Control of rotational motion of a partially inoperable small spacecraft using fuzzy sets

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Abstract. During processing of telemetric information, in particular data on the current from the AIST small satellite (SS) solar panels, in order to control the parameters of rotational motion ambiguous interpretations of primary information have occurred occasionally. The ambiguity was caused by readings from the solar array electric current sensors - significant currents were recorded from two panels located on the opposite sides of the SS. The Sun, however, could only light one of them at a time. In order to resolve this problem, an automated algorithm based on the use of a fuzzy set for controlling the parameters of the small SS rotational motion is proposed. In that approach, the current values from different panels would be included in the set with different values of the membership function. The implementation of presented automated algorithm onboard the SS will not only improve the operating conditions of the target equipment, but also have a backup orientation system, thereby increasing the reliability of the mission.

1. Introduction
In order to successfully implement industrial production in space, it is necessary to maintain favorable conditions for gravitational-sensitive processes. One of the most important conditions is to limit the level of micro-accelerations in the area of technological equipment [1-3]. Figure 1 shows the requirements for the level of micro-accelerations for the successful implementation of pilot production in space from the point of view of specialists in space production [4].

In figure 1- the Upper curve is taken from the SSP41000D official document, which formulates the requirements for the level of micro-accelerations for gravity-sensitive experiments and processes on the ISS, and the lower curve represents the desired requirements formulated by specialists from Baikov Institute of Metallurgy and Materials Science, RAS (BIMMS RAS), for the processes already developed by them and which are still unattainable at the present level of development of space technology. Therefore, it is necessary to develop an algorithm for automated control of the level of micro-accelerations in the area where technological equipment is located. The task of assessing and controlling the level of micro-accelerations during normal operation of measuring instruments has been considered in a number of papers by various authors [5-7].

This paper considers the possibility of maintaining production capabilities for a production satellite that have a failure of its standard measuring instruments. In particular, a scenario of failure or incorrect
operation of the main microacceleration measuring instruments is considered. As an example, we consider the prototype of the AIST SS, launched into orbit from the Plesetsk cosmodrome on December 28, 2013, using the Soyuz-2.1V launch vehicle. At present, the SS operates in a near-circular solar synchronous orbit with an average altitude of about 612 km. Its mass is 39 kg. The appearance of the SS is shown in Figure 2.

Figure 1. Requirements for the level of micro-accelerations for the successful implementation of production in space

Figure 2. General view of the AIST small satellite
Combined effect of internal and external factors, omitted during design of a satellite could potentially lead to serious malfunctions, up to the failure of operation of the SS as a whole. This usually happens with components of the satellite created using integrated circuits (IC) [8]. ICs are a bottleneck in ensuring the reliability and survivability of satellites, since they are most sensitive to temperature changes and the effects of local radiation.

The task of preserving the operability (survivability) of a spacecraft with the aim of maintaining the operation of the payload must certainly be set before the designers of the product. One of the solutions for maintaining performance is the use of the principle of integration in the design of spacecraft, which consists in the systemic integration of elements (constructive, electrical), creating intelligent onboard control algorithms and ensuring interchangeability of individual functions of devices and onboard equipment modules for obtaining higher (compared to individual elements) reliability indicators [8]. In the latter case, if a subsystem of the satellite fails, the intelligent onboard control algorithm tries to allocate lost functions to another subsystems in an attempt to maintain functionality of the satellite as a whole. In any of the possible cases of redistribution of functions, the efficiency of the device, which has received an additional function, or of another system located in the same information circuit with this device, decreases, but the operation continues. This ensures a high level of reliability and survivability of the satellite as a whole.

Therefore, the search for new solutions of integration and backing up of the satellite onboard equipment both on the design stage and during operation is necessary and important.

2. Problem statement

This paper considers integration of attitude control system that is achieved by changing the logic of motion control around the center of mass after changing the source of the initial data on the orientation of the satellite. The peculiarity of the problem to be solved is that the automated algorithm for controlling the parameters of the rotational motion of the SS does not use information from standard measuring instruments, which are considered inoperable, but instead utilized electric current values from solar panels. The task of orientation of the SS according to the current data from the panels was solved by various authors, for example [9–11]. This paper explores the possibility of correct interpretation of primary information (electric current data) using fuzzy sets.

Processing telemetry information is a complex and important process. Obtaining reliable data is directly related to the correctness of the processing of primary information. In cases of poor observation conditions of the spacecraft during a telemetry session, the received information contains bad blocks. Bad conditions can be caused by low spacecraft height above the horizon, a high angular velocity of its rotation, etc. Figure 3 shows a fragment of the on-board telemetry from the prototype of the AIST small spacecraft.

Such failures are emissions of primary information and must be removed from it during processing. However, there are situations when, with correctly working on-board measuring instruments and telemetry information transmitted without failures, it is difficult to unambiguously interpret the values of the measured parameters. For example, data on current from solar panels of the AIST SS contained ambiguous areas when a significant electric current was recorded from two opposite panels [12]. However, only one of them was illuminated by the Sun. The AIST small itself is a cube-shaped body, the surface of which is covered with photo cells (Figure 2).

In [12], the situation when a significant current was recorded from all six panels was described. To analyze such situations an approach using fuzzy sets is proposed.

Therefore, automated algorithm for controlling the SS rotational motion parameters based on the use of fuzzy sets is the task is of this work.
3. Results

All telemetry information from the AIST SS can be divided into two parts. The first part refers to the period of normal operation of the battery. It contains a large amount of data related to the operation of measuring instruments, platform and payload equipment. The payload equipment includes MAGKOM and Meteor scientific equipment [13]. The abundance of telemetric information led to the fact that current data was requested at a frequency of once per minute. Therefore, in this paper, this part of the information will not be analyzed.

The second part of the telemetry information was accumulated after the degradation of the battery. During this period, the payload equipment did not work due to the lack of power on board the satellite required for their regular operation. Therefore, it was possible to transmit electric current data with a frequency of once per second, which is the limit for SS equipment [14]. Ensuring the correctness of this information is especially important due to the fact that current data during this period of operation of the satellite is the only source of primary information for estimating the parameters of the rotational motion of the SS. The data from 15.05.2018 to 08.08.2018, as well as from 16.11.2018 to 22.11.2018 was selected for analysis. In the period from 08/09/2018 to 10/20/2018 telemetry information from the AIST SS was not received.

When analyzing the data, it should taken into account the fact that the degraded rechargeable battery was charged and discharged in very short periods of time. In this case, the switches were triggered, disconnecting the panel from the battery and resetting the current values. In order to prevent such a shutdown, activation commands were sent to the payload hardware, which contributed to the discharge of the battery.

Fuzzy sets allow to interpret the situation when a significant electric current values are obtained from two opposite panels. Moreover, this situation can not be explained in another way. In the case of a significant superiority of one current value over another, it is obvious that bigger current is generated from a panel illuminated by the Sun, and the smaller readings from can be explained by radiation from the Earth’s surface or re-reflection of sunlight from the structural elements of the satellite. In the case of a significant change in current compared to its previous value, one should prefer a value closer to the previous one, even if it turns out to be smaller. Since such a change in current can be explained only by a significant local increase in the angular velocity of the satellite.

Figure 3. Telemetry data obtained on 21.11.2018 with bad blocks at the beginning of the session.
However, the analysis carried out above showed that these conditions are not sufficient for an unambiguous interpretation of the current values. Here then it is worth resorting to fuzzy sets. They allow you to view both current values from opposite panels. We can assume that in this case the current value is a fuzzy number. In this case, the two analyzed values form the carrier of this number.

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\[
\mu_A(x_i) = \begin{cases} 
\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma, & \text{при } \cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma \leq 1; \\
2 - (\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma), & \text{при } \cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma > 1.
\end{cases}
\]

In [12], defuzzification was carried out as follows. An electric current reading for which the value of the membership function (1) was the maximum was chosen as a true reading from a pair of electric current values. This paper proposes to complicate the task. The algorithm for its solution is presented in Figure 4.

![Figure 4. The algorithm of resolving the ambiguity of the primary information using fuzzy sets](image)
4. Discussion of results
The added complexity compared with [12] will be that both measured current values are treated as fuzzy numbers, taking into account the error in their measurement. Thus, it is possible to achieve a stricter fulfillment of the normalization condition. The input to the analysis is still the two measured current values from the opposite panels. Next, these values are transformed into fuzzy numbers with a trapezoid membership function (Figure 3). The carriers of these fuzzy numbers will be segments, the midpoints of which correspond to the measured values of the currents, and the edges are determined according to the three-sigma rule. The fuzzy set with the membership function (1) has an infinite carrier containing all real numbers. To solve the problem, it is necessary to build fuzzy relations between fuzzy numbers (measurements of currents) and the set defined by the membership function (1). In this paper, it is proposed to use the direct product of fuzzy sets as a fuzzy relation. In this case, the membership function of a fuzzy relation will be the product of the membership functions of individual sets. It will be different from zero on the segments corresponding to the carriers of fuzzy numbers. After constructing the membership function of a fuzzy relationship, it is proposed to conduct defuzzification in accordance with the Max-Criterion algorithm, where a clear current value corresponds to the maximum of the membership function of a fuzzy relationship. Unlike work [12], this value will not coincide with one of the two measured current values.

5. Summary
As a result of the research, the following conclusions can be drawn:
- the apparatus of fuzzy sets can correctly interpret the data on the current from the solar panels, taking into account the reflection of solar radiation from the earth's surface, as well as its reflectance from the structural elements of the SS;
- the developed automated algorithm allows you to effectively control the parameters of the rotational motion of the SS at its partial failure;
- creation of on-Board software based on the developed automated algorithm allows to increase survivability and extend the useful life of the SS.

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7. Acknowledgements
This work is supported by the Ministry of education and science of the Russian Federation in the framework of the State Assignments to higher education institutions and research organizations in the field of scientific activity (the project # 9.1616.2017/ПЧ ).