FAULT TOLERANT DIGITAL ATTITUDE CONTROL AND ANIMATION OF A MINI-SATELLITE MOTION

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Abstract
Well-known minimal-redundant scheme General Electric have opportunity to control of a satellite orientation at a fault of any one reaction wheel. In the paper we consider the problem of the survivability guarantee for the attitude control system at a critical situation – a fault of any two reaction wheels. We present the results on efficiency of the suggested method for a land-survey mini-satellite at such situation and results on computer animation of the satellite spatial motion.

1 Introduction

Electromechanical drivers in the form of a reaction wheel (RW) cluster traditionally are applied in the attitude control systems (ACSs) for land-survey mini-satellites, moreover, the cluster unloading from accumulated angular momentum (AM) episodically is fulfilled by the magnetic driver. Well-known minimal-redundant scheme General Electric have opportunity to control of a spacecraft (SC) orientation at a fault of any one reaction wheel (RW).

In the paper we consider the problem of the survivability guarantee for the attitude control system at a critical situation – a fault of any two reaction wheels. We have elaborated a mathematical model of the system and carried out the analytical synthesis of digital algorithms for control of the cluster based on four, any three, and also any two efficient reaction wheels when the magnetic driver (MD) is applied. Taking into account all possible faults of the RWs we have carried out the verification of the developed digital control algorithms for a land-survey mini-satellite on the Sun-synchronous orbit with an altitude of 600 km. We have established that at a fault of any two RWs the developed digital control algorithms ensure fulfillment of a trace scanning observation but with some decrease in the rotation maneuver rate, and, therefore, the space land-survey productivity.

We present some numerical results on efficiency of the suggested method for the fault-tolerant digital attitude control of a land-survey mini-satellite and on animation of its spatial motion.

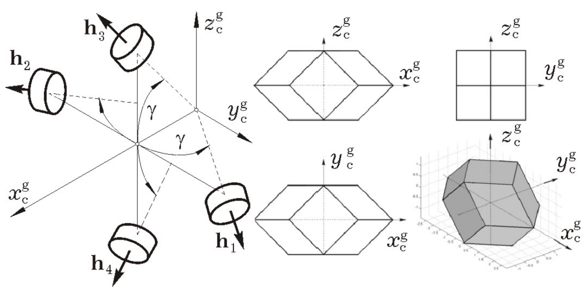

Figure 1. The fault-tolerant scheme *General Electric*

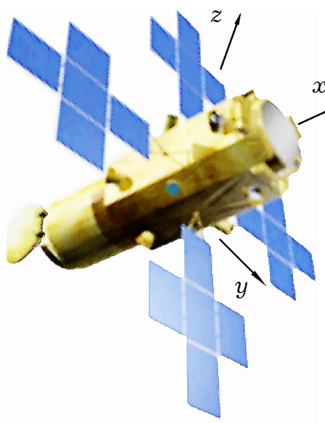

Figure 2. The SC body reference frame

2 The ACS model and the problem statement

Scheme of *General Electric* (*GE*) cluster by four RWs is presented in Fig. 1, the cluster device reference frame (DRF) $\mathrm{O}_c^g x_c^g y_c^g z_c^g$ is fixed into body reference frame (BRF) $\mathrm{O}xyz$, Fig. 2.

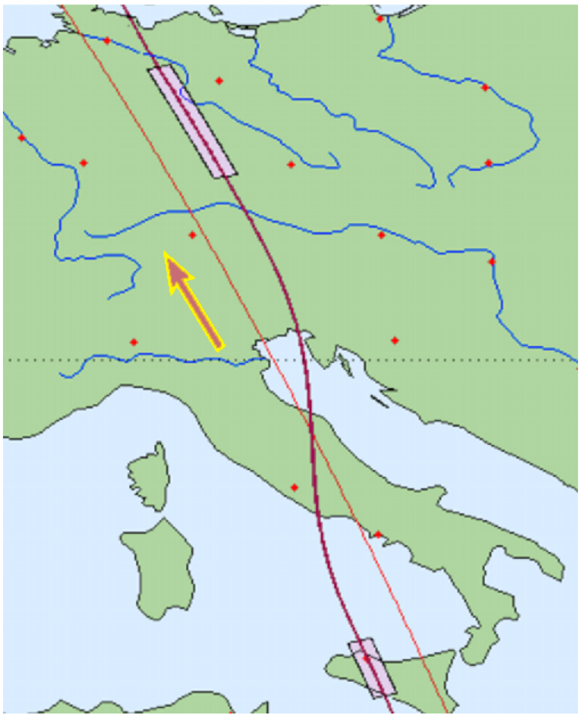

Figure 3. The scanning and maneuvering courses on a map

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 $\det(\mathbf{Q}_e) = e_0$. The error angular rate vector is $\delta\boldsymbol{\omega} \equiv \{\delta\omega_i\} = \boldsymbol{\omega} - \mathbf{C}_e\boldsymbol{\omega}^p$. 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 $\mathbf{\Lambda}^o = \tilde{\mathbf{\Lambda}}_o(t)\circ\mathbf{\Lambda}$, where $\mathbf{\Lambda}_o$ is known quaternion of the ORF orientation with respect to the IRF, by angles of yaw ϕ_1, roll ϕ_2 and pitch ϕ_3 which are applied at a forming of the simple turn matrices $[\phi_i]_i$, $i = 1,2,3 \equiv 1 \div 3 \equiv x, y, z$ in sequence 132, and also by matrix $\mathbf{C}^o = [[\phi_2]_2[\phi_3]_3[\phi_1]_1$. Simplest model of spacecraft angular motion has the form

$$\dot{\mathbf{\Lambda}} = \mathbf{\Lambda}\circ\boldsymbol{\omega}/2;\ \ \mathbf{A}^{\mathrm{o}}\{\dot{\boldsymbol{\omega}}, \ddot{\mathbf{q}}, \dot{\mathbf{\Omega}}\} = \{\mathbf{F}^{\omega}, \mathbf{F}^{q}, \mathbf{F}^{r}\}; \qquad (1)$$

$$\mathbf{F}^{\omega} = -\boldsymbol{\omega}\times\mathbf{G} + \mathbf{M}^{\mathrm{o}};\ \ \mathbf{F}^{q} = \{-a_j^q(\tfrac{\delta^q}{\pi}\Omega_j^q\dot{q}_j + (\Omega_j^q)^2 q_j)\};$$

$$\begin{array}{l} \mathbf{F}^{r} = \mathbf{M} - \mathbf{M}^{\mathrm{f}}; \\ \mathbf{G} = \mathbf{G}^o + \mathbf{D}_q\dot{\mathbf{q}};; \\ \mathbf{G}^o = \mathbf{J}\,\boldsymbol{\omega} + \boldsymbol{\mathcal{H}}; \end{array} \quad \mathbf{A}^{\mathrm{o}} = \begin{bmatrix} \mathbf{J} & \mathbf{D}_q & \mathbf{D}_r \\ \mathbf{D}_q^{\mathrm{t}} & \mathbf{A}^q & \mathbf{0} \\ \mathbf{D}_r^{\mathrm{t}} & \mathbf{0} & \mathbf{A}^r \end{bmatrix};$$

$$\boldsymbol{\omega} = \{\omega_i\}; \mathbf{q} = \{q_j\};\ \ \mathbf{\Omega} = \{\Omega_p\}, p = 1 \div 4;$$

$$\mathbf{M} = \{m_p\};\ \ \mathbf{M}^{\mathrm{f}} = \{m_p^{\mathrm{f}}\};\ \ \mathbf{M}^{\mathrm{o}} = \mathbf{M}^{\mathrm{m}} + \mathbf{M}^{d};$$

$$\boldsymbol{\mathcal{H}} = \{\mathsf{H}_i\} = \mathbf{A}\ \mathbf{h};\ \ \ \mathbf{h} = J_r\mathbf{\Omega} = \{J_r\Omega_p\} \equiv \{\mathsf{h}_p\};$$

$$\mathbf{A} = [\pi/4]_1^{\mathrm{t}}\,\mathbf{A}^{\mathrm{d}};\ \mathbf{A}^q = \lceil a_j^q \rfloor;\ \mathbf{D}_r = J_r\mathbf{A};\ \mathbf{A}^r = J_r\mathbf{I}_4;$$

$$\mathbf{A}^{\mathrm{d}} = \begin{bmatrix} C_\gamma & C_\gamma & C_\gamma & C_\gamma \\ S_\gamma & -S_\gamma & 0 & 0 \\ 0 & 0 & S_\gamma & -S_\gamma \end{bmatrix},$$

where notations $S_\gamma \equiv \sin\gamma$, $C_\gamma \equiv \cos\gamma$ are applied. Here columns $\boldsymbol{\mathcal{H}}$ and $\mathbf{h}$ are combined from the cluster AM vector and own RW AMs; vector of the MD torque $\mathbf{M}^{\mathrm{m}} = -\mathbf{L}\times\mathbf{B} = \{m_i^{\mathrm{m}}\} = \mathbf{e}^{\mathrm{m}}m^{\mathrm{m}}$, where vector of electromagnetic moment $\mathbf{L} = \{l_i\}$ with bounded components $|l_i| \le \mathrm{l}^{\mathrm{m}}$ and vector of the Earth magnetic induction $\mathbf{B} = \mathbf{b}\mathrm{B}$ with unit $\mathbf{b}$ are defined into the BRF; columns $\mathbf{M}$ and $\mathbf{M}^{\mathrm{f}}$ present the control torques and the dry friction torques on axes of RWs' rotation, and vector $\mathbf{M}^{\mathrm{d}}$ presents the external disturbance torques. For each RW the control torque and own AM are limited as per a module, e.g.

$$|m_p(t)| \le \mathrm{m}^{\mathrm{m}};\quad |\mathsf{h}_p(t)| \le \mathrm{h}^{\mathrm{m}},\ p = 1 \div 4, \qquad (2)$$

where parameters m^{m} and h^{m} are *specified* positive constants. These constrains are converted into *fixed* convex domains of allowable variation for the cluster AM vector $\boldsymbol{\mathcal{H}}$ and control torque vector $\mathbf{M}$.

The dry friction torques are presented by relations $m_p^{\mathrm{f}} = \mathrm{Sat}(\Omega_p/\Omega^{\mathrm{o}}), m_{\mathrm{f}}$ and the digital control torques are described as follows

$$m_{pk}(t) = \mathrm{Zh}[\mathrm{Sat}(\mathrm{Qntr}(m_{pk}, m_r^{\mathrm{o}}), m_r^{\mathrm{m}}), T_u], \qquad (3)$$

where functions $\mathrm{Sat}(x,a)$ and $\mathrm{Qntr}(x,a)$ are general-usage ones, while the holder with period T_u is of the type: $y(t) = \mathrm{Zh}[x_k, T_u] = x_k\ \forall t \in [t_k, t_{k+1})$, $t_{k+1} = t_k + T_u$, $k \in \mathbb{N}_0 \equiv [0,1,2,\dots)$. For *GE* scheme the domain envelope of AM variation is presented in Fig. 1 at the *normalized* to h^{m} form

$$\boldsymbol{h} \equiv \boldsymbol{\mathcal{H}}/\mathrm{h}^{\mathrm{m}} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_1 + x_2 \\ S_\gamma(h_1 - h_2) \\ S_\gamma(h_3 - h_4) \end{bmatrix}, \qquad (4)$$

$x_1 = C_\gamma(h_1 + h_2)$, $x_2 = C_\gamma(h_3 + h_4)$, $h_p = \mathsf{h}_p/\mathrm{h}^{\mathrm{m}}$.

Discrete measurements of the SC attitude and angular rate vector are fulfilled with a period T_q, and measurement of the RW AM values and a forming of the RW digital control – with a period $T_u \ge T_q$. The problem consists in the synthesis of digital algorithms for control of the cluster based on four, any three, and also any two efficient reaction wheels when the MD is applied.

3 Distribution of a control vector

For cluster based on four RWs the principal problem is contained in distribution of its angular momentum $\mathcal{H}$ and control torque $\mathbf{M}^{\mathrm{r}} = -\dot{\mathcal{H}}$ vectors into the BRF between redundant numbers of the reaction wheels. At

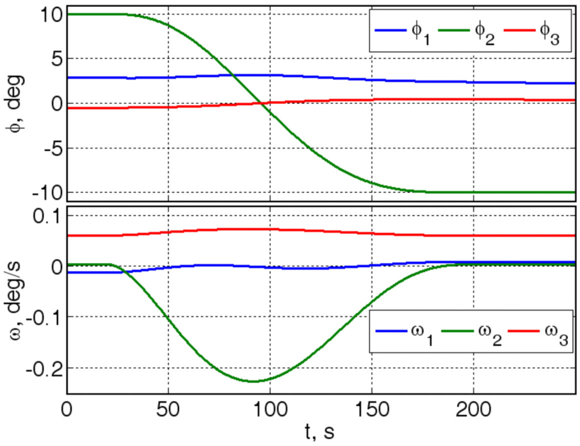

Figure 4. The programmed spacecraft angular motion

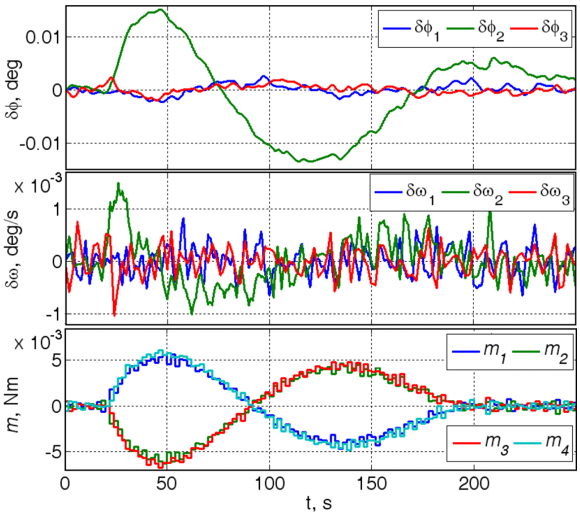

Figure 5. Errors of the SC motion and torques of four RWs

some simplifications the problem consists in simultaneous solving of two equations

$$\begin{aligned} \mathbf{Ah} &= \boldsymbol{\mathcal{H}} \qquad \forall\, \boldsymbol{\mathcal{H}} \in \mathbb{R}^3,\ \mathbf{h} \in \mathbb{R}^4; \\ \mathbf{AM} &= -\mathbf{M}^{\mathrm{r}} = \dot{\boldsymbol{\mathcal{H}}} \quad \forall\, \mathbf{M}^{\mathrm{r}} \in \mathbb{R}^3,\ \mathbf{M} \in \mathbb{R}^4. \end{aligned} \tag{5}$$

Standard application of the pseudoinverse matrix $\mathbf{A}^{\#} = \mathbf{A}^{\mathrm{t}}(\mathbf{A}\mathbf{A}^{\mathrm{t}})^{-1}$ not ensures the unique solution of the equations (5) (Albert, 1972). For solving the equations the author's approach is applied. The approach is based on using a scalar function of the cluster tuning (Somov, 2002; Matrosov and Somov, 2004; Somov *et al.*, 2013*b*; Somov *et al.*, 2013*c*; Somov *et al.*, 2014*a*) and allows to distribute synonymously vectors $\boldsymbol{\mathcal{H}}$ and $\mathbf{M}^{\mathrm{r}} = -\dot{\boldsymbol{\mathcal{H}}}$ between four RWs by explicit analytical relations. For simplification let us consider the variant when the cluster DRF is coaxial to the BRF ($\mathbf{A} = \mathbf{A}^d$) and introduce the normed cluster AM vector $\boldsymbol{h} \equiv \{x, y, z\} = \mathbf{Ah}$, *where* $\mathbf{h} = \{h_p\}$. Distribution of the vector between the RWs is carried out by law

$$f_\rho(\boldsymbol{h}) = \tilde{x}_1 - \tilde{x}_2 + \rho(\tilde{x}_1\tilde{x}_2 - 1) = 0,$$

$\tilde{x}_1 = x_1/q_y$; $\tilde{x}_2 = x_2/q_z$, $q_s = (4C_\gamma^2 - s^2)^{1/2}$, $s = y, z$, taking into account the analytical relations:

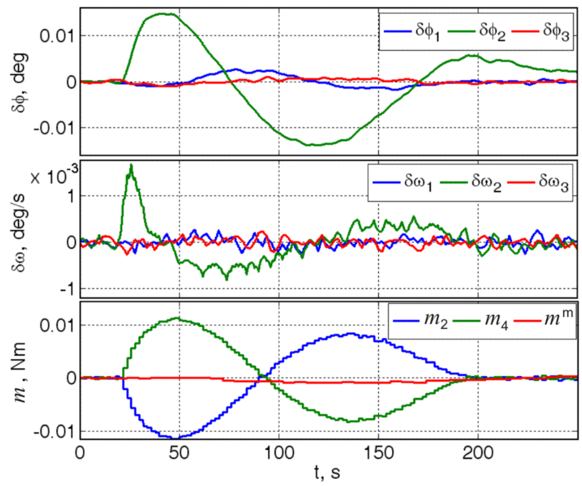

Figure 6. Errors of the SC motion and control torques

(i) $q \equiv q_y + q_z$; $0 < \rho < 1$; $\Delta \equiv (q/\rho)(1 - (1 - 4\rho\,[(q_y - q_z)(x/2) + \rho(q_y q_z - (x/2)^2)]/q^2)^{1/2})$;
$x_1 = (x + \Delta)/2,\ x_2 = (x - \Delta)/2$;
(ii) the AM distribution between the RWs in each pair;
(iii) distribution of vector $\mathbf{M}^{\mathrm{r}}$ by explicit formula

$$\mathbf{M} = (\{\mathbf{A}, \mathbf{a}_f\})^{-1}\{-\mathbf{M}^{\mathrm{r}}, -\mathrm{h}^{\mathrm{m}}\mathrm{Sat}(\phi_\rho, \mu_\rho f_\rho(\boldsymbol{h}))\} \tag{6}$$

with positive parameters ϕ_ρ, μ_ρ and line $\mathbf{a}_f = [a_{fp}]$ components as follows

$$a_{f1,2} = \frac{2C_\gamma}{q_y^3}[2C_\gamma^2 \pm S_\gamma^2 h_2(h_1 - h_2)][1 + \rho\frac{C_\gamma(h_3+h_4)}{q_z}];$$

$$a_{f3,4} = \frac{2C_\gamma}{q_z^3}[2C_\gamma^2 \mp S_\gamma^2 h_4(h_3 - h_4)][1 + \rho\frac{C_\gamma(h_1+h_2)}{q_y}].$$

At a fault of any one RW into the cluster considered matrix $\mathbf{A}$ becomes square and non-singular, but the variation domain of the cluster AM vector is decreased essentially.

At a fault of any two RWs the matrix $\mathbf{A}$ has two columns only, and the AM vector variation domain is presented by a rhomb into corresponding plane. Let us introduce the indexes $p, q \in (1,2,3,4)$, $p \neq q$, which are corresponding to the efficient RWs, calculate the units $\mathbf{s} \equiv \mathbf{a}_p + \mathbf{a}_q$, $\mathbf{e}_{pq} = \mathbf{s}/||\mathbf{s}||$ and unit $\mathbf{e}^{\mathrm{m}} = \mathbf{b} \times \mathbf{e}_{pq}$ of the MD control torque, and also let the matrix $\mathbf{A}_{pq}^{\mathrm{m}} = [\mathbf{a}_p\ \mathbf{a}_q\ \ -\mathbf{e}^{\mathrm{m}}]$ is formed. The problem is reduced to determination of the control torque's modules for the RWs (m_p, m_q) and the MD (m^{m}) from equation $\mathbf{A}_{pq}^{\mathrm{m}}\{m_p, m_q, m^{\mathrm{m}}\} = -\mathbf{M}^{\mathrm{r}}$.

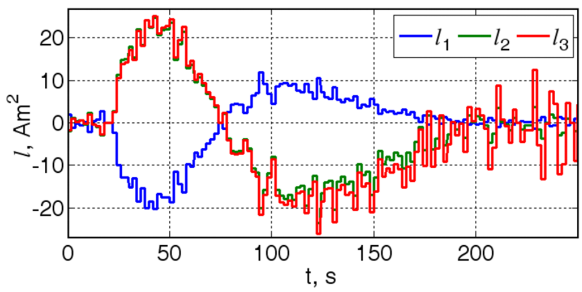

Figure 7. Components of the MD electromagnetic moment

The equation is solving by inversion of the square matrix $\mathbf{A}^{\mathrm{m}}_{pq}$. Note that the matrix is changing by both the SC angular and orbital motion because of essential variation of the Earth magnetic induction vector $\mathbf{B}$ into the BRF. Here real value is important for measure $\kappa \equiv \langle \mathbf{e}^{\mathrm{m}}, \mathbf{b} \rangle$ by the nearness of units $\mathbf{e}^{\mathrm{m}}$ and $\mathbf{b}$. The MD application is efficiently for parts of the orbital motion when condition $|\kappa| \leq \cos(\pi/3) = 1/2$ is carried out. Vector of the MD required electromagnetic moment $\mathbf{L}$ is calculated by explicit formula $\mathbf{L} = (m^{\mathrm{m}}/\mathrm{B})(\mathbf{b} \times \mathbf{e}^{\mathrm{m}})$.

4 Algorithms of digital control

Let us be given the SC program angular motion $\Lambda^p(t), \omega^p(t), \dot{\omega}^p(t)$ corresponded to courses of the trace scanning observations and rotational maneuvers between them. At notation $\mathbf{x}_s \equiv \mathbf{x}(t_s)$, $s \in \mathbb{N}_0$, quaternion Λ^{m}_s of the SC attitude measured into the IRF for the time moments t_s with period T_q is presented in the form $\Lambda^{\mathrm{m}}_s = \Lambda_s \circ \Lambda^n_s$ where Λ^n_s is quaternion of the measuring noise. The mismatch vector $\boldsymbol{\epsilon}_s = -2\mathrm{e}_{0s}\mathbf{e}_s$ corresponds to the error quaternion $\mathbf{E}_s = (\mathrm{e}_{0s}, \mathbf{e}_s) = \tilde{\Lambda}^p_s \circ \Lambda^{\mathrm{m}}_s$ and *Euler* parameters' vector $\boldsymbol{\mathcal{E}}_s$. Next the recurrent discrete filtering is fulfilling for values of vectors $\boldsymbol{\mathcal{E}}_s$, $\boldsymbol{\epsilon}_s$ and $\boldsymbol{\omega}_s$ with a period T_q and values of vectors $\boldsymbol{\mathcal{E}}^{\mathrm{f}}_k$, ϵ^{f}_k and $\boldsymbol{\omega}^{\mathrm{f}}_k$, $k \in \mathbb{N}_0$ are forming for their application in the digital control law with a period T_u multiple to a period T_q. Vector of the required digital control torque is applied in the form

$$\mathbf{M}^{\mathrm{r}}_k = \mathbf{J}(\mathbf{C}_{ek}\dot{\omega}^p_k + \mathbf{C}_{ek}\boldsymbol{\omega}^p_k \times \boldsymbol{\omega}^{\mathrm{f}}_k + \tilde{\mathbf{m}}_k), \qquad (7)$$

where matrix $\mathbf{C}_{ek} = \mathbf{C}(\boldsymbol{\mathcal{E}}^{\mathrm{f}}_k)$ and for $d_u = 2/T_u$, $a = (d_u\tau_1 - 1)/(d_u\tau_1 + 1)$; $b = (d_u\tau_2 - 1)/(d_u\tau_2 + 1)$; $p = (1-b)/(1-a)$; $c = p(b-a)$ the stabilizing control vector $\tilde{\mathbf{m}}_k$ is forming by the algorithm

$$\mathbf{g}_{k+1} = b\,\mathbf{g}_k + c\,\boldsymbol{\epsilon}^{\mathrm{f}}_k; \quad \tilde{\mathbf{m}}_k = k\,(\mathbf{g}_k + p\,\boldsymbol{\epsilon}^{\mathrm{f}}_k). \qquad (8)$$

The RW digital control torques $m_{pk}(t)$ (3) are forming by relations (7) with (8) and (6) with measured values h_{pk} of the RW angular momentums.

5 Results of the computer verification

Developed algorithms for the RW cluster (and in case of need, for the MD) digital control were verified taking into account all possible faults of the reaction wheels. We have considered a land-survey mini-satellite on the Sun-synchronous circular orbit with the flight altitude of 600 km.

On a map in Fig. 3 we have been reflected two courses of the scanning trace observation with rotational maneuver between them by roll on the angle 20 deg. The SC program motion into the ORF is presented in Fig. 4 for the angles $\phi_i(t) = \phi^p_i(t)$ and components $\omega_i = \omega^p_i(t)$ of the program angular rate vector.

Fig. 5 represents the errors on angles $\delta\phi_i(t)$ and on angular rates $\delta\omega_i(t)$ at realization of indicated program for the SC angular motion when the orientation measurements are fulfilling with the error standard deviation $\sigma = 3$ arc sec by period $T_q = 0.25$ s, moreover after a discrete filtering of the mismatch vector $\boldsymbol{\epsilon}_s$ the RW cluster digital control vector $\mathbf{M}_k(t) = \{m_{pk}(t)\}$ is forming by period $T_u = 2$ s. The control torques $m_p(t)$ for all reaction wheels are also represented in the figure. Analogous characteristics on errors and on the control torques are presented in Fig. 6 at realization the same SC program motion by second and fourth reaction wheels only together with the magnetic driver. Components $l_i(t)$ of the MD electromagnetic moment vector are represented in Fig. 7, moreover the components were bounded on module by value $\mathrm{l}^{\mathrm{m}} = 25$ A m^2. One can easy to see a nearness of the accuracy characteristics by the mini-satellite attitude stabilization for the compared variants.

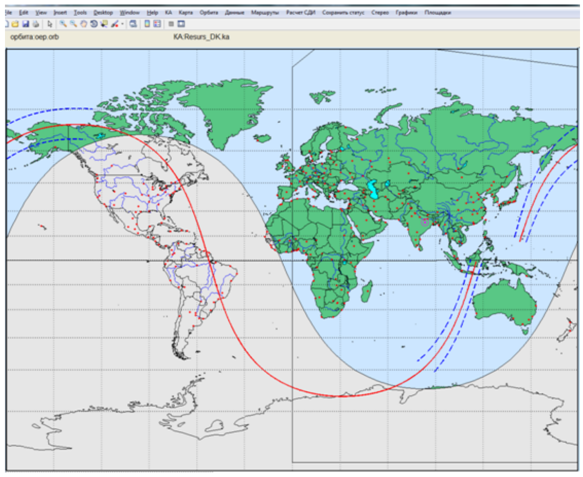

Figure 8. Main dialog window of the *SURIUS-S* software system

6 *SIRIUS-S* software environment

The software system *SIRIUS-S* (Somov *et al.*, 2013*a*) is intended for designing of guidance, navigation and attitude control systems of the information satellites. The software system contains a dialog monitor, subsystems for modeling, synthesis and analysis, and also technological subsystems for animation of the SC spatial motion and documentation of obtained results. As a result, a design engineer obtains a functional representation of the control system for a designed, for an example land-survey spacecraft with respect to periodicity, productivity and activity of observations, a local spatial resolution, the accuracy of guidance and stabilization of the onboard telescope, taking into account disturbances, restrictions and other factors. The main window of the *SIRIUS-S* dialog environment is presented in Fig. 8. Here one can see the top menu, geographic map, the flight trace, bounds of the SC survey zone, and also bounds of light and shade. The dialog is realized by leaked out windows.

Models of the Earth, external environment, the SC structure, its progressive and attitude motions both at the objective- , stereo- and area-observations and at the

Figure 9. Two animation frames of land-survey mini-satellite motion

rotational maneuvers are implemented into *SIRIUS-S* system. These models are based on *Matlab* and allow accurate computing all kinematic parameters of the SC spatial motion and formation of files for the visualization subsystem. Documented results are represented by scenes of surveying routes in the form of charts, tables, and plots of variations in the SC body coordinates and motions of the executive devices as a function of time, the values of the observation quality characteristics and optimality criterions.

The modeling subsystem contains the following components: the Earth model and electronic maps with the data bases for objects on terrestrial surface; the SC structure model – geometrical and inertial characteristics, parameters of telescope, the measuring and executing devices et al.; ballistic model of the SC mass center motion; models of the SC attitude control – schemes for the Earth surface surveying, computing the routes and rotational maneuvers with general boundary conditions et al.

The synthesis and analysis subsystem is intended to carry out the following functions:

- reflection of the Earth surface maps with the observed objects;
- reflection of orbit, the SC flight trace and a survey zone, the SC attitude motions at fulfilling the target tasks, verification of their realization at the bounded resources of executing devices;
- synthesis of algorithms for the SC attitude determination, guidance and attitude control laws;
- analysis of stability and transient processes into the SC attitude control system at fulfilling given programmed attitude motion;
- computing of an image motion velocity into given points of the CCD matrix and the attainable local spatial resolution;
- analysis of variants for the SC control systems on different criterions.

The SC spatial motion animation subsystem is a technological software tool. The subsystem was elaborated into *Delphi 7* environment with the use of *OpenGL* graphic library. The 3D-model of the SC structure has realization into *Blender* environment (Mullen, 2011), reflection of its elements is carried out by the *OpenGL* (Angel, 2002) means taking into account the Sun lighting. Here standard procedure is carried out by "sticking on" a texture of the Earth map onto the Earth surface, the observed objects are marked and their geographic coordinates are calculated into reference frame of the surveying camera.

The SC structure is reflecting together with the trace point, a point of the line-of-sight intersection with the Earth surface and the CCD line projection onto the surface, if a scanning observation is fulfilled at the time moment. The software has possibility to change an image scale and perspective of a scene survey at observation of the Earth rotating surface.

7 Computer animation of a mini-satellite motion

In-flight support is provided for the ACS of a land-survey mini-satellite. The support is implemented in terrestrial control flight centre (CFC) in order to ensure the ACS reliability and survivability at faults of onboard devices.

For the CFC operators an important problem consists in comprehension of a satellite actual orientation with respect to directions on objects of external space environment at emergency situations in the ACS operation when its resources have no possibilities to carry out automatic diagnosis and restoration of the ACS capacity by reconfiguration of the control loop.

The computer animation tool allows to eliminate this problem: the spacecraft spatial motions are simultaneously reflected onto two next monitors – on the first one, based on actual telemetric information and on the second one, based on the results of computer simulation of the satellite attitude motion with the same values of parameters, initial conditions and variants of possible faults in the satellite control loop.

Approximation of a satellite attitude motion by the vector splines makes it possible to simplify computer animation of spacecraft spatial motion. Elaborated visualization software (Somov *et al.*, 2013*a*; Somov *et al.*, 2014*b*; Somova, 2014; Somova, 2015) has applied such approximation and provides for efficient change of the image scale, time rate of animation, and also perspective for a scene observation. Animation of a land-survey mini-satellite motion is presented in Fig. 9 by two frames.

8 Conclusion

We have presented shortly new approach for ensuring the survivability and fault-tolerance of digital ACS for a land-survey mini-satellite at different faults of the reaction wheels into the cluster by the *General Electric* scheme, developed algorithms of digital control and results obtained on their computer verification.

We have established that at a fault of any two reaction wheels, the RW & MD digital control ensure fulfillment of a trace scanning observation but no for any part of the mini-satellite orbit and naturally with some decrease in the accessible rate of its rotation maneuvers.

We also have presented shortly the computer animation tool which allows to support the spacecraft flight by ensuring the ACS reliability and survivability at faults of onboard devices.

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