Application of artificial intelligence technology in the nanosatellite attitude determination problem

I V Belokonov, A V Kramlikh, M E Melnik

Interuniversity Space Research Department, Samara National Research University, Samara, 443086, Russia
E-mail: mashagrigoreva@gmail.com

Abstract. The paper proposes an approach of the nanosatellite attitude determination problem solution using elements of artificial intelligence technology. This approach consists in the reconfiguration of the algorithms of the nanosatellite attitude determination problem solution based on the knowledge database that can be enriched to ensure the robustness of the feedback loop (the nanosatellite attitude determination using different combinations of different types of measurement information by various algorithms). This research results are presented in relation to the nanosatellite of the SamSat family: values of measurement significance coefficients are chosen; then generalized algorithm significance coefficients are calculated for various combinations of operable measuring means using chosen coefficients.

1. Introduction
One of the most important problems for developers of small spacecraft - nanosatellites (NS) is to increase spacecraft reliability and fault tolerance, and it is desirable that failure management takes place without participation of the ground control, i.e. autonomously. To ensure this problem solution, now the intelligent design of on-board systems is being applied [1]. In this research when solving the attitude determination problem, in the NS angular motion control system it is proposed to use elements of the artificial intelligence technology such as the use of the so-called knowledge database [2] that can be enriched and is based on the production model. For this purpose, an approach of reconfiguration of algorithms of the NS attitude determination problem solution has been developed. This approach allows to increase the reliability of attitude determination problem solution by minimizing the number of cases of not receiving the information on current attitude in case of failure of some measurement sensors.

2. Sensor hardware configuration
Traditionally, the NS uses inertial (angular rate sensors (ARS)) and vector (solar sensors, light sensors (LS), magnetometers (M), star trackers, etc.) measurement devices. In order to ensure high-precision reference of measurements, a navigation receiver (NR) is installed on the NS. All these measuring means provide a redundant number of different types of information. It allows to reconfigure algorithms of attitude determination problem solution depending on the current operating conditions of the NS. Despite the fact that the above-mentioned measurement devices are often of low accuracy, they allow, with restrictions on the cost of the NS, to solve the problem with accuracy that is appropriate for the mission. For the vast majority of missions of 2018-2019 (about 70% of the total number of missions)
[3], the requirements for the accuracy of the NS attitude problem solution are low. So for this class of missions a possible error in determining the NS attitude does not exceed 5 degrees.

3. Technique of reconfiguration of algorithms of the nanosatellite attitude determination problem solution

Firstly, to reconfigure the algorithms of the NS attitude determination problem solution, monitoring of normal operation of measuring equipment complex is performed. Then the attitude determination algorithm is chosen in automatic mode without the ground control center participation. The algorithm is chosen using a knowledge database containing the so-called cases of the NS attitude determination problem solution. Its structure is presented in table 1 and includes:

1) values of measurement significance coefficients \(0 \leq k_{iSj}^1 \leq 1, 0 \leq k_{iSj}^2 \leq 1\). The coefficient \(k_{iSj}^1\) is caused by the accuracy of the attitude sensor Isj (the more accurate the sensor is, the higher the significance coefficient is), and the coefficient \(k_{iSj}^2\) is defined by the energy consumption of the attitude sensor Isj (the higher the energy consumption is, the higher the value of the significance coefficient is). Initial values and patterns of these coefficients are set by the developer of the angular motion control system at the NS ground test stage;

2) attitude determination algorithms for various cases of using different types of information (algorithm based on vector coordination method [4], algorithm based on matrix relation [5], Kalman filter [6], etc.).

The scheme of reconfiguration of algorithms of the NS attitude determination problem solution is shown in figure 1. It can be seen, that this algorithm consists of several steps. The knowledge database is enriched as follows. If the current set of measurement significance coefficients does not correspond to the attitude determination algorithms presented in the knowledge database, the analysis and choice of the most effective algorithm from the existing set of algorithms takes place. To make this choice, for each algorithm the corresponding generalized algorithm significance coefficients is calculated by the formula:

\[
k_m = \left(\frac{\sum_{j=1}^{m} (k_{iSj}^1)^2}{m}\right)^{1/2} - \left(\frac{\sum_{j=1}^{m} (k_{iSj}^2)^2}{m}\right)^{1/2},
\]

where \(m\) is number of measurements used in the NS attitude determination algorithm.

| No. | Measurement significance coefficients | NS attitude determination algorithm |
|-----|--------------------------------------|-----------------------------------|
| 1   | \(k_1^1, k_2^1\)                      | Algorithm 1                       |
| 2   | \(k_1^2, k_2^2\)                      | Algorithm 2                       |
| ... | ...                                  | ...                               |
| i   | \(k_i^1, k_i^2\)                      | Algorithm i                       |
| ... | ...                                  | ...                               |
| n   | \(k_n^1, k_n^2\)                      | Algorithm n                       |

*IS1, IS2, ..., ISj are numbers of cases of the NS attitude determination problem solution.
To solve the attitude determination problem, an algorithm with a maximum significance coefficient \( k_{ai} \) is chosen. The maximum significance coefficient characterizes the best relationship between the accuracy of problem solution and the energy spent on solving it. Then, the knowledge database is enriched by a new case containing the current set of measurement significance coefficients and the chosen algorithm of the NS attitude determination problem solution.

4. An Example of the Application of the Developed Approach for the Nanosatellite of the SamSat Family

The following parameters must be determined for reconfiguration of algorithms of the NS attitude determination problem solution:

- a set of attitude determination algorithms. Taking into account the requirement for the accuracy of attitude determination of the NS of the SamSat family of about 5 degrees, the following algorithms are chosen: attitude determination algorithm based on vector coordination method [7], algorithm on spatial visibility of navigation spacecraft [8] and Kalman filter [6];

- measurement significance coefficients. Based on the results of ground tests for sensors of the SamSat family NS, the developer determined the following coefficient values (table 2):

|       | NR | M  | LS | ARS |
|-------|----|----|----|-----|
| \( k_{0}^{NR} \) | 0.6 | 0.7 | 0.6 | 0.5 |
| \( k_{0}^{LS} \) | 0.7 | 0.5 | 0.5 | 0.5 |
| \( k_{0}^{ARS} \) | 0.5 | 0.6 |

When calculating generalized algorithm significance coefficients, two assumptions are made:

1) since the algorithm of spatial visibility of navigation spacecraft is used to obtain the vector of direction cosines of the antenna phase centers that is one of the input data vectors for the algorithm based on vector coordination method, the significance coefficient of navigation receiver measurements in formula (1) is taken into account twice;

Figure 1. Scheme of reconfiguration of algorithms of the NS attitude determination problem solution on the basis of the knowledge database that can be enriched.
2) since using Kalman filter as the NS attitude determination algorithm needs the calculation of the motion model which complicates the computational process, it is necessary to add the correction coefficient $k_2 = 0.1$ to formula (1):

$$k_{ni} = \left( \sum_{j=1}^{m} (k_{IS}^{j})^2 \right)^{1/2} - \left( \sum_{j=1}^{m} (k_{2IS}^{j})^2 \right)^{1/2} - k_2$$  \hspace{1cm} (2)

Thus, at the initial moment of time, the generalized algorithm significance coefficients calculated according to (2) are as follows (table 3):

**Table 3. Initial generalized algorithm significance coefficients.**

| Algorithm                                      | Generalized algorithm significance coefficient |
|------------------------------------------------|-----------------------------------------------|
| Kalman filter using measurements from M, ARS, LS | 0.021                                         |
| Kalman filter using measurements from M, ARS    | -0.1                                          |
| Kalman filter using measurements from M, LS     | 0.115                                         |
| Kalman filter using measurements from ARS, LS    | -0.021                                        |
| Algorithm based on vector coordination method using measurements from NR, M, LS | 0.03644                                 |
| Algorithm based on vector coordination method using measurements from NR, LS | -0.00905                                       |
| Algorithm based on vector coordination method using measurements from NR, M | -0.06982                                      |
| Algorithm based on vector coordination method using measurements from M, LS | 0.21485                                      |
| Algorithm on spatial visibility of navigation spacecraft (NR) | -0.1                                      |

As can be seen from table 3, the best in terms of the relationship between the problem solution accuracy and the energy consumption is the algorithm based on the vector coordination method using magnetometer and light sensor measurements.

Supposing that the light sensors failed, the significance coefficients of the measurements will take the values presented in table 4, and the generalized algorithm significance coefficients - in table 5 (the number of possible algorithms is reduced).

**Table 4. Measurement significance coefficients (light sensor failure).**

|        | NR | M   | LS  | ARS |
|--------|----|-----|-----|-----|
| $k_1^{NR}$ | 0.6 | 0.7 | 0.6 | 0.5 |
| $k_1^{M}$  |    |     |     | 0   |
| $k_1^{LS}$ |    |     |     | 0.5 |
| $k_1^{ARS}$|    |     |     | 0.6 |
Table 5. Generalized algorithm significance coefficients (light sensor failure).

| Algorithm                                                      | Generalized algorithm significance coefficient |
|----------------------------------------------------------------|-----------------------------------------------|
| Kalman filter using measurements from M, ARS                   | -0.1                                          |
| Algorithm based on vector coordination method using measurements from NR, M | -0.07                                         |
| Algorithm on spatial visibility of navigation spacecraft (NR)  | -0.1                                          |

As can be seen from table 5, the best in terms of the relationship between the problem solution accuracy and the energy consumption is the algorithm based on the vector coordination method using magnetometer and navigation receiver measurements.

If in the future the navigation receiver fails, then the measurement significance coefficients will be (table 6):

Table 6. Measurement significance coefficients (light sensor and navigation receiver failure).

| NR | M | LS | ARS |
|----|---|----|-----|
| $k_{1}^{NR}$ | $k_{2}^{NR}$ | $k_{1}^{M}$ | $k_{2}^{M}$ | $k_{1}^{LS}$ | $k_{2}^{LS}$ | $k_{1}^{ARS}$ | $k_{2}^{ARS}$ |
| 0   | 0  | 0.6 | 0.5  | 0    | 0    | 0.5     | 0.6    |

This case leaves only algorithm of Kalman filter using magnetometer and ARS measurements possible to use (table 7).

Table 7. Generalized algorithm significance coefficients (light sensor and navigation receiver failure).

| Algorithm                                                      | Generalized algorithm significance coefficient |
|----------------------------------------------------------------|-----------------------------------------------|
| Kalman filter using measurements from M, ARS                   | -0.1                                          |

The order of failures of the measuring means can be different, in addition, the measuring means can be without fail, but inoperable in certain operating conditions of the NS (for example, light sensors on the shadow turn). And the main advantage of this approach is that the developer does not need to prescribe in advance all cases of possible failure of the NS sensor equipment, software that implements the reconfiguration of algorithms of the NS attitude determination problem solution will determine which algorithm is necessary in given situation and record the decision made (i.e. there will be a program training - adding a new "knowledge") for its further use.

5. Conclusion

Application of the proposed in this research approach makes it possible to increase reliability and fault tolerance of the angular motion control system in terms of the NS attitude determination problem solution.

In the presence of excessive measurement information the reconfiguration of algorithms allows to solve the problem with the required for this class of problems accuracy (about 5 degrees) even from low accuracy measuring means.
Acknowledgments
The work was carried out within the project 0777-2020-0018 financed from the state assignment means given to winners of competition of scientific laboratories of educational organizations of higher education under the authority of Ministry of Science and Higher Education of Russia.

References
[1] Yadava D, Hosangadi R, Krishna S, Paliwal P and Jain A 2018 Attitude Control of a Nanosatellite system using Reinforcement Learning and Neural Networks vol 2018-March (IEEE Aerospace Conf. Proc.) pp 1-8
[2] Belokonov I V, Kramlikh A V Melnik M E 2019 An Alternative Approach to Improving Independence and Fault Tolerance of Solving the Problem of Determining Nanosatellite Attitude (St Petersburg: ICINS 2019 – Proc.) pp 71-74
[3] Nanosats Database http://nanosats.eu
[4] Markley F L and Crassidis J L 2014 Fundamentals of Spacecraft Attitude Determination and Control vol. XV (New York: Springer-Verlag) p 486
[5] Black H 1964 A Passive System for Determining the Attitude of a Satellite 2(7) AIAA J. pp. 1350–1351
[6] Ivanov D S, Ivlev N A, Karpenko S O and Ovchinnikov M Yu 2014 Attitude determination algorithms investigation for microsatellites of "TabletSat" series KIAM Preprint p 24 (Preprint 2014-64)
[7] Wertz J R 1978 Spacecraft Attitude Determination and Control (The Netherland: Dordrecht)
[8] Belokonov I V, Kramlikh A V and Melnik M E 2017 Estimation of the nanosatellite attitude and the angular rate by analyzing the navigation spacecraft geometrical visibility using the controllable pattern of navigation antenna (St. Petersburg: ICINS 2017 – Proc.) 547-550