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An Adaptive Algorithm for Estimating the Mutual Arrangement of Small Satellites in a Group

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Abstract: The subject of the present research is a group of autonomously controlled small satellites, the mutual location of which must be maintained during the flight. The first step in solving this problem is to develop a measurement system and the most accurate estimation of the relative distances. It is believed that the group is accompanied by one or two relatively large satellites, the size and power capacity of which allows one to determine their exact coordinates using GPS or GLONASS systems. Objects that make up the group only have radio equipment for exchanging relatively simple navigation messages and a micromechanical inertial unit.

1. INTRODUCTION[1]

In the early stages of the development of practical astronautics there was a clear tendency to increase the weight of spacecraft (SC) launched into the orbit. Large multi-function devices, equipped with facilities to perform the complex tasks and missions were quite expensive and difficult to manufacture.

Progress in space science and technology has led to the emergence of a different trend. Advances in microelectronics, improvements of onboard communications and control systems, and the appearance of micromechanical sensor elements stimulated the appearance of small SC weighing up to 1 kg or less. This approach can significantly (by 1-2 orders of magnitude) reduce expenses on development and operation of space objects, and shorten their design and manufacture time.

The use of small satellites opens a variety of opportunities for development and improvement of forms and methods of space exploration: the delivery of small satellites into orbit as additional payload, together with a larger unit, the launch of a whole group of small satellites of the same or different class with a single carrier (Lebedev D.B., Tkachenko A.I. 2006 Nebylov, A., 2013).

Introducing group flights (Formation Flying) in addition to reducing the project cost leads to qualitatively new possibilities in terms of expanding research programs of surveying the earth's surface, the investigation of physical fields, mapping the magnetosphere, monitoring the ocean surface, tracking the traffic flows and migration of wild animal herds, short-term forecasting of earthquakes and so on.

There is a number of problems with the implementation of such projects, including the dynamics of the constituent satellites, measuring the relative positions and maintaining a particular spatial configuration. Strict restrictions on the mass, volume and power consumption typical for nanosatellites, greatly complicate the solution of the navigation and orientation problems for such devices. Addition of even a miniature and relatively simple navigation equipment on a nanosatellite will inevitably have to replace scientific and technological equipment.

A promising approach to solving the problem of Formation Flying consists of placing one or two larger leading spacecraft with navigation equipment that allows autonomously and accurately determine their location (Bazarov Y., 1997, Tkachenko A.I.. 2005)). This equipment may contain, for example, hardware of global satellite positioning system of the type GPS or GLONASS. A direct placement of global positioning system on navigation nanosatellites may gives a problem of considerable energy consumption of the equipment.

For these reasons, it is suggested to use measurements of the relative distances to determine the configuration of the group of nanosatellites. Objects that make up the group have only radios to exchange relatively simple navigation messages and micromechanical inertial modules that include 3 accelerometers and 3 angular velocity meters. When measuring relative distances compensation of systematic components of error may occur, but because of the simplicity of the equipment, the noise component remains sufficiently high (Kuzovkov N.G., Salychev O.S. 1982, Lebedev D.B., Tkachenko A.I. 2006)). Moreover, the noise intensity of the

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measurement errors presents an uncertain and time-varying quantity, thereby reducing the effectiveness of simple filtering techniques.

Known adaptive algorithms are quite complex and do not always give the desired effect. Here we consider the adaptive algorithm for filtering relative distance measurements and data from the inertial module, taking into account the requirements of minimum load on the onboard computing unit of the nanosatellites. The algorithm is based on the analysis of the spectral properties of the residual (dynamically updated sequence) signal. Results of modeling demonstrate the effectiveness of the algorithm.

2. STATEMENT OF THE PROBLEM IN A GENERAL FORM

We assume the general form of equation of autonomous navigation to be the following:

$$\dot{x}(t) = Fx(t) + Gw(t), \tag{1}$$

where x(t) is the state vector, F and G are matrices of the system state and input signals, respectively, w(t) is a vector of Gaussian white noise with characteristics $E[w(t)] = 0,\ E[w(t), w(\tau)] = Q\delta(t-\tau)$.

Equation for the corrective system can be written as

$$z(t) = h(x,t) + \xi(t), \tag{2}$$

where ξ(t) is the vector of Gaussian noise measurements with zero mean and the correlation function $E[\xi(t), \xi(\tau)] = R\delta(t-\tau)$, $h(x,t)$ is the vector of the function that reflects the transformation of the estimated vector x (t) in the reference frame of the corrected system.

Measuring system, which is described by equations (1) and (2) corresponds to the equation of the generalized Kalman filter

$$\dot{\hat{x}}(t) = F\hat{x}(t) + K[z(t) - h(\hat{x},t)],$$

$$K = P\left(\frac{\partial h}{\partial \hat{x}}\right)^T R^{-1}, \tag{3}$$

$$\dot{P} = FP + PF^T + GQG^T - P\left(\frac{\partial h}{\partial \hat{x}}\right)^T R^{-1}\left(\frac{\partial h}{\partial \hat{x}}\right)P.$$

In problems of synthesis of adaptive algorithms one usually consideres only steady state filtering. Then the a priori set values $R = R_a$ and $Q = Q_a$ we will have

$$K_a = P_a\left(\frac{\partial h}{\partial \hat{x}}\right)^T R_a^{-1}$$

where P_a - is a the only positive definite solution of the algebraic Riccati equation

$$FP_a + P_aF^T + GQ_aG^T - P_a\left(\frac{\partial h}{\partial \hat{x}}\right)^T R_a^{-1}\left(\frac{\partial h}{\partial \hat{x}}\right)P_a = 0\,. \tag{4}$$

In the rated conditions, the dynamically updated sequence or the measurement residual signal $\nu(t) = z - h(\hat{x},t)$ is a white noise, whereas in the case of a deviation of the actual characteristics of the noise of measuring instruments relative to of the rated conditions, correlations between individual instants appear. This leads to deformation of the spectral characteristics of the updated process. To determine the shape of the spectrum of the residual we first obtain an expression for its correlation function. This correlation function has the following form (Evlanov L.P.,Konstantinov V.M. 1982), (Ponomarev V.K., Panferov A.I. 1987):

$$C(t-\tau) = C(\eta) = \frac{\partial h}{\partial \hat{x}}\left[1(\eta)\Phi(\eta)P_\infty + 1(-\eta)P_\infty\Phi^T(-\eta)\right]$$
$$\cdot\left(\frac{\partial h}{\partial \hat{x}}\right)^T - 1(\eta)\frac{\partial h}{\partial \hat{x}}\Phi(\eta)K_aR^{-1}(-\eta)RK_a^T\Phi^T(-\eta)\left(\frac{\partial h}{\partial \hat{x}}\right)^T \tag{5}$$
$$+ R\delta(\eta).$$

where $\Phi(\eta)$ is a matrix weighting functions for equation (1). Conditions of physical capabilities of equations (1) explicitly takes into account introduction of the unit functions as a factor at the matrix of weighting functions:

$$1(t-\tau)\Phi(t,\tau) = \begin{cases} \Phi(t,\tau) & t > \tau; \\ 0{,}5I & t = \tau\ ; \\ 0 & t < \tau. \end{cases}$$

From the correlation functions is not difficult to pass to the energy spectra of the updated processes

$$S(\omega) = \frac{\partial h}{\partial \hat{x}}W(j\omega)P_\infty\left(\frac{\partial h}{\partial \hat{x}}\right)^T + \frac{\partial h}{\partial \hat{x}}P_\infty W^T(-j\omega)\left(\frac{\partial h}{\partial \hat{x}}\right)^T -$$
$$-\frac{\partial h}{\partial \hat{x}}W(j\omega)K_aR - RK_a^TW^T(-j\omega)\left(\frac{\partial h}{\partial \hat{x}}\right)^T + R, \tag{6}$$

where $W(j\omega)$ is the frequency response of the system:

$$W(j\omega) = \left[j\omega I - \left(F - K_a\frac{\partial h}{\partial \hat{x}}\right)\right]^{-1}, \tag{7}$$

and P_∞ is the solution of the following algebraic Riccati equation

$$P_\infty\left(F - K_a\frac{\partial h}{\partial \hat{x}}\right)^T + \left(F - K_a\frac{\partial h}{\partial \hat{x}}\right)P_\infty + K_aRK_a^T + GQG^T = 0\,. \tag{8}$$

If we take into account that

$$for\ \omega \to 0 \qquad \lim W(j\omega) = \left(-F + K_a\frac{\partial h}{\partial \hat{x}}\right)^{-1} \tag{9}$$
$$\text{and for } \omega \to \infty \quad \lim W(j\omega) = 0,$$

then for the spectrum of (6) we obtain: