An Alternative Approach to Improving Independence and Fault Tolerance of Solving the Problem of Determining Nanosatellite Attitude

I.V. Belokonov
Samara University
Samara, Russia
ibelokonov@mail.ru

A.V. Kramlikh
Samara University
Samara, Russia
kramlikh@mail.ru

M.E. Melnik
Samara University
Samara, Russia
mashagrigoreva@gmail.com

Abstract — **The approach proposed in this paper is based on the idea of creating a knowledge database aboard a nanosatellite that allows the reconfiguration of onboard software in order to choose the most appropriate algorithm for attitude determination and change parameters of the algorithms used. The paper presents the results of the research concerned with the SamSat nanosatellite platform: analysis of performances and formation of requirements to the instrument errors of the sensors used in the attitude control system to ensure the required accuracy of the problem solution; structure of knowledge database; logic of the onboard computer operation in terms of the choice of the applied attitude determination problem solution algorithm; simulation results of realization of the given approach on the model problem.**

Key words—attitude determination, independence, fault-tolerance, algorithm, nanosatellite

I. INTRODUCTION

By now a large number of the spacecraft attitude determination algorithms using various structures of measurement information has been developed. These algorithms are adapted to be used aboard nanosatellites. Depending on the nanosatellite mission, the capabilities of its onboard computer and some other factors, the attitude determination problem can be solved as follows: with the use of one-time measurements (by the algorithms based on the vector coordination method, for example, the QUEST algorithm [1,2], the TRIAD algorithm [3] and their modifications); by the algorithms based on processing of the accumulated sample of measurements (the Kalman filter and its modifications [4]; the algorithms based on minimization of the objective function with the use of motion model, the computing basis of which are the Levenberg-Marquardt method, the Gauss-Newton method, the differential evolution algorithm [5,6,7]).

As a rule, aboard the nanosatellite, the attitude determination problem is solved by one or two algorithms that are prestored in the onboard computer. The development of an approach that should improve the nanosatellite fault tolerance is a relevant problem since nanosatellites make use of commercial measuring sensors and measurement information sources (for example, solar battery panels) whose error and long-term stability characteristics are low in near-earth space. Fault tolerance can be increased by improving the intelligence and adaptability of the onboard software. As regards solution of the problem of determining the nanosatellite attitude under redundancy of measurement information, the goal can be achieved by reconfiguration of algorithms and the adaptation of their parameters to the current state of nanosatellite onboard systems.

II. NANOSATELLITE ATTITUDE DETERMINATION PROBLEM STATEMENT

The nanosatellites of the SamSat family developed at Samara University are made as nanosatellites of the CubeSat 3U format that are intended to carry out scientific and technological experiments in low-earth orbits [8, 9]. To ensure the performance of such experiments, it is necessary to control the nanosatellite attitude. The typical missions of the CubeSat 3U nanosatellites concerned with scientific experiments are the international QB50 project (study of the Earth thermosphere), the project on studying the Earth ionosphere and magnetosphere (initiated by Samara University, project participants are the Russian higher education institutions and RAS institutions). The required attitude accuracy of the nanosatellites in these projects must be no worse than 5 degrees.

A. *The sensors and other measurement information sources used*

Let's consider a nanosatellite with the following sensors and measurement information sources: a navigation receiver and three navigation antennas (A1, A2 and A3), two magnetometers (M1 and M2), six solar sensors (SS) and six solar battery panels (SB). They provide a set of measurement information that is sufficient to solve the nanosatellite attitude determination problem with various algorithms:

- navigation solutions $x, y, z, \dot{x}, \dot{y}, \dot{z}$, ephemerides of navigation satellites x_i, y_i, z_i ($i = \overline{1, N}$), numbers of visible and invisible navigation satellites, $\mathbf{A}_1^i = \left(x_1^i, y_1^i, z_1^i\right)^T$ are the vectors of direction cosines of the antenna phase centers in the body reference frame (*i=1,2,3* are the antenna numbers) from the navigation receiver;
- the Earth magnetic field vectors $\mathbf{H}_1^i = \left(h_{X_1}^i, h_{Y_1}^i, h_{Z_1}^i\right)^T$ (*i=1,2*) from the magnetometers;
- the Sun position information $\mathbf{S}_1^1 = \left(s_{X_1}^1, s_{Y_1}^1, s_{Z_1}^1\right)^T$ from the solar sensors;
- the values of current $\mathbf{S}_1^2 = \left(s_{X_1}^2, s_{Y_1}^2, s_{Z_1}^2\right)^T$ from the solar battery panels.

The above-mentioned sensors and sources of measurement information have the following errors: 400 nT for the magnetometers; 5 ° for the navigation receiver; 0.06 ° for the solar sensors. The error values are standard for this class of sensors [9, 10]. To determine the quality of value of current from the solar battery panels the model of their degradation is used [11].

The research was carried out at the expense of a grant from the Russian Science Foundation (project no. 17-79-20215).

B. *The mathematical models used*

To solve the problem of attitude determination, there is the necessity to calculate some mathematical models onboard the nanosatellite: models of the nanosatellite motion for obtaining values of orbit elements [12]; models of the Earth magnetic field [13]; models of the Sun motion [14].

III. AN ALTERNATIVE APPROACH TO IMPROVING INDEPENDENCE AND FAULT TOLERANCE OF SOLVING THE PROBLEM OF DETERMINING NANOSATELLITE ATTITUDE

A. *Knowledge database structure*

The main idea of this approach is to create a knowledge database aboard the nanosatellite including:

- initial (nominal) values of measurement reliability coefficients (MRC)that define their contribution to the attitude determination problem solution;
- initial (nominal) instrument errors of sensors and measurement information sources that have to be considered in forming the weight coefficients;
- models of changes in the instrument errors of sensors and measurement information sources including the models formed as a result of the ground thermal vacuum and vibration tests used in forming the weight coefficients of the objective function that is applied in the attitude determination problem solution depending on the nanosatellite current operating conditions;
- a set of the attitude determination algorithms used for various cases of different types of information integration (algorithm of vector coordination (Wahba problem) [15,16], algorithm based on matrix relation [15], algorithm for spatial visibility of navigation satellites [10]).

The structure of the knowledge database is presented in Table I.

TABLE I. THE KNOWLEDGE DATABASE STRUCTURE

No.	MRC SS	MRC SB	MRC M1	MRC M2	MRC A1	MRC A2	MRC A3	Algorithm
1	k_1^{SD}	k_1^{SB}	k_1^{M1}	k_1^{M2}	k_1^{A1}	k_1^{A2}	k_1^{A3}	Attitude determination algorithms that correspond to the current MRC
2	k_2^{SD}	k_2^{SB}	k_2^{M1}	k_2^{M2}	k_2^{A1}	k_2^{A2}	k_2^{A3}	
…	…	…	…	…	…	…	…	
i	k_i^{SD}	k_i^{SB}	k_i^{M1}	k_i^{M2}	k_i^{A1}	k_i^{A2}	k_i^{A3}	

B. *Logic of functioning of the nanosatellite attitude determination algorithm*

The logic of functioning of the algorithm for the nanosatellite attitude determination that takes into account a set and quality of measurement information is presented in Fig. 1. In the nanosatellite orbital flight, the knowledge database is replenished as a result of the analysis of current state of sensors and measurement information sources and also owing to the use of models of their instrument error variations.

In the course of the nanosatellite operation, the onboard computer accesses the knowledge database and carries out the reconfiguration of the onboard software, changing the parameters of the algorithms used. It is realized by the analysis of quantity and quality of measurement information (the value of angular rate, the aprioristic attitude information) depending on the angular motion character (the uncontrolled motion or reorientation process). In addition, two measurement vectors from magnetometers are to be matched, as well as two vectors from solar sensors and solar battery panels. As a result a decision is made on the choice of measurement set and the applied algorithm for attitude determination problem solution; new weight coefficients of measurements are formed.

IV. SIMULATION RESULTS

Mathematical simulation was carried out for the model problem of attitude determination with the following initial data: circular orbit (height is 300 km); the longitude of ascending node is 170 °, orbit inclination is 63 °.

Figs. 2 and 3 and also Reference [10] present the results of solution of the model problem of the nanosatellite attitude determination using various algorithms with different sets of measurement information. Of the problem solutions with all possible combinations of the available measuring information, only two results are presented in Fig. 2, the one with the minimum (A2+S) and the one of the maximum (A1+A2+A3+S+H) accuracy.

V. CONCLUSION

Errors of the sensors used and methodical errors of the applied algorithms enable to reach the required accuracy of solution of the nanosatellite attitude determination problem.

The approach proposed in this paper allows to expand significantly the range of cases, in which it is possible to find the solution of the nanosatellite attitude determination problem with the reconfiguration of onboard software.

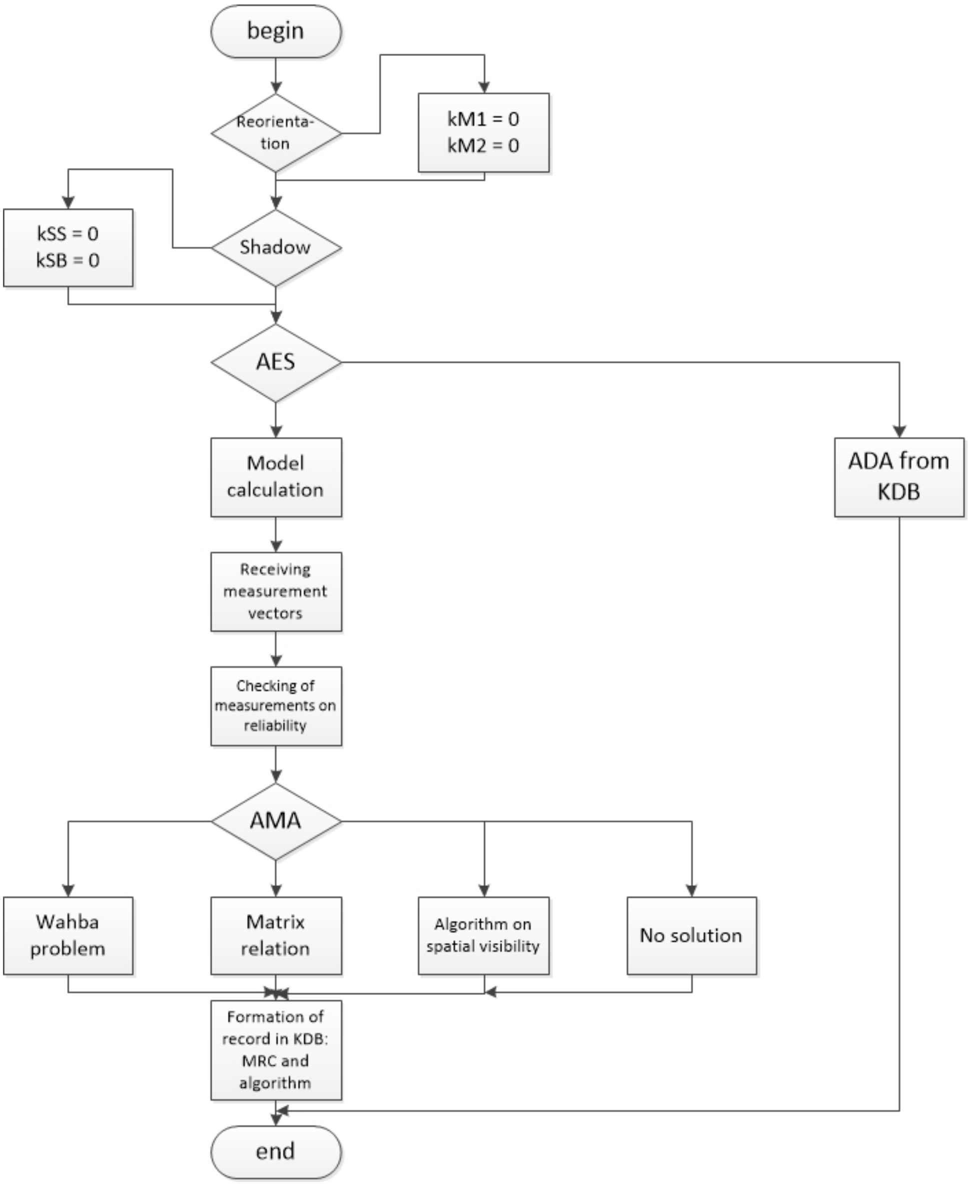

Fig. 1. Logic of functioning of the nanosatellite attitude determination algorithm (AES – analysis of existing solutions, ADA – attitude determination algorithm, KDB – the knowledge database, AMA - analysis of measurement availability)

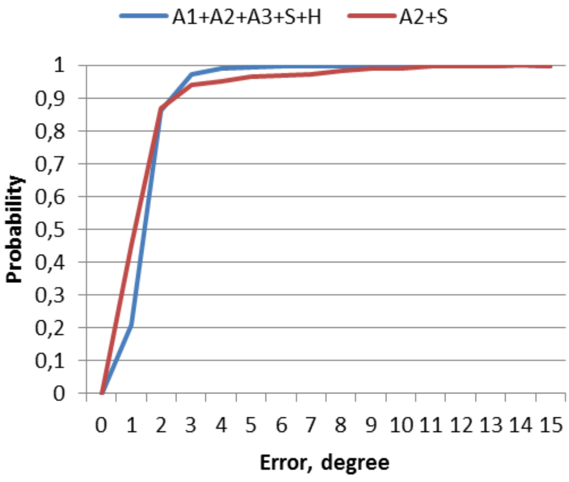

Fig. 2. Results of simulation of finding of a precession angle (ψ) by means of algorithm based on matrix relation with one measurement vecto

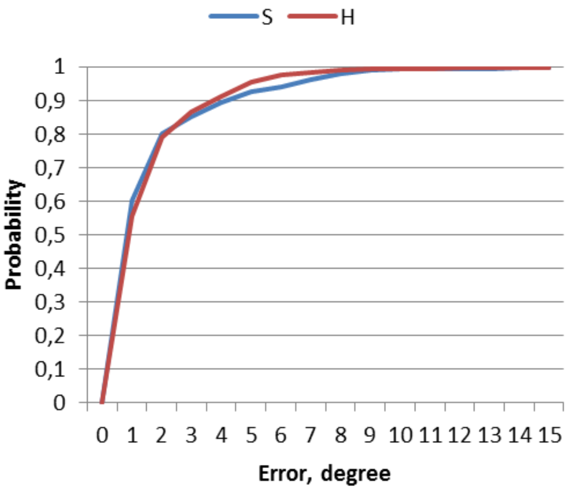

Fig. 4. Results of simulation of finding of a precession angle (ψ) by means of algorithm for vector coordination with different sets of measurement information

REFERENCES

[1] Shuster, M. D., Approximate Algorithms for Fast Optimal Attitude Computation, AIAA Guidance and Control Conference, Palo Alto, California, 1978, pp. 88-95.

[2] Shuster, M. D., Oh, S. D., Three-Axis Attitude Determination from Vector Observations, Journal of Guidance and Control, 1981, Vol. 4, No. 1, pp. 70-77.

[3] Black, H., A Passive System for Determining the Attitude of a Satellite, AIAA Journal, 1964, 2 (7), pp. 1350–1351. Bibcode:1964AIAAJ...2.1350. DOI:10.2514/3.2555.

[4] Ivanov D.S., Karpenko S.O., Ovchinnikov M.Yu., Algoritm oczenki parametrov orientaczii malogo kosmicheskogo apparata s ispol`zovaniem fil`tra Kalmana (Kalman Filter Algorithm for Satellite Attitude Parameters Estimation), KIAM Preprint, 2009, № 48, 32 c. URL: http://library.keldysh.ru/preprint.asp?id=2009-48.

[5] Belokonov, I.V., Kramlikh, A.V., Metodika vosstanovleniya orientaczii kosmicheskogo apparata pri kompleksirovanii magnitometricheskikh i radionavigaczionny`kh izmerenij (Space vehicle attitude control recovery procedure combining magnetometric and padionavigation measurements), Vestnik Samarskogo gosudarstvennogo ae`rokosmicheskogo universiteta imeni akademika S.P. Korolyova, 2007, №1 (12), pp.22-30.

[6] Kramlikh, A.V. Lomaka, I.A., Nanosatellite's rotational motion parameters determination using light sensor and angular velocity sensor measurements, 25th Saint Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, CSRI Elektropribor, 2018, pp. 1-3.

[7] Beuselinck, T, van Bavinchove, C., Abrashkin, V.I., Kazakova, A.E., Sazonov, V.V., Determination of attitude motion of the Foton M-3 satellite according to the data of onboard measurements of the Earth's magnetic field, Cosmic Research, 2010, Vol. 48, Issue 3, pp. 246-259.

[8] Kirillin A., Belokonov I., Timbai I., Kramlikh A., Ustiugov E., Egorov A., Shafran S., Melnik, M., SSAU nanosatellite project for the navigation and control technologies demonstration // Scientific and Technological Experiments on Automatic Space Vehicles and Small Satellites, Procedia Engineering, 2015, V.104, p. 97-106.

[9] Belokonov I.V., Timbai I.A., Nikolaev P.N. Analysis and Synthesis of Motion of Aerodynamically Stabilized Nanosatellites of the CubeSat Design. Gyroscopy and Navigation, 2018, vol. 9, №4, pp. 287-300. doi.org/10.1134/S2075108718040028

[10] Canuto, E., Novara C., Massotti L., Carlucci D., Montenegro C.P., Spacecraft Dynamics and Control. The Embedded Model Control Approach, Elsevier, 2018, 761 p.

[11] Belokonov, I.V., Kramlikh A.V., Melnik M.E., Estimation of the nanosatellite attitude and the angular rate by analyzing the navigation spacecraft geometrical visibility using the controllable pattern of navigation antenna, 24th Saint Petersburg International Conference on Intergrated Navigation Systems, St. Petersburg, CSRI Elektropribor, 2017, pp 547-550. DOI 10.23919/ICINS.2017.7995676.

[12] Pis`menny`j, N.I., Czokur, A.G., Nosikov, S.V., Kulagin, S.N., Degradacziya moshhnosti solnechny`kh batarej kosmicheskikh apparatov v ionosfere i magnitosfere Zemli (Degradation of the spacecraft solar battery power in the Earth ionosphere and magnetosphere), Tekhnicheskaya mekhanika, 2011, № 3, pp. 79-90.

[13] E`l`yasberg, P.E., Vvedenie v teoriyu poleta iskusstvenny`kh sputnikov Zemli (Introduction to the theory of the Earth artificial satellite flight), Moscow, Nauka, 1965, 540 p.

[14] Kovalenko, A.P., Magnitny`e sistemy` upravleniya kosmicheskimi letatel`ny`mi apparatami (Spacecraft magnetic control systems), Moscow, Mashinostroenie, 1976, 250 p.

[15] Abalakin, V.K., Osnovy` e`femeridnoj astronomii (Fundamentals of ephemerides astronomy), Moscow, Nauka, 1979, 448 p.

[16] Grigoreva, M.E., Kramlikh, A.V., Joint use of different types of information in the spacecraft orientation determination algorithms, 20th Saint Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, CSRI Elektropribor, 2013. pp. 240-243.

[17] Belokonov, I.V., Kramlikh, A.V., Small satellite attitude determination using navigational receiver and magnetometer, 60th International Astronautical Congress, 2009, Vol. 6, pp. 4800-4807.