Solution of the problem of remote sensing small spacecraft onboard equipment integration through mathematical and simulation modeling of its operation

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Abstract. Due to the ever-increasing complexity of target tasks solved by remote sensing small satellites, and increase of the operational period of their active existence, problems arise in ensuring reliability and trouble-free operation of satellite payloads and spacecraft as a whole. To solve these problems, an advance in design, construction and management technologies is required. In contrast to the use of the principles of redundancy and backup of the main functional units of the on-board system component (OSC) in order to improve reliability and survivability, the problem of intersystem integration of OSC is considered, which allows to change the behavior and structure of the system not only at the design stage, but also during the target operation.

1. Introduction
Spacecraft should be very reliable and have high survivability due to the fact that interfering with the hardware after its delivery to the orbit, as it is done in terrestrial laboratory conditions is difficult, and the repetition of the experiment will cost a significant amount of time and money.

Typically, survivability refers to the property of the system to adapt, to resist and maintain a minimum set of critical functions in the context of unforeseen (emergency, non-routine) impacts on the system of external and internal destabilizing factors due to changes in the behavior and structure of the system. External and internal destabilizing factors can include: the impact of space factors on the equipment, halting and failures of the on-board equipment, structural deformation, loss of control and resources, unauthorized interference in the control loop, off-nominal operating modes, etc.

The reliability and survivability of the system can be increased by increasing the reliability of its components, structural and functional redundancy, creating and implementing new design and construction techniques, models for building and organizing the system [1-6].

A remote Earth sensing satellite is a complex technical object, comprised from multiple OSC. Each OSC performs a particular function. The set of functions performed simultaneously by variety of OSC, describes a certain mode of operation of the satellite. Typically, within the mission there can be from five to 30 separate modes or more. A single OSC can be involved in one, in several or even in all modes or on-board tasks. Thus, there is a multi-purpose nature of the OSC application. Nevertheless, the degree of OSC participation in operating modes for modern satellites is insufficient. Some OSC participate only in one mode, occurring only once.

One of the ways to increase the degree of system’s involvement, as well as to improve the efficiency and reliability of the satellite for remote sensing, is the development of a comprehensive
model and new design and construction principles aimed at expanding the OSC functionality and their integration.

To integrate OSC into larger-scale functional structures, each component (device, bracket, assembly) should be described by a complex model, including the description of the force loading, heat transfer patterns, assembly and installation and functions. At the same time, the design and manufacturing methods should be aimed at reducing the mass of the components and the satellite as a whole, improving the reliability of the payload, and increasing the survivability in non-standard flight scenarios.

Solving the problems of increasing survivability and reliability calls for setting and solving optimization problems for the choice of composition and parameters of onboard systems.

2. Integration problem description

The problem is described as follows: let a certain range of external and internal factors $X$ be given, to each of which there corresponds a vector of task defining characteristics $x_j = \{x_{j1}, x_{j2}, \ldots, x_{je}\}$. It is necessary to define a strategy $A$, that would include a minimum number of elements (centers) of the solution set $Y$ ensuring the satellite’s response to any external and internal factors from the set $X$, while:

a) onboard composition of satellite’s systems defined by parameters $\vec{p}$ can respond to any internal or external factor $x \in X$;

b) the number of permissible actions $a_{\mu i}$ to any internal or external factor should be maximal, but not less than two;

c) the number of strategy elements (onboard elements) $p$ must be the maximal;

d) the vector function of relative losses in the implementation of the strategy on the set $X$ reaches its minimum value when $\min_{i=1...n} \phi(x, Y, a_{\mu i})$.

The algorithm of the problem of OSC integration can be reduced to determining the vector of the basic composition $\vec{p}$, finding the optimal set of admissible reactions for each external or internal factor for any state vector of the satellite and analyzing the vector function of the relative losses.

Within the regular functioning of the satellite, the relative loss when implementing an external factor by a strategy with optimal responses will always be less than the relative loss when the external factor is implemented with a strategy that is not optimal but acceptable. The value of the vector efficiency criterion will be high.

In case of abnormal functioning of the satellite, the relative loss when implementing an external factor by a strategy with reactions that are not optimal, but acceptable will not be minimal, but the value of the vector efficiency criterion will be higher than the value of such a criterion without an appropriate replacement.

3. Indicators and criteria of ensuring survivability

Quantitatively, survivability can be described in various ways. Survivability can be represented as a functional that depends on the composition of the deviations of the calculated values of the system’s indicators from their nominal values as they are given in the technical specification [7, 8]:

$$\delta I = \int_{T_{\mu}} \left[ f_1(\Delta x_1) * f_1(\Delta x_2) * \ldots * f_1(\Delta x_{n}) \right] dx_n dx_{n-1} \ldots dx_1. \quad (1)$$

In the equation (1) $*$ composition sign; $\Delta x_i$ – deviation of system performance from nominal values; $n$ – number of system indicators considered.

If we take into account the deviations in relative values, then for the remote sensing small satellite basic exponent the functional can be represented in the following form:
\[ \Delta I = F \left( \frac{\Delta T_{nom,i}}{T_{nom,i}}, \frac{\Delta K}{K}, \frac{\Delta N_{CP}}{N_{CP}}, \frac{\Delta N_{nom,i}}{N_{nom,i}}, \frac{\Delta T_{cons}}{T_{cons}}, \frac{\Delta T_{AL}}{T_{AL}}, \ldots \right). \]  

(2)

In the equation (2): \( \Delta T_{nom,i} \) is the temperature deviation of the \( i \)-th equipment unit from the nominal value \( T_{nom,i} \); \( \Delta K \) is the deviation of the stability vector of the installation sites of the sensing elements of the motion control system from the nominal value \( K \); \( \Delta N_{CP} \) is the number of deviated values from the whole set of controlled parameters of the satellite \( N_{CP} \); \( \Delta N_{nom,i} \) is the number of deviated values from the whole set of controlled parameters of the satellite \( N_{nom,i} \); \( \Delta T_{cons} \) is the deviation of the delivery speed of information to the consumer; \( T_{cons} \); \( \Delta T_{AL} \) is the deviation of the active life of the satellite from the nominal value \( T_{AL} \); \( \Delta N_{nom,i} \) is the power consumption deviation of the \( i \)-th unit from the nominal value \( N_{nom,i} \); \( \Delta T_{cons} \) is the deviation of the speed of delivery of information to the consumer; \( T_{cons} \); \( \Delta T_{AL} \) is the deviation of the active life of the satellite from the nominal value \( T_{AL} \); \( \ldots \) - deviations in other indicators considered by the satellites developer.

The task of selecting the parameters of the MCA that ensure maximum survivability can be described in general form as a problem of mathematical programming:

\[ F \left( \frac{\Delta T_{nom,i}}{T_{nom,i}}, \frac{\Delta K}{K}, \frac{\Delta N_{CP}}{N_{CP}}, \frac{\Delta N_{nom,i}}{N_{nom,i}}, \frac{\Delta T_{cons}}{T_{cons}}, \frac{\Delta T_{AL}}{T_{AL}}, \ldots \right) \rightarrow \text{min}. \]  

(3)

Constraints:
- mass of the satellite should not exceed the specified limit;
- the cost of development, manufacturing and testing of the satellite should not exceed the specified limit;
- development time should not exceed the specified limit.

In this paper we have used the indicator of Biessiot as an indicator of survivability, [7, 8] is used:

\[ \beta 1 = \frac{C_{reac}}{C_{dang}}. \]  

(4)

In the equation (4) \( C_{reac} \) is the response rate, and \( C_{dang} \) is the speed of the threat spreading within the system.

Survivability should be determined not only for a particular system, but also for a chain of systems that form contours solving specific functional problems [7]. There are quite a few of such contours in the structure of the satellite.

The contour satisfies the requirement of survivability, if for the whole set of included systems the following expression holds true:

\[ \Lambda_{in} \left( \beta 1 \bigg|_{t_{add}} - t_{c.c} \geq 0 \right) = 1. \]  

(5)

In most cases, the moment of occurrence of an abnormal situation does not coincide with the moment of its detection. Let us call the difference in the onset of these moments the lifetime of the hidden state of the contingency (\( t_{c.c} \)).

Taking into account \( t_{c.c} \) and \( t_{add} \) the survivability requirement can be presented as:

\[ \int_{t_{c.c}}^{t_{add}} C_{reac} dt \geq \int_{0}^{t_{add}} C_{dang} dt . \]  

(6)

If \( C_{reac} \) and \( C_{dang} \) are constants then \( C_{reac} (t_{add} - t_{c.c}) \geq C_{dang} t_{add} \). In this case, the modified indicator of Biessiot for the survivability takes the following form:

\[ \beta 2 = \frac{C_{pea}}{C_{yp}} \geq \frac{t_{dang}}{t_{c.c}} - t_{dane} \cdot \text{или } \beta 2 \geq \frac{1}{1-t_{c.c}/t_{dane}}. \]  

(7)

For various systems and contours, the values used in these indicators \( C_{reac}, C_{dang}, t_{add}, t_{c.c} \) have different values. For example, the contours of the power supply system and the thermal control system can be referred to as "slow" circuits \((1.5 \leq t_{c.c} \leq 3 \text{ hours})\), the contour of the orientation control system - to the more "fast", the processes in the products of semiconductor electronics - to "very fast". Therefore, each of the contours must be approached accordingly.
4. Principles of integration in small satellites design

The principle of integration consists in combining elements (structural, electrical) into a system and creation of intelligent control algorithms in order to obtain higher (compared with individual elements) performance indicators and reliability. Within the framework of this direction, models of different technical aspects are developed, each of them contains parameters of all components of the satellite: the model of power loading, heat balance, technological scheme and payload operation. These models have a close connection with each other.

Integration is achieved by [9]:
- OSC combine. It can be manifested as a structural unification and interconnection of OSC without loss of functions for each of the elements;
- OSC unification in accordance with accepted standards, unified design requirements, using standard sizes. At the same time, OSC are included in the satellite’s assembling scheme. This might also increase the convenience of the satellite’s structural arrangement with a simultaneous decrease in the weight of the satellite, the assembly and disassembly of the satellite could be also simplified, the thermal regime optimized, the replacement of the failed OSC is facilitated;
- unification of the communication interfaces and information exchange protocol of the OSC;
- integration of some satellite OSC into the design of another OSC or the load-bearing structure of the satellite. In this case, however, the structural loads applied to the satellite will also transition to the integrated equipment;
- interchangeability of individual functions of instruments and OSC. In case of a malfunction of a single unit it would be possible to redistribute the lost functions between the instruments and OSC modules using the intelligent algorithms for controlling the on-board software. At the same time, the further accomplishment of the main task of the satellite is ensured, the reliability and survivability of the satellite as a whole is increased.

5. Integration of modules into the structural scheme of the satellite

One of the key directions of integration, allowing a decrease in the mass of the satellite and an increase in the degree of participation of the onboard elements in operating conditions, is the OSC unification in accordance with accepted standards and the integration of separate OSC into each other or the load-bearing structure of the satellite.

Such unification can be implemented by comprising unified OSC into packages and their installation on the honeycomb panels (see Figure 1).

In order to implement this approach:

- the principles of unification were developed for suggesting recommendations for the choice of form factor (sizes) of modules, based on the required onboard targets for the satellite and the smallest OSC and recommendations for the OSC integration if several small in size OSC are available;
- OSC integration requirements, including:
  a) the need for solid-state and simulation modeling to optimize the internal and external layout of standardized modules, optimize the length of communication lines, optimize the thermal regime, optimize the accuracy of mutual installation of modules and sensors of the attitude control system;
  b) the need to ensure the convenience of working with the product at all stages of ground operation (assembly, testing, repair);
  c) the need for implementation into the design documentation techniques that guarantee a high level of unification of modules (the unity of the basing surfaces, geometry, size, surface accuracy, requirements, attributes);
  d) other production requirements;
- the method of arranging unified and non-unified modules in the satellite’s layout, providing optimization of the composition of the module packages (number of packets, composition of OSC in each package), optimizing the thermal conditions of the satellite, optimal aerodynamic configuration, maximum assembly density, minimizing the length of the on-board cable network.
Figure 1. Layout of unified modules of onboard equipment.

6. Modeling

Solid-state and simulation modeling have been carried out to optimize the internal and external layout of unified modules, optimize the lengths of communication lines, optimize the thermal regime, optimize the accuracy of the mutual installation of modules and sensors of the attitude control system.

A project of the optoelectronic remote sensing satellite has been chosen as a prototype (see Figure 2). It consists of two unsealed modules -payload and supporting systems. The structure consists of a frame with honeycomb panels of material B95, 18 mm thick. Inside the honeycomb panel there are threaded and smooth bushings made of material D16 and heat pipes made of corrosion-resistant alloy AD31. To redistribute heat between adjacent and opposite housing panels, contour heat pipes are installed. All honeycomb panels are mounted on the frame on heat-conducting paste. All OSC are installed on the inner or outer surface of the honeycomb panels by attaching them to the threaded bushings.

The mass of the satellite, its payload, and structure are 124.38 kg, 27.77 kg, and 23.5 kg, respectively. Axial moments of inertia: 8.5; 39 and 40 Nm². The ratio of the mass of the payload to the mass of the satellite is 0.22 and does not correspond to the current level of development of space technology (0.25 ... 0.5).

The satellite, designed using the developed principles of integration, is shown in Figure 2 on the right. All on-board equipment, including 37 instruments, was modeled anew except for six instruments (two units for determining the coordinates of stars, four flywheel engines, antenna communication devices), since it is not beneficial to standardize them.

The modernized satellite received an open architecture. The prototype’s payload is reused. Standardized modules of onboard equipment with unified dimensions of seating surfaces 150mm x 150mm or 150mm x 300mm (depending on the volume of a particular element) are assembled in two packages that are located on both sides of the payload. The grouping of modules in packages meets the requirements of minimizing temperature gradients and minimizing the length of the on-board cable network. The basic assembly element is the lower honeycomb panel with a thickness of 32 mm, on which the module packages and the payload are mounted. Another honeycomb panel is located in the upper part of the case. The load-bearing structure of the satellite is formed with the lower honeycomb panel and the module housings. Non-integrated OSC are installed on special brackets and then on one of their two panels. The mass of the modernized apparatus and its construction is estimated to 115.2 kg and 16.5 kg, respectively. The average density of the layout has increased from 347.2 to 597.5 kg/m³. The mass of the payload to the mass of the satellite ratio became 0.25. Axial moments of inertia: 7.6; 33 and 37 Nm².

The propulsion system is made in the form of a standardized module. The xenon feed unit and the fuel storage tank were also integrated into the design of the standardized module.
In order to analyze the effectiveness of the proposed unification from the viewpoint of estimating the energy costs for the operation of the attitude control system, the thermal management system, and the fulfillment of the strength and rigidity requirements, the operation of the executive bodies of the attitude control system in the MathCad package and finite element simulation in the ANSYS package were performed.

To assess the energy resources spent on the management of the satellite, a numeric simulation of the spatial rotation with executive bodies such as flywheel motors was performed. The rotors were parallel to the main central axes of the satellite. The simulation was carried out according to the method described in [10], based on the principle of minimum control. Figure 3 shows a graph of the change in the total power consumption by the engines of flywheels when performing a typical turn of the satellite-prototype and the satellite with integrated equipment composition.

A comparative analysis of the energy requirements for the satellite-prototype and the satellite-integrated equipment was carried out. The average power consumption of the flywheel assembly during the maneuver for the prototype was 6.93 W, while for the satellite-integrated equipment it was 5.75 W, which is 17% less.

The finite element simulation in the ANSYS package confirmed the compliance of structural parameters of the satellite.

Implementation of the developed methods makes it possible to reduce the weight of the satellite's structure by 11 ... 23% by including OSC into the structural-scheme.

Doing so:
- increases the rigidity of the MKA power structure
- improves the accuracy of determining the planar coordinates of the objects (by increasing the stability of the installation sites of sensitive elements of the motion control system);
- increases the average density of the layout from 300...400 to 550...620 kg / m$^3$;
The energy consumption of the thermal control system is reduced (by 45 ... 65%) due to the optimization of the temperature conditions of the operation of the OSC modules; 
the energy consumption of the motion control system is reduced (by 15 ... 24%) due to the reduction of the satellite main moments of inertia.

The result is the significant minimization of the target survivability function \( F \) (see equation (3)). Integration of the onboard equipment into the load-bearing frame allows to achieve survivability indicators not lower than the values presented in table 1. The results were obtained by processing the results of numerical simulation of satellites functioning.

### Table 1. Norms and values of the indicator of Biesiot.

| System name            | Norm of the indicator of Biesiot \( \beta_1 / \beta_2 \) | Value of the Biesiot indicator for a satellite without/with integration |
|------------------------|----------------------------------------------------------|------------------------------------------------------------------------|
| Thermal control system | 1 / 1.14                                                  | 9.6 / 12                                                               |
| Power supply system    | 1 / 1.5                                                   | 2 / 4.2                                                                |
| Navigation equipment   | 1 / 1.55                                                  | 3.5 / 5                                                               |
| Communication system   | 1 / 1.06                                                  | 16 / 18                                                               |
| Payload                | 1 / 1.6                                                   | 3 / 8.5                                                                |

According to table 1, the satellite with system’s integration has an increased survivability relative to its prototype without system’s integration.

7. Integrated design recommendations

The principles of integration should be taken into account from the stage of formulation of "Terms of reference", developed at the stage of "Draft design" and finalized at the stage of "Technical design". The later design stages are not affected significantly.

The decision on the integration inevitably leads to the implementation of the solid modeling of the packages of modules layout at the design stage in order to:

- optimize the mass-inertial characteristics of the assembled satellite;
- ensure the convenience of working with the product at all stages of ground operation (assembly, testing, repair);
- ensure the accuracy of mutual installation of modules and sensors of the attitude control system;
- optimize the heat distribution through thermal modeling.

Each of these requirements sets a task that has its own efficiency criterion. The task of design generalizes these criteria into a complex one.

8. Units and systems functions integration

The impact on the satellite of various combinations of internal and external factors that were not anticipated during the design stage often lead to serious failures, up to the termination of the entire spacecraft. This, as a rule, occurs with OSC, created using integrated circuits (ICs) [3, 4]. 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 effects.

Creation of on-board software capable of integrating functions of onboard units and systems allows to increase survivability and extend the life of the satellite by redistributing functions between operational equipment and implementing a new logic of work. Here is a list of the investigated possibilities of such integration:

- transfer of the solver functions from the onboard control system (OCS) processor to service system’s control elements - in the event of a OCS failure;
- use of the payload’s communication link for transmission to the ground control complex of the service information - in the event of the failure of the “satellite-to-ground” radio link;
- determination of orientation using current values from solar panels - if the solar sensor fails;
- use of the power capabilities of the low-thrust propulsion system for moving the satellite into a working orbit - in the event of a failure of the main propulsion system;
For any of the possible cases of redistribution of functions, the efficiency of the device that received an additional function, or of another system in the same information circuit with this device, decreases, but the operation of the satellite as a whole continues. The useful lifespan of the satellite also increases.

9. Conclusion

To implement the principles of integration, it is necessary to develop techniques for the design, development and use of new standards in the creation of satellite equipment, the indispensable use of solid-state, finite element and simulation modeling.

The OSC integration helps to reduce the satellite's mass, increase the density of its layout and, accordingly, the life span, reduce the power consumption of attitude and thermal control systems, improve reliability and survivability of the system.

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