SSAU nanosatellite project for the navigation and control technologies demonstration

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Abstract

The article describes nanosatellite SamSat-218D designed in Samara State Aerospace University. SamSat-218D is created for testing navigation and control technologies. The experimental on-board computer is additionally installed on the board, it have the elements of “intellectual control”. Algorithms of experimental computer are based on the principles of ensuring survivability, can detect and parry of failures of on-board elements in flight conditions.

Keywords: Nanosatellite; CubeSat; on-board computer; control technology; intellectual control; survivability

1. Introduction

Modern effective way to carry out experiments in space and work through of new technologies is based on utilization of nanosatellites of CubeSat standard. Such nanosatellites have mass up to 3 kg and form of one or two or three cubes (units) with side of 10cm (1U, 2U or 3U size). Nanosatellites have a short development period and orbiting like piggyback payload.

The increasing complexity of the problems solved by such satellites requires the creation of more efficient and fault-tolerant communication, navigation and control subsystems.

In SSAU had been developed nanosatellite SamSat-218 for demonstration of those new technologies. This nanosatellite has two modifications: demo-version and full-version.
The demo-version named SamSat-218D and will be launched in the end of 2015. This version demonstrates improving navigation and control algorithms that give impact to property of fault tolerance for nanosatellite.

The full-version of nanosatellite will be launched in 2017 and in addition to tested algorithms for navigation and control will demonstrate communication technology through the Russian low orbital satellite telecommunication system, such as Gonetz, video navigational technologies etc.

Concept of configuration of on-board control system is discussed in this paper.

2. The aims and features of SamSat-218D mission

The aims of the SamSat-218D are:

- Testing of the experimental on-board computer;
- Testing of the control technology of nanosatellite in normal and abnormal conditions of flight;
- Testing integration technology on-board control system and ground control center for parry of failures;
- Testing of new solar panels;
- Adjustment of a technology of the nanosatellite aerodynamic stabilization (precursor flight experiment for the SamSat-QB50 nanosatellite). [1]

SamSat-218D has mass about of 3 kg, belongs to the CubeSat standard and has size 3U (10x10x30 cm). The internal structure of nanosatellite is shown in the Fig. 1.

![Fig. 1. Samsat-218D nanosatellite internal structure.](image-url)
As figure shows, half of nanosatellite is space volume. This arrangement is made to shift the center of mass. Similar aerodynamic characteristics will have the nanosatellite SamSat-QB50. Thus, SamSat-218D can be interpreted as prototype for testing of passive aerodynamic orientation to the velocity vector of flight.

To ensure all functions SamSat-218D nanosatellite equipped elements:

- Control units: commercial Nanomind on-board computer (OBC) and experimental on-board computer SSAU developed;
- Radio transmitter-receiver and antennas for the communication with control center;
- Power supply subsystem, including battery, controllers for supply any elements, solar panels of two types: commercial and experimental;
- Magnetic coils for orientation;
- Sensors: magnetometers, accelerometers, gyroscopes, sun light sensors.

Diagram of interoperability on-board systems is shown in the Fig. 2.

Most of nanosatellite’s elements are interconnected by 104-pin interface for information communications and power supply.

On the board are used two types of solar panels: commercial and experimental. Both types of panels are composed of sensors, solar cells and light sensors. Commercial solar panels also incorporate the accelerometer and the magnetometer.

Energy from solar panels falls into the power system, which stores it in batteries and distributes between the elements of the satellite depending on control signals from the on-board computers.

Communication with ground control center is carried out by the transmitter-receiver, which interconnect with on-board computers via main I2C bus. Antennas block complete with deployment device and are used of two types: commercial and experimental.

Orientation and stabilization of the nanosatellite into space are achieved by magnetic coils and restoring aerodynamic torque.
Control operation of all elements of the nanosatellite functions are assigned to on-board computers. On the board is installed tested commercial computer Nanomind, as well as new experimental computer developed in SSAU. Experimental computer will be held flight qualification and tested.

On the basis of the experimental computer implemented on-board control system. There are two modes of its operation:

- Autonomous operation. In this mode nanosatellite attitude control is performed automatically on the board. Control actions are produced based on on-board sensor measurements and calculations. A special base of algorithms is saved on the board. It allows depending on the current situation, to choose one or the other algorithm for fault tolerance of nanosatellite.
- Working in conjunction with a ground control center. This mode is used when the on-board system is not able to solve the control problem nanosatellite, since it laid too simple algorithms or the flow of information to compute a very large. In this case information to compute will be sent to the ground control center. On the next turn result of computation will be sent to the nanosatellite for right control actions.

Commercial computer Nanomind on SamSat-218D has ability to control all elements of nanosatellite as experimental on-board computer. Commercial computer is used for alternate to experimental on-board computer in case its failure.

There are any sensors in experimental computer to improve reliable of nanosatellite and high precision of measurements.

Chart of the interaction of the constituent elements of experimental computer is presented in the Fig. 3.

![Diagram of SSAU experimental on-board computer](image)

The computer has two processors. Since the processors will also be flying skills, it was decided to use different processor manufacturers. More productive processor LPC 4300 is dual core and manages the magnetic coils, has
interfaces to communicate with the memory SDRAM and flash. Less productive ATxmega128 used to improve the reliability of the onboard computer. Both processors have the relationship part on UART interface, they can track the status of each other and restart neighbor.

To increase the reliability of nanosatellite both computers have the ability via the internal bus is to get information from embedded sensors: gyroscope, accelerometer, magnetometer. Using the multiplexer on internal I2C bus also be able to receive information from sensors experimental solar panels. The obtained information is stored in the memory elements. To improve the reliability and the purpose of flight qualification were applied different types of memory elements. The on-board computer has as a shared memory for both processors and optional, used only with LPC4300 processor.

Power to all elements of experimental on-board computer is controlled by a special module, which in case of an accident in the consumer return the alarm to the processors to exclude information from the alarm module from the calculations.

All telemetry from sensors of experimental computer, if necessary, can be transmitted over the common UART bus in the commercial computer Nanomind.

3. SamSat-218D algorithms structure

Control on-board system executes the software, which consists of two blocks. First block implements the solution of navigation, orientation and stabilization tasks and second block is the “intellectual element”.

The navigation algorithms have three information sources on the board: magnetometers, sun light sensors and angular rate sensors, that provide us with the following information: \([HX, HY, HZ]^T\) – the components of Earth magnetic vector; \([SX, SY, SZ]^T\) – the components of the deviation from the direction of the Sun; \([\omega X, \omega Y, \omega Z]^T\) – the projections of the nanosatellite momentary angular rate. Depending on the possibility of obtaining data from the information sources used different modifications of navigation algorithms.

If all information sources are available, in navigation algorithm apply the Kalman filter by three dimensions. In the case of magnetic coils work and cope with the task orientation, B-dot algorithm is used. If no information is available from angular-rate sensors, the Kalman filter by one dimension and Triad algorithm according magnetometer and light sensors is used. If information from the solar sensor is not available, loosely coupled scheme by magnetometer is used. [2]

As on the board there are any similar sensors (experimental and commercial magnetometers, gyroscopes, light sensors in the solar panels), the algorithm of navigation, orientation and stabilization is provided by replacing source of information source on the similar in case of failure one of the sensor.

There may be situations when the on-board control system cannot calculate the navigation solution. This may be caused by the necessity of frequent use of data samples from the sensor (due to sensor failure) or processing power on-board computer. In this case, on-board system of control proceeds to an integrated mode of operation with a ground control center.

Scheme of interaction onboard control system and ground control center is shown in Fig. 4.

![Communication between SamSat-218D and the ground control center.](image)

Telemetry data is transmitted from the board to the ground control center. Using this information as the initial conditions, a motion prediction nanosatellite is completed using complex mathematical models. As a result such
data processing is generated set of control commands. It is a program of flight for the period of time before the next communication session. During this time, the on-board control system operates on the program of flight received from the ground control center only. Own control algorithms are not used.

At the next communication session on-board control system transmits telemetry information, which is compared with the results of preliminary calculations and is used to further flight program.

Effectiveness of the implementation of the nanosatellite aims is linked to ensuring the survivability of nanosatellite, which is understood as the ability to adapt to the current situation, to resist and to save the set of critical functions under unforeseen effects on the nanosatellite. [3] Thus, besides implementing algorithms navigation and orientation, the computer control of nanosatellite elements to achieve its high survivability.

The state of nanosatellite elements is necessary to be considered when on-board system controlling of these. So, when a failure occurs in any element, it can’t properly perform the task assigned to him onboard control system. In this case is possible to issue an incorrect control to the other elements of the nanosatellite.

Verification of component’s failures can be performed either sequentially cycle with a certain interval of time, or in fact refer to an item (before receiving or transmitting data or send control signals). The second way has the advantage, since it is the least expensive in relation to energy and computational resources of the side that is most relevant for nanosatellites.

Also the sequentially cycle verification algorithm does not give information about the state of the element up until the element is not used. Therefore, there is a case when the command queue will be loaded on the board to use a defective item satellite.

The failure of the nanosatellite element may leading to increased power consumption, thus for saving energy balance of the nanosatellite is advisable to disconnect the faulty element.

Method for determination of failure in each element depends directly on the type of item. Thus, the sensor failure can be found by the following methods:

- Range checking the return value. Failure is recorded if the value is outside the allowable range (is not real);
- The majority logic. The return value is different from the two values obtained from alternative elements;
- Check power failure. On error, the element corresponding to the power supply controller will issue in the on-board computer error signal.

Failure of memory elements can be detect by checksum read information. Before writing data to the memory test is performed by one cycle read and write operations. Failure of the memory element is fixed, if there is a checksum error, or if the data read-after-write did not coincide with the original data.

To prevent a complete discharge of the battery is necessary to monitor the voltage level on it. When the voltage value is reached the minimum, the power of all the elements of the nanosatellite is switched off, except the receiver-transmitter and a main onboard computer. The flight program is interrupted until the partial recharge the battery to the allowable value.

In addition to information about the element failures on the board to ensure the survivability, need to have a base of possible ways of exception of defective nanosatellite element from the on-board flight program.

In order to avoid the usage of a defective item is not in break of the mission the board must have redundancy. Redundancy may be of any types:

- Structural redundancy – any copies of the nanosatellite elements on the board;
- Informational redundancy – opportunity of get the same information from any sources;
- Functional redundancy – several different elements of nanosatellite can perform the same function. [4]

Analysing the composition of nanosatellite SamSat-218D, its elements can be divided into groups by type of redundancy:
- Structural redundancy: duplicate of SDRAM and microSD memory elements in an experimental computer, any solar panels;
- Informational redundancy: sun light sensor and solar panel as light sensor, commercial and experimental magnetometers, accelerometers, gyroscopes, solar panels and antenna elements;
- Functional redundancy: commercial and experimental on-board computers, any memory elements of different types, any sensor sets for the same tasks.

Redundancy resource on the board is a potential that should be used to improve the survivability of the spacecraft. This requires the algorithm to determine at what point should use excessive resources. This algorithm identifies the elements of the nanosatellite, which has occurred a situation that happened a failure, or has a tendency to go into denial.

In this case, the algorithm must imply operative selection and use of alternative elements or a different algorithm. To this must be stored onboard database of alternative elements on board of each type of element. This information is provided in the form of sequences in Table 1.

| On-board system or element | Sequence of alternative hardware elements |
|---------------------------|------------------------------------------|
| On-board computer         | Experimental SSAU computer               |
|                           | Commercial Nanomind computer             |
| Accelerometer             | Accelerometer in experimental SSAU computer |
|                           | Accelerometer in commercial solar panel  |
| Magnetometer              | Magnetometer in experimental SSAU computer |
|                           | Magnetometer in commercial Nanomind computer |
| Gyroscope                 | Gyroscope in experimental SSAU computer  |
|                           | Gyroscope in commercial solar panel      |
| Solar panel               | Commercial solar panels                  |
|                           | Experimental solar panels                |
| Sun sensor                | Sun sensors in commercial solar panels    |
|                           | Sun sensors in experimental solar panels  |
|                           | Voltage value on commercial solar panels as sun sensor |
|                           | Voltage value on experimental solar panels as sun sensor |
| Memory element            | MicroSD memory in commercial computer    |
|                           | MicroSD memory (two elements) in experimental computer |
|                           | Flash memory in experimental computer    |
|                           | SDRAM memory (two elements) in experimental computer |

For each sequence we can select one element as the default, it is recorded in a first sequence position. Each next element is the most preferable among available on board and serviceable minimum energy criteria for maximum precision and the minimum error. Some elements do not have a nanosatellite provision, there is no element capable of performing the function of an alternative.

These elements include: the power supply system, including the controller and battery, receiver-transmitter, including the antenna feed lines. The failure of one of these elements leads to a loss of control of nanosatellite.
4. Modeling and test algorithm

The purpose of the modeling is to test and improve the algorithm to ensure the survivability of the board. During the modeling must simulate each of the possible (provided) nanosatellite element's failures.

Failure of the individual elements nanosatellite leads to the inability of other elements or system of the board. The identification of such relationships is possible by building the fault tree.

This tree has at its top the most common element. It is “nanosatellite”. Each next level are the constituent elements of the previous level. Thus, the “nanosatellite” is composed of control, power and communication system. If one of these systems fails, it can be said that the nanosatellite also failed.

Each of these systems can be divided into smaller parts whose failure jointly or separately, leading to system failure. This level of detail continues for as long as possible to accurately determine the cause of failure in any element. Thus, in case of failure of receiving and transmitter is able to determine out of order receiving part or transferred. At the lowest level of the tree are written specific ways to detect failures.

Simplified fault tree for SamSat-218D in part of communication and electric power supply system is shown in the Fig. 5 and in part of control system is shown in the Fig 6.

This fault tree can serve as a map for the validation of the “intellectual element” of the on-board control system.

In the processes of modeling and testing algorithms is made deliberate violation of the board of one of the proposed methods or a combination thereof:

Fig. 5. Faults of communication and power supply systems.
- Switch power off one of the some elements of the board. For minimum changing of the nanosatellite hardware it can be present as disabling refer to these “switched off” elements.
- Modeling over-consumption in one of the elements of the board. It can be present by simulating error signal from power supply controller.
- Break data bus data exchange. It can be preset in software level too as disabling refer to the bus interface.
- Modeling deviation measurement results issued by the sensor.

Reaction of on-board system to the effects is a reconfiguration of the board: changes in the set of elements that be used in the algorithms work, changing schemes of information exchange on the board, changing algorithms for processing data received from the sensors.

In case of failure important element of nanosatellite (for example, all magnetometers, all gyroscopes) and on-board system can not effectively control flight, control goes to the ground control center, as described above.

The consequences of the accident in the on-board system is minimized, on-board system is able to perform the tasks of the nanosatellite with maximum efficiency in the new conditions of flight.

After mathematical modeling the algorithm of detection of the failure in the elements of the nanosatellite will be tested during ground tests, as well as in space flight. In the result of using this algorithm is planned successful testing of new technologies.
5. Conclusions

Nanosatellites owing to the small size and weight have low reserves of energy. In those conditions we should strive to use all available measurements, which even indirectly help to get an idea of the important flight parameters.

In addition to the equipment aboard the modern appliances need to worry about the safety of the spacecraft, to implement a system to detect and localize failures.

Intelligence is relevant for nanosatellites because they are made from commercial components that are not designed for space use.

The provided fault tree will be tested in flight by active experimentation. The results of the experiment will allow to realize nanosatellite, which is intended to remote sensing of the Earth.

Building an effective system to ensure survivability nanosatellites will make space experiments qualitative and effective, as well as to enter the new stage of development nanosatellites.

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