm{y}(t) &= \psi^{o}(\mathrm{x}(t), \gamma_{\nu}^{f}(t));\\ \mathrm{z}^{o}(t) &= \phi^{o}(\mathrm{x}(t), \mathrm{y}(t), \mathrm{p}(t,\mathrm{x})), \end{aligned} \quad (2)$$

where $\mathrm{x}(t) \in \mathcal{H} \subset \mathbb{R}^{n_\nu}$ is a state vector with an initial condition $\mathrm{x}_0 \in \mathcal{H}_0 \subseteq \mathcal{H}$; $\mathrm{y}(t) \in \mathbb{R}^{r_{\nu}^{s}}$ is an output vector for measurement and diagnosis of object's state, and $\mathrm{z}^{o}(t) \in \mathbb{R}^{r_{\nu}^{f}}$ is a vector for description of its failure conditions; $\mathrm{u} = \{u_j\} \in \mathrm{U} \subset \mathbb{R}^{r_{\nu}^{c}}$ is a control vector, and $\mathrm{p}(t,\mathrm{x}) \in \mathcal{P}$ is the vector-function of disturbances in class $\mathcal{P}$; D^{+} is symbol of a right derivative with respect to time, and $\gamma_{\nu}^{f}(t) \in \mathcal{B}^{m} \equiv \mathcal{B}\times\mathcal{B}\cdots\times\mathcal{B}$ with $\mathcal{B} = \{0,1\}$ is vector of logic variables, which are outputs of a "fault's" asynchronous logic automaton (ALA) $\boldsymbol{\mathcal{A}}^{f}$ with memory

$$\gamma_{\nu}^{f} = \delta^{f}(\kappa_{\nu}^{f}, \mathrm{l}_{\nu}^{f});\ \kappa_{\nu+1}^{f} = \lambda^{f}(\kappa_{\nu}^{f}, \mathrm{l}_{\nu}^{f}),\ \ \kappa_{0}^{f} = \kappa^{f}(0), \quad (3)$$

for its time $\nu \in \mathbb{N}_0 \equiv [0,1,2,\dots)$. Here logic vectors of object's state $\kappa_{\nu}^{f} = \kappa^{f}(\nu)$ and input $\mathrm{l}_{\nu}^{f} = \mathrm{l}^{f}(\nu) = \mathrm{g}^{f}(\mathrm{z}^{o}(t_{\nu}^{f}))$ are used for representation of fault occurrences and damage development depending on the automaton time ν, bound up with the continuous time as $t = t_{\nu}^{f} + (\tau^{f} - t_{\nu}^{f});\ \tau^{f} \in \tau_{\nu}^{f} \equiv [t_{\nu}^{f}, t_{\nu+1}^{f}),\ \nu \in \mathbb{N}_0$. Moreover, $\mathrm{l}_{\nu}^{f}(t) = \mathrm{const}\ \forall t \in \tau_{\nu}^{f}$ and change of the logic vector γ_{ν}^{f} in general case leads to variation of *dimensions* for vectors $\mathrm{x}(t)$ and $\mathrm{y}(t)$ under mappings in time moments $t = t_{\nu}^{f}$:

$$\mathrm{x}(t_{\nu+}^{f}) = \mathcal{P}_{\nu}^{x}(\mathrm{x}(t_{\nu-}^{f}));\quad \mathrm{y}(t_{\nu+}^{f}) = \mathcal{P}_{\nu}^{y}(\mathrm{y}(t_{\nu-}^{f})).$$

Let $\mathrm{T}_u, \mathrm{T}_q \leq \mathrm{T}_u$ and $\mathrm{T}_r \geq \mathrm{T}_u$ are fixed sampling periods of control, state measurement and the control reconfiguration, moreover, multiplicity conditions must be satisfied for these periods, and

$$\begin{gathered} x_k = x(t_k);\ t_k = k\mathrm{T}_u,\ t_s = s\mathrm{T}_q,\ t_\mu = \mu\mathrm{T}_r;\\ x_k^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_{\mathrm{T}_u}(x_s);\quad x_\mu^{\mathrm{f}} = \boldsymbol{\mathcal{F}}_{\mathrm{T}_r}(x_k), \end{gathered}$$

where x_k^{f} is the value of the variable x_s measured with the sampling period T_q, which is filtered out at the time $t = t_k$; $\boldsymbol{\mathcal{F}}_{\mathrm{T}_y}(\cdot)$ is the *digital* filtering operator with the sampling period $\mathrm{T}_y, y = u, r$.

Let be also given subsystem of discrete measurement of the object state and digital filtering:

- for diagnostics of the object $\mathcal{O}$

$$\mathrm{y}_s^{d} = \psi^{d}(\mathrm{y}_s);\ \mathrm{z}_k^{\mathrm{df}} = \mathcal{F}_{\mathrm{T}_u}(\mathrm{y}_s^{d}),\ k, s \in \mathbb{N}_0; \quad (4)$$

- for forming the control and its reconfiguration

$$\begin{aligned} \mathrm{y}_s^{u} &= \psi^{u}(\mathrm{y}_s);\ \ \mathrm{y}_k^{\mathrm{f}} = \mathcal{F}_{\mathrm{T}_u}(\mathrm{y}_s^{u});\\ \mathrm{z}_\mu^{\mathrm{f}} &= \mathcal{F}_{\mathrm{T}_r}(\mathrm{z}_k^{\mathrm{df}}),\quad \mu, k, s \in \mathbb{N}_0. \end{aligned} \quad (5)$$

Principal problems are contained in synthesis of:

- synchronous logic automaton (SLA) $\boldsymbol{\mathcal{A}}^{d}$ with memory for the structural state diagnosis

$$\gamma_k^{d} = \delta^{d}(\kappa_k^{d}, \mathrm{l}_k^{d});\ \kappa_{k+1}^{d} = \lambda^{d}(\kappa_k^{d}, \mathrm{l}_k^{d}),\ \kappa_0^{d} = \kappa^{d}(t_0), \quad (6)$$

with logic vectors of state κ_k^{d}, input $\mathrm{l}_k^{d} = \mathrm{g}^{d}(\mathrm{z}_k^{\mathrm{df}})$ and output γ_k^{d};

- SLA $\boldsymbol{\mathcal{A}}^{r}$, also with memory, for description of damage's block-keeping and reconfiguration

$$\gamma_\mu^{r} = \delta^{r}(\kappa_\mu^{r}, \mathrm{l}_\mu^{r});\ \kappa_{\mu+1}^{r} = \lambda^{r}(\kappa_\mu^{r}, \mathrm{l}_\mu^{r}),\ \kappa_0^{r} = \kappa^{r}(t_0), \quad (7)$$

with logic vectors of state κ_μ^{r}, input $\mathrm{l}_\mu^{r} = \mathrm{g}^{r}(\mathrm{z}_\mu^{\mathrm{f}}, \gamma_\mu^{\mathrm{df}})$, where $\gamma_\mu^{\mathrm{df}} = \mathcal{F}_{\mathrm{T}_r}(\gamma_k^{d})$, and output γ_μ^{r};

- nonlinear control law (NCL) with its reconfigurations due to SLA $\boldsymbol{\mathcal{A}}^{r}$ routine

$$\begin{aligned} &\mathrm{u}_k = \mathcal{U}(\hat{\mathrm{x}}_{e\,k}, \mathrm{y}_{e\,k}^{\mathrm{f}}, \mathrm{y}_{o\,k}, \gamma_\mu^{r});\\ &\hat{\mathrm{x}}_{e\,k+1} = \hat{\mathcal{F}}_e(\hat{\mathrm{x}}_{e\,k}, \mathrm{y}_{e\,k}^{\mathrm{f}}, \mathrm{y}_k^{o}, \mathrm{u}_k, \gamma_k^{d}, \gamma_\mu^{r}),\\ &\hat{\mathrm{x}}_{e\,0} = \hat{\mathrm{x}}_e(t_0);\ \ k, \mu \in \mathbb{N}_0, \end{aligned} \quad (8)$$

where $\mathrm{y}_{e\,k}^{\mathrm{f}} = \mathcal{F}_{\mathrm{T}_u}(\psi_e^{u}(\mathrm{y}_{e\,s}))$; $\mathrm{y}_{e\,s} = \psi_e^{o}(\mathrm{x}_{e\,s}, \gamma_k^{d})$, and $\mathrm{x}_{e\,s} = \mathrm{x}_e(t_s) \in \mathbb{R}^{n_\mu^{e}}$ is the state vector of a simplified discrete object's model

$$\mathrm{x}_{e\,s+1} = \mathcal{F}_e(\mathrm{x}_{e\,s}, \mathrm{u}_k, \gamma_k^{d}, \gamma_\mu^{r}),\ \mathrm{x}_{e\,0} = \mathrm{x}_e(t_0), \quad (9)$$

and $\hat{x}_{e\,k} = \hat{x}_e(t_k) \in \mathbb{R}^{n^e_\mu}$ is its estimation; $n^e_\mu \le n = \max\{n_\nu\}$, and y^o_k is a programmed vector.

Feedback loops (4)–(9) are intended for fault-tolerant control of the object (1)–(3).

To the FDI carry out a three-level logic-digital system is generally applied onboard information spacecraft:

on lower level — *integral local* SLAs $\boldsymbol{\mathcal{A}}^d_d$ with memory for automatic monitoring of relevant device status by measurement of available physical variables (currents, movements, rates etc.)
on middle level — *local loop* SLAs $\boldsymbol{\mathcal{A}}^d_c$ with memory for automatic monitoring of control loop status (roll, yaw and pitch channels, SAP loop etc.);
on higher "system" level — a SLA $\boldsymbol{\mathcal{A}}^d$, also with memory, for the *global* functional diagnostics of main control loop by comparison of outputs for normal and emergency models of the ACS operation.

At two last levels the functional diagnostics is executed with using any reference model – by comparison of output signals by modeled and measured values of the system state coordinates.

Results of the ACS state diagnosis, carried out by specialists of the spacecraft mission control center, indicate high performance of the methods based on applying detailed information about instruments, control algorithms, control laws and set of other options of the SC functioning, and also some invariant relations between system state variables. For high fail-safe operation of the ACS, maximum employment of functional redundancy has been provided by using the SLA to apply all the reverse complete sets of devices or their electric circuits. At synthesis of diagnosis SLAs $\boldsymbol{\mathcal{A}}^d_d, \boldsymbol{\mathcal{A}}^d_c$ and $\boldsymbol{\mathcal{A}}^d$ (6) and also of a damage block-keeping and reconfiguration SLA $\boldsymbol{\mathcal{A}}^r$ (7), the *Natural Tricks* are used. They are based on both well-known physical invariant relations (for example, general momentum invariant for the "SC+GMC" mechanical system) and engineering inventiveness, presented at the perfect logic-inconsistence forms. Mathematical description of failure conditions and these forms are the base for designing all kinds of logic automata (3), (6) and (7) by well-known methods (Glushkov, 1962; Pospelov, 1974; Gavrilov *et al.*, 1977; Glushkov *et al.*, 1987; Ostroff, 1990) and contemporary software.

Further we will consider only following problems: diagnosis by a consecutive classification of failures; fault-tolerant structure of the GMC; provision of the ACS fault-tolerance at the GMC failures.

3 The modified Wald criterion

Implemented at programmed level (into the SC onboard computer) any plan for localization of system's failures is related with necessity to solve a problem on choice of informative parameters. As a rule, in practice number of the system's controlled parameters includes all significant coordinates of its state, which characterize the basic dynamic indexes and determine the quality of functioning.

The onboard algorithm for the ACS diagnosis is based on its reference model work in a background regime, i.e. at the SC mission control in real time. Thus at first, for detection of an anomalous situation on each control period the vector of discrepancies between measured $\mathbf{x} = \{x_i\}$ and modeled $\hat{\mathbf{x}} = \{\hat{x}_i\}$ coordinates is computed: $\mathbf{e} = \{e_i\} = \mathbf{x} - \hat{\mathbf{x}}$. Then, the obtained data are analyzed concerning their conformity to chosen criteria, in the elementary case – their coincidence with limits of possible modification of controlled parameters a priori defined from design performances. The main disadvantage of the plan of automatic diagnosis of a current state (in real time) is difficulty of obtaining (a priori assignment) evaluation of decision making credibility about a failure of a system structural element and its dependence on quantity of control periods.

The sequential probability ratio test (SPRT) is a well-known specific sequential hypothesis test, developed by *Abraham Wald* (1954). The CUSUM (cumulative sum) method was announced a few years after the publication of Wald's SPRT algorithm (Basseville and Nikiforov, 1993; Kramer and Schotman, 1992; Xiao and Phillips, 2002). The CUSUM control chart is also a sequential analysis technique, at times it is used for monitoring change detection into aerospace systems (Basseville *et al.*, 2006).

Applied approach to a system diagnosis and making a decision on a failure consists in the following. Temporal behavior of control parameters $\mathrm{ej}(t)$, j=1,2 is possible to be considered as a random process which performances depend on set of factors. These are measurement errors: inaccuracy of control actions optimization and an object motion modeling as a result of its model simplification; inexactness of knowledge of spacecraft design data, perturbation actions etc. In this case the classification can be conducted not on instantaneous values of discrepancies $\mathrm{ej}(t)$ in the end of each control period T_k, but according to random process presented by discrete sequence of values $\mathrm{ej}_k = \mathrm{ej}(t_k)$, where $k \in \mathbb{N} \equiv [1, 2, 3, \dots)$.

Classification of such random process is implemented by a mathematical apparatus of a consecutive analysis of hypothesis in the form of the modified Wald's SPRT. In this modified Wald criterion the threshold values depend on time (or numbers of the control periods), and also on taken value inaccuracy. Generally the modified SPRT possesses following important properties:

convergence with probability 1, and by alignment of threshold values α and β it is possible to supply with flexible tracing of classification inaccuracy levels;
does not demand independence and equality of probability distributions of classified casual vectors;
supplies minimization of average number of the observations necessary for reaching the given level of reliability of the value, and minimization of av-

erage volume of information stored for classification, that considerably simplifies its implementation in the SC onboard software.

Procedure for analysis is implemented by modified Wald criterion as follows. For each parameters discrepancy value vector of the log – likely-hood ratio

$$\lambda \mathrm{j}_k = -\ln(P(\mathrm{ej}_k/W_1)/P(\mathrm{ej}_k/W_2))$$

is computed where ej_k is a value of vector ej on k-th step of computation, and $P(\mathrm{ej}_k/W_j)$ is a function of the conventional density of probabilities ej_k at the fixed event, consisting of the fact that ej_k belongs to the class $\mathrm{j} \in \{1, 2\}$. Value $\lambda \mathrm{j}_k$ is also random, therefore, for independent allocation of ej_k the summarized log - like-hood criterion L after n observations is equal

$$L = -\ln\{P[(\mathrm{e1}_1, ...\mathrm{e1}_\mathrm{n})/W_1]/P[(\mathrm{e2}_1, ...\mathrm{e2}_\mathrm{n})/W_2]\} = -\sum_{k=1}^{\mathrm{n}} \ln\{P[(\mathrm{e1}_k)/W_1]/P[(\mathrm{e2}_k)/W_2]\} = \sum_{k=1}^{\mathrm{n}} \lambda \mathrm{j}_k,$$

where $k = 1, 2, \ldots \mathrm{n}$ is number of a control step, and W_1 and W_2 are classes of a system state (accordingly "norm" and "not the norm"). The modified SPRT decision rule is presented in the form

$$\begin{aligned} L \leq \alpha_k &\rightarrow \mathrm{ej} \in W_1; \\ \alpha_k < L < \beta_k &\rightarrow \text{(to prolong processing of measurements)}; \\ L \geq \beta_k &\rightarrow \mathrm{ej} \in W_2. \end{aligned}$$

In essence this rule consists in comparison of the L value with *aligned* limits α_k and β_k unlike constant values in classical Wald criterion. Limits α_k and β_k are monotone decreasing functions of current discrete time k. It allows to build the consecutive classifier with a "sliding window" in such a way that it is possible to align the average number of indications processing necessary for final decision as well as the probability of a false discerning.

4 A Gyro Moment Cluster

For information spacecraft it is important to minimize the GMC mass and provide the possibility for reconfiguration of its structure and control algorithms for 2–3 possible faults in any electro-mechanical executive device of the GMC. We have been executed multilateral analysis of schemes for constructing the small-mass GMC based on RWs or GDs with both the gear stepping drives and the moment gearless drives (MGDs) on their precession axes, in combination with unloading loops of accumulated angular momentum (AM) by the reaction trusters and/or magnetic torques.

The following *minimal*-excessible GMC structure is most rational for providing fault-tolerance: *2-SPE* scheme based on four GDs , Fig. 1. Sometimes for the main mode of a spacecraft attitude control only 3 executive devices are used — fourth executive device is in "cold" reserve.

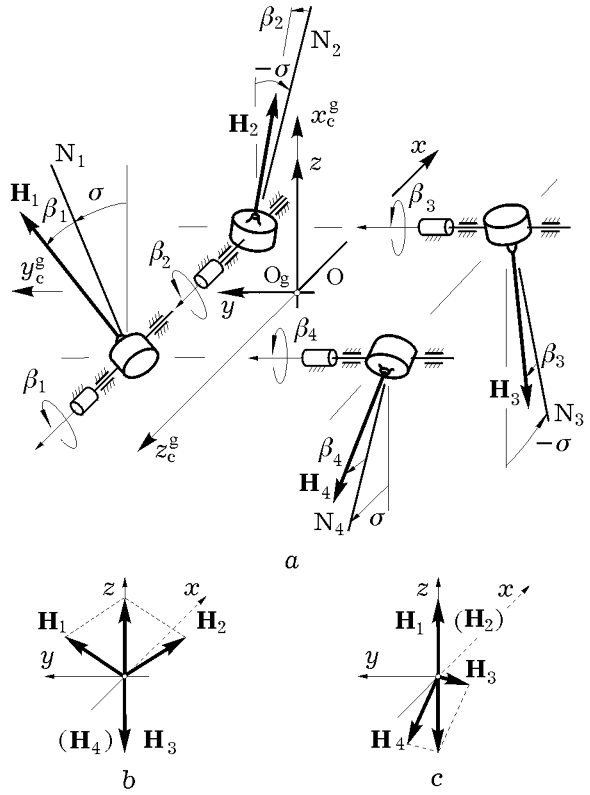

Figure 1. The fault-tolerant *2-SPE* scheme of the GMC

Let point O be the spacecraft mass center and Oxyz is body reference frame (BRF), see Fig. 1a. In the GMC canonical reference frame $\mathrm{O_g} x_c^\mathrm{g} y_c^\mathrm{g} z_c^\mathrm{g}$ the angular momentum projections of the first (GD-1 & GD-2) and the second (GD-3 & GD-4) pairs of gyrodines always are summed up along axis $\mathrm{O_g} x_c^\mathrm{g}$. The gyrodine neutral positions $N_p, p = 1:4$ are directed at angles $\pm\sigma$ with respect to positive (for 1st GD's pair) and to negative (for 2nd GD's pair) directions of axis $\mathrm{O_g} x_c^\mathrm{g}$, see Fig. 1$a$. At the GMC Z -arrangement on the spacecraft body, when axis $\mathrm{O_g} x_c^\mathrm{g}$ is the same as axis Oz of BRF, for $\sigma = \pi/6$ and $\beta_p \in [-\pi/2, \pi/2]$ the following 4 efficient (for 3-axis spacecraft attitude control) GMC configurations are possible on the basis of *only* 3 *active* gyrodines: configurations Z-I, I=1:4 — the GMC without GD-I, represented at the nominal state in Fig. 1b (configurations Z-4 or Z-3) and in Fig. 1c, (configurations Z-2 or Z-1).

So, the gyro cluster scheme in Fig. 1a is *fault-tolerant* under diagnostics of faulted GD and the GMC reconfiguration by *passages* between configurations Z - I under *specific logic conditions*.

5 Mathematical Models

The BRF attitude with respect to the inertial reference frame (IRF) is defined by quaternion $\mathbf{\Lambda} = (\lambda_0, \boldsymbol{\lambda}), \boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3)$. Let $\mathbf{\Lambda}^p(t)$ is a quaternion, and $\boldsymbol{\omega}^p(t) = \{\omega_i^p(t)\}$ and $\dot{\boldsymbol{\omega}}^p(t)$ are angular rate and acceleration vectors of the programmed SC body's motion in the IRF. The error quaternion is $\mathbf{E} = (e_0, \mathbf{e}) = \tilde{\mathbf{\Lambda}}^p(t) \circ \mathbf{\Lambda}$, *Euler* parameters' vector is $\boldsymbol{\mathcal{E}} = \{e_0, \mathbf{e}\}$, and attitude error's matrix is $\mathbf{C}_e \equiv \mathbf{C}(\boldsymbol{\mathcal{E}}) = \mathbf{I}_3 - 2[\mathbf{e}\times]\mathbf{Q}_e^{\mathrm{t}}$, where $\mathbf{Q}_e \equiv \mathbf{Q}(\boldsymbol{\mathcal{E}}) = \mathbf{I}_3 e_0 + [\mathbf{e}\times]$ with $\det(\mathbf{Q}_e) = e_0$. Here symbols $\langle\cdot,\cdot\rangle$, $\times$, $\{\cdot\}$, $[\cdot]$ for vectors and $[\mathbf{a}\times]$, $(\cdot)^{\mathrm{t}}$ for matrices are conventional notations.

The BRF attitude with respect to orbital reference frame (ORF) $\mathrm{O}x^o y^o z^o$ is defined by quaternion $\boldsymbol{\Lambda}^o = \tilde{\boldsymbol{\Lambda}}_o(t)\circ\boldsymbol{\Lambda}$, where $\boldsymbol{\Lambda}_o$ is known quaternion of the ORF attitude with respect to the IRF, by angles of yaw ψ, roll φ and pitch θ for the rotational sequence 132, by matrix $\mathbf{C}_e^o = [\varphi]_2\,[\theta]_3\,[\psi]_1$, where $[\alpha]_i$ is the matrix of elementary rotation, and also by vector of *Euler*'s parameters $\boldsymbol{\mathcal{E}}^o$, moreover the matrix $\mathbf{C}_e^o = \mathbf{C}(\boldsymbol{\mathcal{E}}^o)$. For a fixed position of *flexible* structures on the SC body with some simplifying assumptions, standard notations (Somov, 2000; Somov, 2001) and $t \in \mathrm{T}_{t_0}$ a SC angular motion model appears as follows:

$$\dot{\boldsymbol{\Lambda}} = \boldsymbol{\Lambda}\circ\boldsymbol{\omega}/2;\;\; \mathbf{A}^o\{\dot{\boldsymbol{\omega}}, \ddot{\mathbf{q}}, \ddot{\boldsymbol{\beta}}, \dot{\boldsymbol{\Omega}}\} = \{\mathbf{F}^\omega, \mathbf{F}^q, \mathbf{F}^\beta, \mathbf{F}^h\}, \qquad (10)$$

$$\begin{aligned}
&\mathbf{F}^\omega = \mathbf{M}^{\mathrm{g}} - \boldsymbol{\omega}\times\mathbf{G} + \mathbf{M}_d^o + \mathbf{Q}^o(t,\boldsymbol{\omega},\dot{\mathbf{q}});\;\; \mathbf{M}^{\mathbf{g}} = -\mathbf{A}_{\mathrm{h}}\dot{\boldsymbol{\beta}};\\
&\mathbf{F}^q = \{-a_{jj}^q((\delta^q/\pi)\Omega_j^q\dot{q}_j + (\Omega_j^q)^2 q_j) + \mathrm{Q}_j^q(\boldsymbol{\omega},\dot{q}_j,q_j)\};\\
&\mathbf{F}^\beta = \mathbf{A}_{\mathrm{h}}^{\mathrm{t}}\boldsymbol{\omega} + \mathbf{M}_c^g + \mathbf{M}_d^g + \mathbf{M}_b^g + \mathbf{M}_f^g + \mathbf{Q}^g(\boldsymbol{\beta},\dot{\boldsymbol{\beta}},\boldsymbol{\omega});\\
&\mathbf{F}^h = \mathbf{M}_c^h + \mathbf{M}_d^h + \mathbf{M}_f^h + \mathbf{Q}^h(\cdot);\;\; \mathbf{M}_c^h = \mathbf{M}^h + \mathbf{M}^{ha};
\end{aligned}$$

$$\mathbf{A}^o = \begin{bmatrix} \mathbf{J}^o & \mathbf{D}_q & \mathbf{D}_g & \mathbf{D}_h \\ \mathbf{D}_q^{\mathrm{t}} & \mathbf{A}^q & \mathbf{0} & \mathbf{0} \\ \mathbf{D}_g^{\mathrm{t}} & \mathbf{0} & \mathbf{A}^g & \mathbf{0} \\ \mathbf{D}_h^{\mathrm{t}} & \mathbf{0} & \mathbf{0} & \mathbf{A}^h \end{bmatrix};\quad
\begin{aligned}
&\mathbf{M}_c^g = \mathbf{M}^g + \mathbf{M}^{gd} + \mathbf{M}^{ga};\\
&\mathbf{G} = \mathbf{G}^o + \mathbf{D}_q\dot{\mathbf{q}} + \mathbf{D}_g\dot{\boldsymbol{\beta}};\\
&\mathbf{G}^o = \mathbf{J}^o\,\boldsymbol{\omega} + \boldsymbol{\mathcal{H}}(\boldsymbol{\beta});\\
&\mathbf{A}_{\mathrm{h}} = [\partial\boldsymbol{\mathcal{H}}(\boldsymbol{\beta})\,/\,\partial\boldsymbol{\beta}];
\end{aligned}$$

$$\begin{aligned}
&\mathbf{H} = \{\mathrm{H}_p\};\; \boldsymbol{\Omega} = \{\Omega_p\};\; \boldsymbol{\beta} = \{\beta_p\};\; \boldsymbol{\omega} = \{\omega_i\};\\
&\mathbf{q} = \{q_j\};\; \mathbf{H}_p(\beta_p) = \mathrm{H}_p\mathbf{h}_p;\; \boldsymbol{\mathcal{H}}(\boldsymbol{\beta}) = \textstyle\sum \mathbf{H}_p(\beta_p);
\end{aligned}$$

torques $\mathbf{M}_d^g$ and $\mathbf{M}_d^h$ of a physical damping, and also electro-magnetic damper (EMD) torques $\mathrm{M}_{dp}^g(k_d^g, \dot{\beta}_p)$ with gain k_d^g are nonlinear continuous functions; vectors of the rolling friction torques in bearings on gyro-rotor (GR) axes $\mathbf{M}_f^h$ and on GD's precession axes $\mathbf{M}_f^g$, and also in general case torque's vector $\mathbf{M}_b^g$ describing influence of limiting supports on GD's precession axes, are *nonlinear discontinuous* functions.

The components of GMC control vectors $\mathbf{M}_c^g$ and $\mathbf{M}_c^h$ with regard for the possible *faults* in electric circuits of MGDs as well as the EMDs on the GD precession axes, and also that of the electric drives on GD's rotor axes and arresters (cages) are described by *hybrid functions*

$$\mathrm{M}_p^x = \sum_{l=1}^{2} \gamma_p^{fxl}(\nu)\,\gamma_p^{rxl}(\mu)\,a_p^x\,i_p^{xl}, \qquad (11)$$

where indexes $x = g, gd, ga, h, ha$, coordinates $\gamma_p^{yxl}, y = f, r$ are *logic* variables
$\gamma_p^{yxl} \in \{0,1\};\; \gamma_p^{yx1}\wedge\gamma_p^{yx2} = 0;\; \gamma_p^{yx1}\vee\gamma_p^{yx2} = 1, p = 1:4;$
i_p^{xl} are the control currents and currents at the GD electro-magnetic arresters in main ($l = 1$) and in reserve ($l = 2$) circuits, and a_p^x are constants. The functions $\gamma_p^{fxl}(\nu)$ are outputs of an ALA $\boldsymbol{\mathcal{A}}^f$ with memory for representing fault occurrences and damage development depending on automaton time $\nu \in \mathbb{N}_0$. Functions $\gamma_k^{rxl}(\mu)$ are outputs of a SLA $\boldsymbol{\mathcal{A}}^r$, also with memory, for description of damage's or fault's block-keeping and the reconfiguration sequence depending on automaton time $\mu \in \mathbb{N}_0$. The currents in GD's control circuits $i_p^{gl}(t)$ for $\gamma_p^{rgl} = 1$ and $i_p^{hl}(t)$ for $\gamma_p^{rhl} = 1$ are proportional to GD's digital control voltages

$$u_p^x(t) = \mathrm{Zh}[\mathrm{Sat}(\mathrm{Qntr}(u_{pk}^x, b_u^x), B_u^x), \mathrm{T}_u]$$

where $u_{pk}^x, x = g, h$ are the outputs of NCLs on the GDs precession and GRs axes, and functions $\mathrm{Sat}(x,a)$ and $\mathrm{Qntr}(x,a)$ are general-usage ones, while the holder model with the period T_u is of the type: $y(t) = \mathrm{Zh}[x_k, \mathrm{T}_u] = x_k \quad \forall t \in [t_k, t_{k+1})$. It is clear that equations (10) and (11) correspond to ones for generalized controlled object (1) and (2).

6 Provision of Fault-Tolerance

The *verbal* description of provision of fault-tolerance for a spacecraft ACS with the gyro cluster in Fig. 1*a*, for its initial configuration Z-4, when $\mathrm{H}_p = \mathrm{h}_g, p = 1:3$ and

$$\gamma_p^{fxl} = \gamma_p^{rx1} = 1, x = \mathrm{g}, gd, \mathrm{h};\; \gamma_p^{rx1} = 0, x = ga, ha,$$

with the GD-4 in the stopping state: $\mathrm{H}_4 = \beta_4 = 0$ and

$$\gamma_4^{rxl} = 0, x = \mathrm{g}, gd, h;\; \gamma_4^{rxl} = 1, x = ga, ha,$$

see (11), is as follows.

In the normal mode, the magnetic unloading loop ensures the condition $\mathbf{G}^o \approx \mathbf{0}$ for the AM vector at forming the magnetic control torque vector

$$\mathbf{M}_{mc}^o = \mathbf{L}_m(t)\times\mathbf{B}_\oplus;\; \mathbf{L}_m(t) = \mathbf{Zh}[\mathbf{L}_{mk}, \mathrm{T}_u],$$

where $\mathbf{B}_\oplus$ is a magnetic vector of geomagnetic field,

$$\begin{aligned}
&\mathbf{L}_{mk} = -l_m^o\phi_m^o(\mathrm{R}_0, \lambda_m, b_m, \mathrm{R}_k)\mathbf{e}_{mk};\; \mathbf{e}_{mk} = \mathbf{c}_k/\mathrm{c}_k;\\
&\phi_m^o(a, \lambda_m, b_m, x) = \{(1\,\forall x > \lambda_m b_m)\vee(0\,\forall x < b_m)\};\\
&\mathbf{c}_k = \mathbf{R}_k\times\mathbf{B}_{\oplus k}^{\mathrm{f}};\;\; \mathrm{R}_k = \mathbf{J}^o\,\boldsymbol{\omega}_k^{\mathrm{f}} + \boldsymbol{\mathcal{H}}(\boldsymbol{\beta}_k^{\mathrm{f}});
\end{aligned}$$

l_m^o is the modulus of the magnetic driver dipole torque, $\phi_m^o(a, \lambda_m, b_m, a) = a$, $a \in \{0,1\}$ is a scalar relay hysteresis function with threshold of operation b_m and coefficient of return $0 < \lambda_m < 1$, and $\mathbf{x}_k^{\mathrm{f}} = \mathbf{x}^{\mathrm{f}}(t_k)$ is measured and filtered vector value, $\mathbf{x} = \mathbf{B}_\oplus, \boldsymbol{\omega}, \boldsymbol{\beta}$.

Let the fault of the torque gearless driver current circuit in the GD-3 occurred at any time moment

$$t = t_\nu^f \in [t_{k_*-1}, t_{k_*});\; \nu = 1,\; \gamma_3^{fg1}(1) = 0.$$

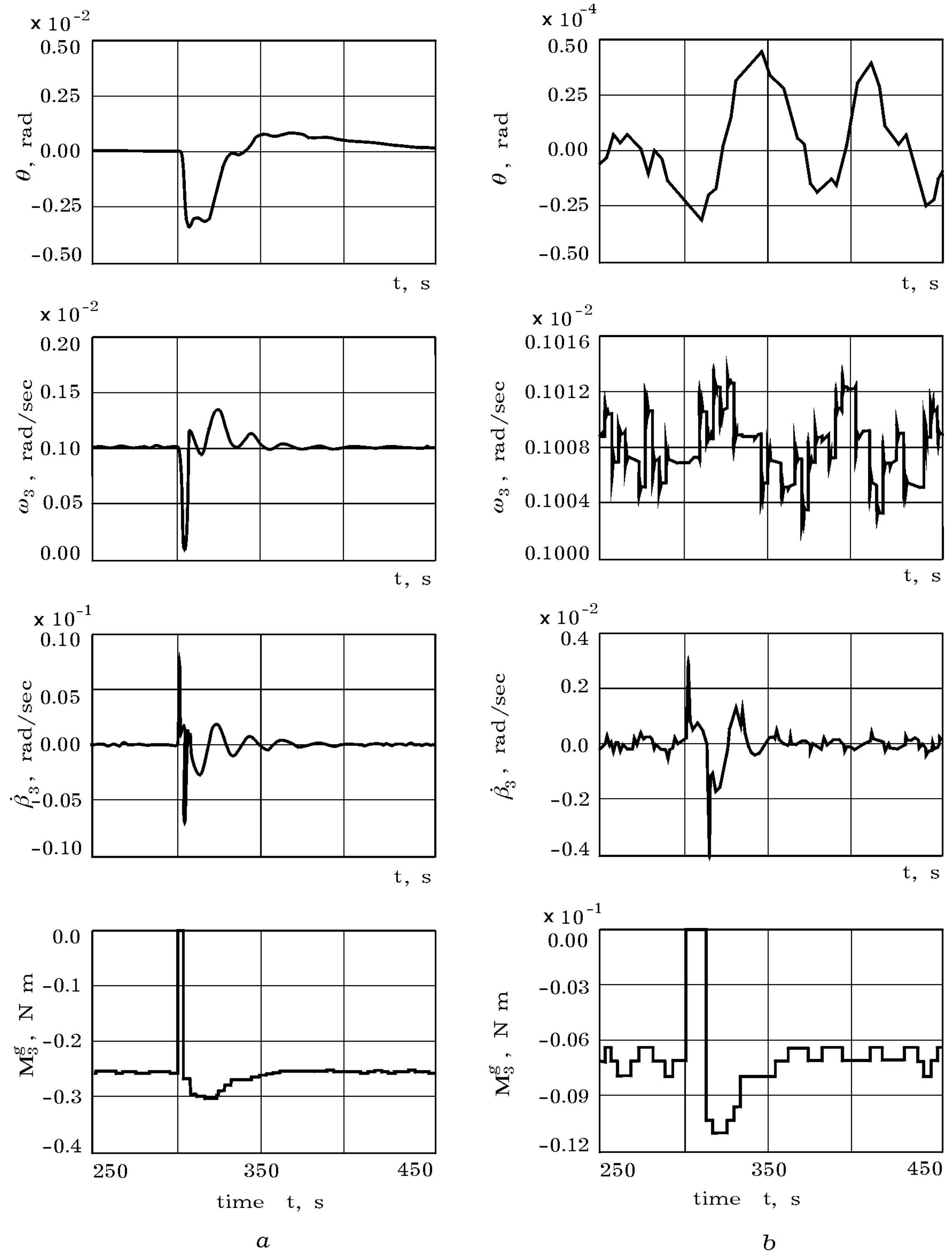

Figure 2. The dynamic processes under fault in the control current circuit of the GD-3 torque driver

Then by the SLAs $\mathcal{A}^d_{\mathrm{GD-3}}$ or $\mathcal{A}^d$, and by the SLA $\mathcal{A}^r$ in the result of circuits switching ($\gamma_3^{rg1} = 0; \gamma_3^{rg2} = 1$) is guaranteed for discrete time $k = k^* = k_*$ or $k = k^* = k_* + 1$, respectively.

Moreover, the intensity of dynamic processes for the attitude control channels is essentially dependent not only on the time interval duration $\delta t^f_{k_*} = t_{k^*} - t^f_\nu$, when there is no control, but also on the potentialities of the gyrodines, which remained operable in the aspect of compensation of disturbing influence of the angular rate vector $\boldsymbol{\omega}_{\mathrm{o}}$ because of the spacecraft orbital motion.

After such *isolation* of the fault, the scheduled reconfiguration of Z-4 ⇒ Z-3 process starts:

$\gamma_4^{rha1} = 0$ and $\gamma_4^{rh1} = 1$ with speeding-up from the rest state of the GD-4 rotor,

at unloading loop the magnetic driver operates with the values $\mathbf{R}_k = \boldsymbol{\mathcal{H}}(\boldsymbol{\beta}_k^{\mathrm{f}})$,

at achieving a small neighborhood for the GMC "park" state $\mathrm{H}_p = \mathrm{h}_g$; $\beta_p = 0$, $p = 1:4$, there takes place *simultaneous*:

the GD-3 caging ($\gamma_3^{rga1} = 1$),

GD-4 uncaging ($\gamma_4^{rga1} = 0$) and switching ($\gamma_4^{rg1} = 1$) on-line the control closed-loop.

On final stage of this process:

the magnetic unloading loop is returned into the nominal mode,

the SLA's $\boldsymbol{\mathcal{A}}^r$ output $\gamma_3^{rh1} = 0$ and the GD-3 rotor is speeding-down to the rest state,

finally, after reaching the condition $\mathrm{H}_3 \approx 0$, the GD-3 is caged ($\gamma_3^{rha1} = 1$).

Thus, the GMC restores its redundancy with respect to control circuits of torque gearless drivers for the on-line gyrodines, and it is prepared for the rapid isolation of any new gyrodine fault and for new reconfiguration.

As discussed above, the intensity of dynamic processes is essentially dependent on the potentialities of the gyrodines which remained operable in the aspect of compensation of the spacecraft orbital motion. This fact is illustrated in Fig. 2, where the sampling period values $\mathrm{T}_q = 0.25\,s$ and $\mathrm{T}_u = 4\,s$. Such processes are presented with respect to the pitch channel of ACS under the SC orbital stabilization for configurations Y-4 (Fig. 2a) and Z-4 (Fig. 2b), when the GD-3 fault takes place under $t = 300.1\,s$.

In the Y-4 case, there are no operable gyrodines needed for creating control torques along the axis $\mathrm{O}z$, so despite the "fast" fault diagnostics by the SLA $\boldsymbol{\mathcal{A}}^d_{\mathrm{GD-3}}$ and switching the torque gearless driver's reserve circuit into on-line the control closed-loop at the time $t = t_{k^*} = 304\,s$, there take place substantial overshoots of attitude errors.

Such overshoots are absent for similar fault in GD-3 within the GMC according to the configuration Z-4 , since GD-1 and GD-2 in this case remain operable for creating control torques along the axis $\mathrm{O}z$, see Fig. 1b. So, even for the "slow" GD-3 fault diagnosis with the aid of SLA $\boldsymbol{\mathcal{A}}^d$ and switching the torque gearless driver's reserve circuit in GD-3 by the time $t = t_{k^*} = 308\,s$, the precision angular stabilization with respect to pitch remains the same.

7 Conclusion

Contemporary methods were presented, which closely connected to designing the precise robust and active fault-tolerant attitude control systems applied at Russian information spacecraft.

With the aid of these methods and software we have been conducted dynamic research and designing such spacecraft ACSs, including those in accordance with international projects (Somov *et al.*, 2002; Somov *et al.*, 2003; Somov *et al.*, 2007; Somov *et al.*, 2013; Somov *et al.*, 2014*a*; Somov *et al.*, 2014*b*; Somov *et al.*, 2014*c*; Somov *et al.*, 2015).

Acknowledgements

The work was supported by the Russian Foundation for Basic Research, project nos. 14-08-01091, 14-08-91373 (international project), and Division on EMMCP of the Russian Academy of Sciences, program no. 13.

References

Basseville, M. and I.V. Nikiforov (1993). *Detection of Abrupt Changes: Theory and Application*. Prentice-Hall.

Basseville, M., M. Goursat and L. Mevel (2006). Multiple CUSUM tests for flutter monitoring. In: *Proceedings of 14th IFAC Symposium on System Identification http://www.ifac-papersonline.net/Detailed/25459.html*.

Bertoni, G., P. Castaldi, N. Bertozzi, M. Bonfe and S. Simani (2009). Guidance and nonlinear active fault tolerant control for general aviation aircraft. In: *Proceedings of the IFAC Workshop "Aerospace Guidance, Navigation and Flight Control Systems", http://lib.physcon.ru/?item=1881*. SSC of RAS. pp. 1–12.

Bertoni, G., P. Castaldi, N. Mimmo and S. Simani (2010). Active fault tolerant control system for a high accuracy planet - image and stellar - pointing satellite. In: *Preprints of 18 IFAC Symposium on Automatic Control in Aerospace*. University of Tokyo, Department of Aeronautics and Astronautics.

Blanke, M., M. Kinnaert, J. Lunze and M. Staroswiecki (2006). *Diagnosis and Fault-Tolerant Control*. Springer.

Bodson, M. (2002). Evaluation of optimization methods for control allocation. *Journal of Guidance, Control, and Dynamics* **25**(4), 703–711.

Bonfe, M., P. Castaldi, W. Geri and S. Simani (2006). Fault detection and isolation for onboard sensors of a general aviation aircraft. *International Journal of Adaptive Control and Signal Processing* **20**(8), 381–408.

Bonfe, M., P. Castaldi, W. Geri and S. Simani (2007). Design and performance evaluation of residual generators for the FDI of an aircraft. *International Journal of Automation and Computing* **4**(2), 156–163.

Cieslak, J., D. Henry, A. Zolghadri and P. Goupil (2008). Development of an active fault tolerant flight control strategy. *Journal of Guidance, Control, and Dynamics* **31**(1), 135–147.

Cieslak, J., D. Henry and A. Zolghadri (2010). A solution for management of fault diagnosis and fault tolerance performances in active FTC schemes. In: *Proccedings of 18 IFAC Symposium on Automatic Control in Aerospace*. University of Tokyo, Department of Aeronautics and Astronautics. pp. 410–415.

De Persis, C. and A. Isidori (2001). A geometric approach to nonlinear fault detection and isolation. *IEEE Transactions on Automatic Control* **45**(6), 853–865.

Ding, S. (2008). *Model-based Fault Diagnosis Techniques: Design Schemes, Algorithms, and Tools*. Springer.

Ducard, G. and H. Geering (2008). Efficient nonlinear actuator fault detection and isolation system for unmanned aerial vehicles. *Journal of Guidance, Control, and Dynamics* **31**(1), 225–237.

Falcoz, A., F. Boquet, M. Dinh, B. Polle, G. Flandin and E. Bornschlegl (2010). Robust fault diagnosis strategies for spacecraft: Application to LISA pathfinder experiment. In: *Preprints of 18 IFAC Symposium on Automatic Control in Aerospace*. University of Tokyo, Department of Aeronautics and Astronautics.

Frank, P.M. (1990). Fault diagnosis in dynamic systems using analytical and knowledge-based redundancy - a survey and some new results. *Automatica* **26**(3), 459–474.

Frank, P.M. (1994). Enhancement of robustness in observer-based fault detection. *International Journal of Control* **59**(5), 955–981.

Frank, P.M., E. Alcorta-Garcia and B. Koppen-Seliger (2001). Modelling for fault detection and isolation versus modelling for control. *Mathematical and Computer Modelling of Dynamical Systems* **7**(1), 1–46.

Frank, P.M., S.X. Ding and T. Marcu (2000). Model-based fault diagnosis in technical processes. *Transactions of the Institute of Measurement and Control* **22**(1), 57–101.

Gavrilov, M.A., V.V. Devyatkov and E.I. Pupyrev (1977). *Logic Design of Discrete Automata*. Nauka. Moscow. In Russian.

Glushkov, V.M. (1962). *Synthesis of Digital Automata*. Nauka, Fizmatlit. Moscow. In Russian.

Glushkov, V.M., Yu.V. Kapitonova and A.T. Mischenko (1987). *Logic Design of Discrete Devices*. Naukova Dumka. Kiyev. In Russian.

Hajiyev, C. and F. Caliskan (2003). *Fault Diagnosis and Reconfiguration in Flight Control Systems*. Kluwer.

Henry, D. (2008). From fault diagnosis to recovery actions for aeronautic and aerospace missions: A model-based point of view. In: *Proceedings of 23rd IAR Workshop on Advanced Control and Diagnosis*. Coventry University. pp. 13–19.

Henry, D. and A. Zolghadri (2005). Design and analysis of robust residual generators for systems under feedback control. *Automatica* **41**(2), 251–264.

Isermann, R. (2005*a*). *Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance*. Springer.

Isermann, R. (2005*b*). Model-based fault detection and diagnosis: status and applications. *Annual review in Control* **29**, 71–85.

James, M. and L. Dubon (2000). An autonomous diagnostic and prognostic monitoring system for NASA's Deep Space Network. In: *2000 IEEE Aerospace Conference Proceedings*. Vol. 2. pp. 403–414.

Jiang, T., K. Khorasani and S. Tafazoli (2008). Parameter estimation-based fault detection, isolation and recovery for nonlinear satellite models. *IEEE Transactions on Control System Technology* **16**(4), 799–808.

Kramer, W. and P. Schotman (1992). Range vs. maximum in the OLS-based version of the CUSUM test. *Economics Letters* (40), 379 – 381.

Kurakin, A.L. (1999). Computer Science: from Artificial Intelligent to Natural Tricks. *Software & Systems Intrnational* (1), 2–5. In Russian.

Liao, F., J. Wang and G. Yang (2002). Reliable robust flight tracking control: An LMI approach. *IEEE Transactions on Control Systems Technology* **10**(1), 76–89.

Maki, M., J. Jiang and K. Hagino (2004). A stability guaranteed active fault-tolerant control system against actuator failures. *International Journal of Robust and Nonlinear Control* **14**(12), 1061–1077.

Matrosov, V.M. and Ye.I. Somov (2004). Nonlinear problems of spacecraft fault tolerant control systems. In: *Nonlinear Problems in Aviation and Aerospace. Vol. 12: Advanced in Dynamics and Control*. pp. 309–331. CRC Press / Taylor & Francis Group.

Matrosov, V.M., M.F. Reshetnev, V.A. Rayevsky and Ye.I. Somov (1997). Nonlinear methods for dynamic synthesis of fault-tolerant spacecraft attitude control systems. *Journal of Computer and Systems Sciences International* **36**(6), 949–959.

Mattone, R. and A. De Luca (2006). Relaxed fault detection and isolation: An application to a nonlinear case study. *Automatica* **42**(1), 109–116.

Narasimhan, S., P. Vachhani and R. Rengaswamy (2008). New nonlinear residual feedback observer for fault diagnosis in nonlinear systems. *Automatica* **44**(8), 2222–2229.

Ostroff, J.S. (1990). *Temporal Logic of Real-Time Systems*. Research Studies Press. New York.

Patton, R., P. Frank and R. Clark (2000). Issues of fault diagnosis for dynamic systems. *International Journal of Robust and Nonlinear Control* **10**(4), 1209–1236.

Pospelov, D.A. (1974). *Logic Methods for Analysis and Synthesis of Schemes*. Energiya. Moscow. In Russian.

Qu, Z., C. M. Ihlefeld, J. Yufang and A. Saengdeejing (2003). Robust fault tolerant self-recovering control of nonlinear uncertain systems. *Automatica* **39**(10), 1763–1771.

Rodrigues, M., D. Theilliol, M. Adam-Medina and D. Sauter (2008). A fault detection and isolation scheme for industrial systems based on multiple operating models. *Control Engineering Practice* **16**(2), 225–239.

Rodrigues, M., D. Theilliol, S. Aberkane and D. Sauter (2007). Fault tolerant control design for polytopic LPV systems. *International Journal of Applied Mathematics and Computer Science* **17**(1), 27–37.

Shin, J.-Y and C.M. Belcastro (2006). Performance analysis on fault tolerant control system. *IEEE Trans-*

actions on Control System Technology **14**(9), 1283–1294.

Somov, Ye.I. (2000). Nonlinear synthesis, optimization and design of the spacecraft gyromoment attitude control systems. In: *Proceedings of 11th IFAC Workshop "Control Applications of Optimization"*. Vol. 1. Elsevier Science. Oxford. pp. 327–332.

Somov, Ye.I. (2001). Robust stabilization of a flexible spacecraft at partial discrete measurement and a delay in forming control. *Journal of Computer and Systems Sciences International* **40**(2), 287–307.

Somov, Ye.I. (2002). Methods and software for research and design of the spacecraft robust fault tolerant control systems. In: *Automatic Control in Aerospace 2001*. Elsevier Science. Oxford. pp. 28–40.

Somov, Ye.I., A.G. Kozlov, V.A. Rayevsky, G.P. Anshakov and Yu.G. Antonov (2002). Nonlinear dynamic research of the spacecraft robust fault tolerant control systems. In: *Proceedings of 15th World IFAC Congress*. Barcelona. pp. 1–6.

Somov, Ye.I. and S.A. Butyrin (1999). Software tool DYNAMICS in simulation of fault-tolerant spacecraft attitude control systems. *Gyroscopy and Navigation* (2(25)), 92–107.

Somov, Ye.I., S.A. Butyrin and S.Ye. Somov (2013). Economical attitude and orbit control of information satellites by electromechanical, magnetic and plasma drivers. In: *Proceedings 6th IEEE/AIAA International Conference on Recent Advances in Space Technologies*. Istanbul. pp. 1009–1014.

Somov, Ye.I., S.A. Butyrin, G.P. Anshakov, Yu.G. Antonov, V.P. Makarov, A.I. Manturov and Yu.M. Ustalov (2003). Dynamics and flight support of a vehicle IKAR control system at orbiting Globalstar satellites. *Control Engineering Practice* **11**(5), 585–597.

Somov, Ye.I., S.A. Butyrin, G.P. Titov and Ye.N. Yakimov (2007). Robust gyromoment spacecraft attitude control with precise pointing a flexible antenna. In: *Proceedings of 17th IFAC Symposium on Automatic Control in Aerospace*. Toulouse. pp. 1–6.

Somov, Ye.I., S.A. Butyrin, S.Ye. Somov and V.V. Salmin (2014*a*). Economical digital and pulse-width control of land-survey mini-satellites. In: *Proceedings of 6th IEEE International Congress on Ultra Modern Telecommunications and Control Systems*. Saint Petersburg. pp. 316–323.

Somov, Ye.I., S.A. Butyrin, V.P. Makarov and S.Ye. Somov (2014*b*). Ensuring the survivability of the attitude control system for a land-survey mini-satellite at critical situations. In: *Proceeding of 21 Saint Petersburg international conference on integrated navigation systems*. Saint Petersburg. pp. 28–31.

Somov, Ye.I., V.A. Rayevsky and G.P. Titov (1999*a*). Fault-tolerant precision attitude control of communication and navigation spacecraft. *Space Technology* **19**(3&4), 165–172.

Somov, Ye.I., V.A. Rayevsky, G.P. Titov, Ye.N. Yakimov and M.G. Mathylenko (2015). Fault tolerant gyromoment control of information spacecraft with fine pointing of large-scale antennas. In: *Proceeding of IFAC Workshop on Advanced Control and Navigation of Autonomous Aerospace Vechicles*. Seville. pp. 210–215.

Somov, Ye.I., V.M. Matrosov, M.F. Reshetnev, A.G. Kozlov, V.A. Rayevsky and G.P. Titov (1999*b*). Fault-tolerant attitude control systems of the communication and navigation spacecraft. In: *Proceedings of the 14th IFAC Symposium on Automatic Control in Aerospace*. pp. 128–133. Elsevier Science. Oxford.

Somov, Ye.I., V.M. Sukhanov and C.M. Hacizade (2014*c*). Guidance and precise motion control of free-flying robots and land-survey mini-satellites. In: *Proceedings of 13th IEEE International Conference on Control, Automation, Robotics and Vision*. Singapore. pp. 1092–1097.

Somov, Ye.I., V.P. Makarov and V.M. Matrosov (2009). Diagnosis and reconfiguration of the spacecraft fault tolerant gyromoment control systems. In: *Proceedings of the IFAC Workshop "Aerospace Guidance, Navigation and Flight Control Systems", http://lib.physcon.ru/?item=1877*. SSC of RAS. Samara. pp. 1–6.

Venkatasubramanian, V., R. Rengaswamy, K. Yin and S.N. Kavuri (2003). A review of process fault detection and diagnosis. part 1: Quantitative model-based methods. *Computer and Chemical Engineering* **27**(3), 293–311.

Wang, D., W. Wang and P. Shi (2009). Robust fault detection for switched linear systems with state delays. *IEEE Transaction on Automatic Control* **39**(3), 800–805.

Wu, N.E., Y. Zhang and K. Zhou (2000). Detection, estimation, and accommodation of loss of control effectiveness. *International Journal of Adaptive Control and Signal Processing* **14**(7), 775–795.

Xiao, Zh. and P.C.B. Phillips (2002). A CUSUM test for cointegration using regression residuals. *Journal of Econometrics* (108), 43–61.

Yang, H., B. Jiang and M. Staroswiecki (2009). Supervisory fault tolerant control for a class of uncertain nonlinear systems. *Automatica* **45**(10), 2319–2324.

Zhang, Y. and J. Jiang (2008). Bibliographical review on reconfigurable fault-tolerant control systems. *Annual reviews in Control* **32**, 229–252.

Zhang, Y.M., J. Jiang, Z. Yang and D.M.A. Hussain (2005). Managing performance degradation in fault tolerant control systems. In: *Proceedings of 16th IFAC World Congress*. Prague. pp. 1872–1872.