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IFAC-PapersOnLine 48-9 (2015) 222–227

Attitude Guidance, Navigation and Control of Land-survey Mini-satellites ⋆

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Abstract: Contemporary land-survey mini-satellites have general mass up to 500 kg and are placed onto the orbit altitudes up to 800 km. For such spacecraft some principle problems on optimal attitude guidance, navigation and robust control are considered and elaborated methods are presented for their solving.

Keywords: mini-satellite, guidance, navigation, attitude control

1. INTRODUCTION

Problems of the spatial attitude guidance, navigation and control are actual for contemporary small information spacecraft (SC). The land-survey mini-satellites today are applied for optoelectronic observation (Fig. 1) at the orbit altitudes from 600 up to 800 km and their structure consists the large-scale solar array panels (SAPs) for an energy supplying of the electromechanical and magnetic drivers. Studied the SC attitude determination and control system (ADCS) has a strap-down inertial navigation system (SINS) witch contains an inertial measurement unit (IMU) based on gyro sensors and an astronomical system (AS) based on star trackers (STs) with wide field-of-view, the that are fixed to the SC body. Standard the SINS scheme is applied to determine the SC attitude: the IMU is principle measuring unit, and the AC signals are applied for its position correction, in-flight calibration and alignment. The ADCS has following executive equipment: electromechanical driver (ED) – cluster of three gyrodines (GDs) with digital control and magnetic driver (MD) based on three current carrying coils whereby their magnetic torque vector interacts with the geomagnetic field vector. Pulse-width control is applied for forming of the MD external torque vector, but this vector is generated via the cross-product of its magnetic moment vector and the Earth magnetic field vector, therefore direction of the torque vector is not arbitrary. The ED is principle executive unit for the SC attitude control, its unloading from an accumulated angular momentum (AM) vector is fulfilled by activity of the MD, moreover its pulse-width control algorithms must to take into account bounded opportunity on a torque direction.

The SC attitude guidance laws are presented by a sequence of time intervals for a target application – the courses and the rotational maneuvers (RMs) with variable direction of angular rate vector. In the paper we consider the optimization problems on attitude guidance of such SC, their attitude determination with the SINS on-orbit calibration, discrete filtering of measured signals, economical control with respect to the onboard energy resources and present elaborated methods for their solving. We present some results on dynamic synthesis of the SC attitude robust digital control by the gyro moment cluster (GMC) of three GDs with its unloading by the MD pulse-width control.

Fig. 1. The land-survey mini-satellite

2. MATHEMATICAL MODELS

We introduce the unit's bases and reference frames:

- the base $\mathbf{I}_{\odot}$ and the inertial sun-ecliptic reference frame (ISRF) $\mathrm{O}_{\odot}\mathrm{X}_s^{\mathrm{I}}\mathrm{Y}_s^{\mathrm{I}}\mathrm{Z}_s^{\mathrm{I}}$;
- the base $\mathbf{I}_{\oplus}$ and the inertial reference frame (IRF) $\mathrm{O}_{\oplus}\mathrm{X}_e^{\mathrm{I}}\mathrm{Y}_e^{\mathrm{I}}\mathrm{Z}_e^{\mathrm{I}}$ of the present time which origin is replaced in the ISRF ecliptic plane by angular rate $\omega_{\odot}$;
- the base $\mathbf{E}_e$ and the geodesic Greenwich reference frame (GRF) $\mathrm{O}_{\oplus}\mathrm{X}^e\mathrm{Y}^e\mathrm{Z}^e$ which is rotated with respect to the IRF by angular rate vector $\boldsymbol{\omega}_{\oplus}$;

⋆ This work was supported by RFBR (Russian Foundation for Basic Research, Grant 14-08-91373), TUBITAK (The Scientific and Technological Research Council of Turkey, Grant 113E595) and Division on EMMCP, Russian Academy of Sciences (Program no. 13)

10.1016/j.ifacol.2015.08.087

- the base $\mathbf{E}_{\mathrm{e}}^{\mathrm{m}}$ and the Earth magnetic reference frame (MRF) $\mathrm{O}_{\oplus}\mathrm{X}_{\mathrm{e}}^{\mathrm{m}}\mathrm{Y}_{\mathrm{e}}^{\mathrm{m}}\mathrm{Z}_{\mathrm{e}}^{\mathrm{m}}$ which is fixed into the GRF;
- the base $\mathbf{B}$ and the SC body reference frame (BRF) $\mathrm{O}xyz$ with origin in the SC mass center O;
- the base $\boldsymbol{\mathcal{S}}$ and telescope (sensor) reference frame (SRF) S $x^{\mathrm{s}}y^{\mathrm{s}}z^{\mathrm{s}}$ with origin in center S of optical projection;
- the base $\mathbf{V}$ and the visual reference frame (VRF) $\mathrm{O}_{\mathrm{v}}x^{\mathrm{v}}y^{\mathrm{v}}z^{\mathrm{v}}$ with origin in center O_{v} of the CCD array;
- the image field reference frame (FRF) $\boldsymbol{\mathcal{F}}$ $(\mathrm{O}_i x^i y^i z^i)$ with origin in center O_i of the focal plane $y^i\mathrm{O}_i z^i$;
- the IMU virtual base $\mathbf{G}$ which is computed by processing the measuring information from the sensors;
- the AS virtual base $\mathbf{A}$ that is calculated by processing an accessible measuring information from the STs.

The BRF attitude with respect to the IRF $\mathbf{I}_{\oplus}$ is defined by quaternion $\mathbf{\Lambda} = (\lambda_0, \boldsymbol{\lambda}), \boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3)$, and with respect to the ORF – by column $\boldsymbol{\phi} = \{\phi_i, i = 1 \div 3\}$ of angles $\phi_1 = \psi, \phi_2 = \varphi, \phi_3 = \theta$ in the sequence $13'2''$.

The quaternion $\mathbf{\Lambda}$ is an one-one related to the modified Rodrigues parameters vector (hereafter, simply the Rodrigues vector) $\boldsymbol{\sigma} = \mathrm{tg}(\theta/4)\,\mathbf{e}$ by the explicit analytic relations $\boldsymbol{\sigma} = \boldsymbol{\lambda}/(1+\lambda_0)$; $\lambda_0 = (1-\sigma^2)/(1+\sigma^2)$; $\boldsymbol{\lambda} = 2\boldsymbol{\sigma}/(1+\sigma^2)$. To the direct and backward quaternion kinematic equations there are corresponded the direct and backward equations

$$\dot{\boldsymbol{\sigma}} = \tfrac{1}{4}\{\mathbf{I}_3(1-\sigma^2) + 2[\boldsymbol{\sigma}\times] + 2\boldsymbol{\sigma}\boldsymbol{\sigma}^{\mathrm{t}}\}\boldsymbol{\omega};$$
$$\boldsymbol{\omega} = \tfrac{4}{(1+\sigma^2)^2}\{\mathbf{I}_3(1-\sigma^2) - 2[\boldsymbol{\sigma}\times] + 2\boldsymbol{\sigma}\boldsymbol{\sigma}^{\mathrm{t}}\}\dot{\boldsymbol{\sigma}}.$$

Let vectors $\boldsymbol{\omega}(t)$ and $\mathbf{v}(t)$ are standard notations of the SC body angular rate and its mass center velocity with respect to the IRF, respectively, and vector $\mathbf{v}_{\delta}(t)$ presents the $\mathbf{v}(t)$ deviation with respect to nominal SC orbital motion at the Earth gravity field. Applied further symbols $\langle\cdot,\cdot\rangle$, $\times$, $\{\cdot\} \equiv \mathrm{col}(\cdot)$, $[\cdot] \equiv \mathrm{line}(\cdot)$ for vectors and $[\mathbf{a}\times]$, $\lceil\cdot\rfloor = \mathrm{diag}\{\cdot\}$, $(\cdot)^{\mathrm{t}}$ for matrixes are conventional notations. Let us $\mathbf{\Lambda}^p(t)$ is a quaternion and $\boldsymbol{\omega}^p(t) = \{\omega_i^p(t)\}$ is an angular rate vector of 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 $\det(\mathbf{Q}_e) = e_0$. Moreover the angular rate error vector is $\delta\boldsymbol{\omega} = \boldsymbol{\omega} - \mathbf{C}_e\boldsymbol{\omega}^p(t)$.

At applied the GMC scheme *Star* (Fig. 2) for a fixed position of *flexible* structures on the SC body with some simplifying assumptions the angular motion model of flexible SC is as follows

$$\dot{\mathbf{\Lambda}} = \mathbf{\Lambda}\circ\boldsymbol{\omega}/2; \quad \mathbf{A}^o\{\dot{\boldsymbol{\omega}}, \ddot{\mathbf{q}}, \ddot{\boldsymbol{\beta}}\} = \{\mathbf{F}^{\omega}, \mathbf{F}^q, \mathbf{F}^{\beta}\}, \tag{1}$$
$$\mathbf{F}^{\omega} = -\mathbf{A}_{\mathrm{H}}\dot{\boldsymbol{\beta}} - \boldsymbol{\omega}\times\mathbf{G} + \mathbf{M}^{\mathrm{m}} + \mathbf{M}^{\mathrm{e}} + \mathbf{M}^d;$$
$$\mathbf{F}^q = \{-a_j^q(\tfrac{\delta^q}{\pi}\Omega_j^q\dot{q}_j + (\Omega_j^q)^2 q_j)\};$$
$$\mathbf{F}^{\beta} = \mathbf{A}_{\mathrm{H}}^{\mathrm{t}}\boldsymbol{\omega} + \mathbf{M}_b^g + \mathbf{M}_f^g + \mathbf{M}^g;$$
$$\mathbf{A}^o = \begin{bmatrix} \mathbf{J} & \mathbf{D}_q & \mathbf{D}_g \\ \mathbf{D}_q^{\mathrm{t}} & \mathbf{A}^q & \mathbf{0} \\ \mathbf{D}_g^{\mathrm{t}} & \mathbf{0} & \mathbf{A}^g \end{bmatrix}; \quad \begin{array}{l} \mathbf{G} = \mathbf{G}^o + \mathbf{D}_q\dot{\mathbf{q}} + \mathbf{D}_g\dot{\boldsymbol{\beta}}; \\ \mathbf{G}^o = \mathbf{J}\,\boldsymbol{\omega} + \boldsymbol{\mathcal{H}}(\boldsymbol{\beta}); \\ \mathbf{A}_{\mathrm{H}}(\boldsymbol{\beta}) = \partial\boldsymbol{\mathcal{H}}(\boldsymbol{\beta})/\partial\boldsymbol{\beta}; \end{array}$$
$$\boldsymbol{\omega} = \{\omega_i\}; \ \mathbf{q} = \{q_j\}; \ \boldsymbol{\beta} = \{\beta_i\}; \ \boldsymbol{\mathcal{H}}(\boldsymbol{\beta}) = \textstyle\sum \mathbf{H}_i(\beta_i);$$
$$\boldsymbol{\mathcal{H}} = H\begin{bmatrix} -S_1 - aC_2 + aC_3 \\ aC_1 - S_2 - aC_3 \\ -aC_1 + aC_2 - S_3 \end{bmatrix}; \ \mathbf{D}_g = J_g a\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix};$$

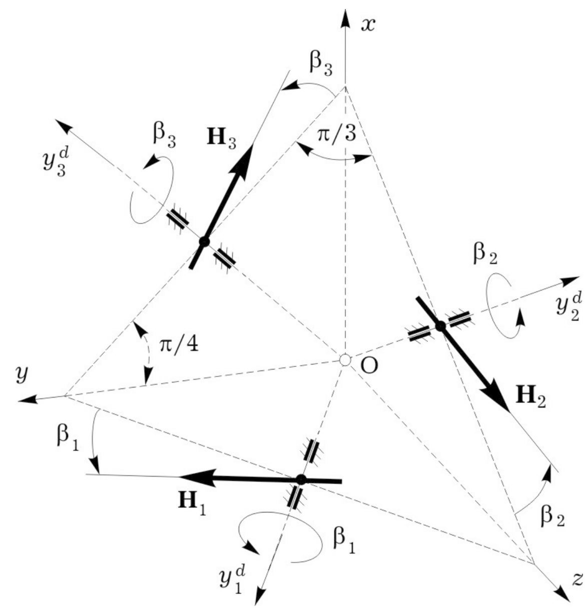

Fig. 2. The GMC scheme *Star* by 3 gyrodines

$$\mathbf{A}_{\mathrm{H}}(\boldsymbol{\beta}) = H\begin{bmatrix} -C_1 & aS_2 & -aS_3 \\ -aS_1 & -C_2 & aS_3 \\ aS_1 & -aS_2 & -C_3 \end{bmatrix}; \quad \begin{array}{r} S_i = \sin\beta_i; \\ C_i = \cos\beta_i; \\ a = 1/\sqrt{2}; \end{array}$$
$$\mathbf{A}^q = \lceil a_j^q \rfloor; \ \mathbf{A}^g = J_g\mathbf{I}_3; \ \mathbf{M}_b^g = \{m_{bi}^g\}; \ \mathbf{M}_f^g = \{m_{fi}^g\};$$
$$m_{bi}^g = \begin{cases} 0 & |\dot{\beta}_i| \le \dot{\beta}_g^{\mathrm{o}}; \\ b_i^g(\dot{\beta}_i - \dot{\beta}_g^{\mathrm{o}}\mathrm{Sign}\dot{\beta}_i) & |\dot{\beta}_i| > \dot{\beta}_g^{\mathrm{o}}; \end{cases} \quad m_{fi}^g = \mathrm{Sat}(m_g^{\mathrm{f}}, \tfrac{\dot{\beta}_i}{\dot{\beta}_g^{\mathrm{o}}});$$
$$\mathbf{M}^g = \{m_i^g(t)\}; \ m_i^g(t) = \mathrm{Zh}[\mathrm{Sat}(\mathrm{Qntr}(m_{ik}^g, m_g^{\mathrm{o}}), m_g^{\mathrm{m}}), T_u],$$

where functions $\mathrm{Sat}(x,a)$ and $\mathrm{Qntr}(x,a)$ are general-usage ones, while the holder with the period T_u is of the type: $y(t) = \mathrm{Zh}[x_k, T_u] = x_k \ \forall t \in [t_k, t_{k+1})$, $t_{k+1} = t_k + T_u$, $k \in \mathbb{N}_0 \equiv [0,1,2,\dots)$. Here vector $\mathbf{M}^{\mathrm{g}} \equiv -\mathbf{A}_{\mathrm{H}}\dot{\boldsymbol{\beta}}$ is the GMC torque for the SC body attitude control, vector $\mathbf{M}^{\mathrm{m}}$ is the MD torque and vector $\mathbf{M}^d$ presents the external disturbance torques – gravitational, by forces of solar pressure et al.

The MD torque vector $\mathbf{M}^{\mathrm{m}}$ is forming by the relation $\mathbf{M}^{\mathrm{m}}(t) = \{m_i^{\mathrm{m}}(t)\} = -\mathbf{L}_n(t)\times\mathbf{B}(t)$, where $\mathbf{B}(t)$ is vector of the Earth magnetic induction and the MD electromagnetic moment vector $\mathbf{L}_n(t) = \{l_i(t)\}$ with $l_i(t) \in [-\mathrm{l}^{\mathrm{m}}, 0, \mathrm{l}^{\mathrm{m}}]$ $\forall t \in [t_n, t_{n+1}]$, $t_{n+1} = t_n + T_u^{\mathrm{m}}$, $n \in \mathbb{N}_0$ presents a pulse-width control by the period $T_u^{\mathrm{m}} >> T_u$.

The problems on the SINS algorithms are connected with using the quasi-coordinate increment vector

$$\boldsymbol{\phi}_s \equiv \mathbf{i}_s^{\omega} = \int_{t_s}^{t_{s+1}} \boldsymbol{\omega}(\tau)d\tau \equiv \mathbf{Int}(t_s, T_q, \boldsymbol{\omega}(t))$$

obtained by the IMU over the period T_q, a filtering of noises, identification and compensation of errors on a mutual angular position of the IMU and the AS reference frames, variation of a measure scale factor and the IMU bias with respect to the vector $\boldsymbol{\omega}$. Let us measured values of a vector $\mathbf{i}_{m\,s}^{g\omega}$, $s \in \mathbb{N}_0$ be obtained from the IMU with period $T_q << T_{\mathrm{o}}$, and from the AS – measured values of quaternion $\mathbf{\Lambda}_{m\,k}$ with period T_{o}:

$$\boldsymbol{\omega}_m^g(t) = (1+m)\mathbf{S}^{\Delta}\boldsymbol{\omega}(t) + \mathbf{b}^g; \ \mathbf{\Lambda}_{m\,k} = \mathbf{\Lambda}_k \circ \mathbf{\Lambda}_k^n; \tag{2}$$
$$\mathbf{i}_{m\,s}^{g\omega} = \mathbf{Int}(t_s, T_q, \boldsymbol{\omega}_m^g(t)) + \boldsymbol{\delta}_s^n.$$