Cognitive-synergetic approach to the design of automated spacecraft with onboard systems with variability properties

Vladimir S. Kovtun[a] and Alexander N. Pavlov[b,c]

[a] *S.P. Korolev Rocket and Space Corporation Energia (RSC Energia).4A Lenin Street, Korolev, Moscow area, 141070, Russia*
[b] *Federal state budgetary military educational institution of higher education «Military space Academy named after A.F.Mozhaysky» of the Ministry of Defence of the Russian Federation, Zhdanovskaya st., 13, Saint-Petersburg, 197198, Russia*
[c] *Saint Petersburg Federal Research Center of the Russian Academy of Sciences (SPC RAS).14th line of Vasilievsky island, 39, Saint Petersburg, 199178, Russia*

Abstract
Increasing the resource support for the flight of automatic spacecraft (AS) under the existing design restrictions on the mass of onboard systems (OS) and the power of power sources is an important scientific problem. One of the ways to solve the problem is to form relationships between elements of different systems during the design and development of control systems, which allow simultaneous control of several control objects (CO) using one system, thereby providing the solution of two or more functional tasks. At the same time, the composition of on-board controls is reduced or additional functional reserves are formed while maintaining it. This provides additional resources and increases the survivability of the AS.
The article discusses a general approach to the design of OS control systems that simultaneously perform several functions in synergistic interaction. The possibility of practical implementation of the system construction based on the proposed approach is shown by the example of designing a phased antenna array of an on-board radio engineering complex.
Keywords
Automatic spacecraft, phased array antenna, control object, synergy, variability, onboard resources, cognitive, system.

1 Introduction

To supplement the on-Board structural and functional resources of the AS with *synergetic resources* [1,2], a *cognitive-synergetic**) system approach to the development and construction of OS management methods was developed. The essence of the approach is a cognitive system study of the characteristics of AS as an open, nonlinear complex technical system, taking into account the synergistic phenomena in its OS. Based on the cognitive-synergetic approach, a new principle of synergetic - variable design of control systems are developed, which includes *subsystems* that have the *ability to control* several on-Board processes in different control objects (the property of variability). Systems that have this property are called "variable process control systems".

To explain the initial provisions of the principle, Figure 1 shows a diagram of a dynamic model of a variable system-a process controller, which shows two control systems CS1 and CS 2 that have a synergistic energy relationship. Each of the systems initially consists of control subsystems CSS1, CSS2 and control objects CO1, CO2 [3]. In turn, each CO is represented by its own state blocks SB1, SB2, which are on-board AS systems, and output blocks OB1, OB2.

*) cognitive-synergetic approach - "cognizing joint activity": adjective "cognitive" from Latin cognitio knowledge, cognition; "synergetic" adjective from "synergy" - from Greek. συν-prefix with the meaning of compatibility and εϱγον "activity".

Models and Methods for Researching Information System in Transport, Dec. 11-12, St.Petersburg, Russia
EMAIL: kovtun_v11@mail.ru (V.S. Kovtun); Pavlov62@list.ru (A.N. Pavlov);
ORCID: 0000-0002-1201-6558 (V.S. Kovtun); 0000-0002-6193-8882 (A.N. Pavlov).

In addition to these, the following set designations are introduced: X1, X2 - States of CO1, CO2; Y1, Y2-outputs of CO1, CO2; Ξ-disturbing effects; U_1, U_2-control effects on CO1, CO2. In this case, the control is carried out through the sets of input actions V_1 and V_2, built on the binary relations of Cartesian products $V_1 = U_1 \times \Xi$, $V2 = U_2 \times \Xi$.

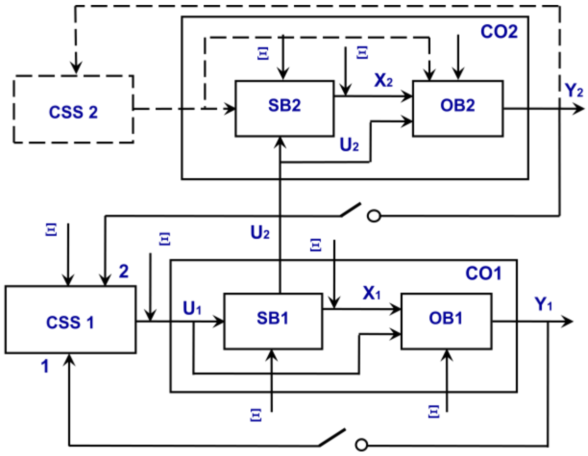

Figure 1. Diagram of a dynamic model of a variable system-process controller in SB1, SB2

As can be seen from Figure 1, the traditional control of SB2 in CS2 through CSS2 is replaced by control through SB1, taking into account the second feedback between OB2 and CSS1. In this case, the output of OB1 is connected to the first input of CSS1. The control action U_1 is formed taking into account the fact that when SB1 performs its functions, the processes simultaneously form the control action U_2 for SB2. At the same time, the condition of maintaining the functionality of SB1 is met, including after the termination of control over the U_2 line. SB1 as part of CO1 is the "control subsystem" for SB2 in CO2. The presence of control over the U_2 line creates a functional reserve for the control of the CO2. If you do not use the line, then you need to use an additional CSS2 to control the OP2. Thus, CS1 has the "property of variability" in the form of existing control options SB1 or SB1 and SB2, i.e. it is simultaneously a process control system in two on-Board systems SB1 and SB2.

The criterion for evaluating the properties of a variable process control system can be the coefficient of variability (K_{var}), which is equal to the maximum possible number of processes controlled by a single system. In this case, K_{var} = 2. the use of synergistic phenomena as a result of process interactions makes it possible to design systems that control several processes at once.

In contrast to the property of multi-functionality of systems, in which a separate system-process controller performs several functional purposes due to its structure in the form of a set of elements and relationships between them, variable systems implement additional functions due to the interaction of systems, in the presence of synergistic relationships in the processes. The multi-functionality in figure 1 would be denoted by the set of outputs of the CO1. For example, jet flywheels (JF) with regenerative rotor control windings simultaneously perform the functions of a power gyroscope and an electric power generator when the rotor is decelerated [4]. Thus, each JF is a two-function system. Therefore, if the considered principle of synergetic - variable design of control systems is observed, a multifunctional system can also become variable.

The design task is to obtain and use a priori information about the variability properties of regulatory systems to create new methods for controlling AS. This expands the scope of searching for solutions to functional problems in the complex process of flight control of the vehicle, complementing its structural and functional onboard resources with synergistic resources. In addition, the variability of process control systems can provide pre-prepared technical measures that increase the survivability of on-Board systems. The calculated reserve for parrying abnormal flight situations in case of failures are elements of other variable control systems used in the new functional purpose.

2 Phased array antenna as a control object

Currently, flat phased array antennas (PAA) are increasingly used on Board the AS in solving problems of providing personal satellite communications, including retransmission of signals from a personal mobile subscriber trunk and exchange of special control information with ground vehicles via the main communication channel [5]. Due to a number of technical advantages, large-sized mirror antennas are gradually being "replaced" by PAA. The primary element of the PAA are radio signal emitters that provide electronic movement of the beam in one plane [5]. Circular controlled (switchable) left or right direction of rotation polarization of radiation and signal reception is created in a system of orthogonally polarized emitters with a combined phase center.

Each PAA contains a construction plane on which the working surface is placed, formed from the receiving and transmitting modules (RTM) (figure 2), combined in panels. The external surface of the modules consists of a set of emitters of the same type.

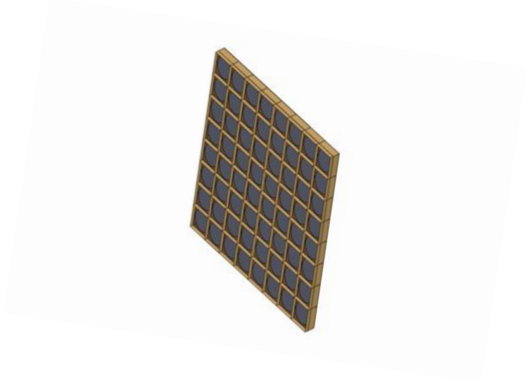

Figure 2. The design of the PAA module

Each RTM consists of an antenna web made in the form of a multi-layer printed circuit Board divided into cells (for example, see figure 2, a total of 64 square cells, with an 8×8 placement). In this case, the RTM contains an emitter, a matching circuit, a power amplifier (which is the main consumer of electricity), an attenuator and a phase shifter in each cell of the modular element. Control units for attenuators and phase shifters, power supply, switchgear, and beam control and correction devices are used one at a time for several RTM [6], and their placement on panels is positioned with the placement of the RTM and is performed inside the web at the joints of modular elements. High-frequency currents flowing along asymmetric micro strip lines and RTM emitters do not create permanent magnetic moments [5]. In addition, currents that have their own magnetic moments flow through the primary and secondary power supply circuits of the RTM in the PAA [7].

The diagram of the current circuits of the secondary power supply of the RTM, projected on the working surface of the PAA module, is shown in figure 3, where the current directions in the modules are shown. The primary power supply is indicated by a line with a voltage of 100 V, and the secondary power supply is indicated by a line with a voltage of 5 V. At the same time, Figure 3a shows the scheme of separate power supply of modules from secondary power sources (SPS) SPS1 and SPS2 with multidirectional current flow, and in figure 3b — with the possibility of powering the module from one of the two SPS.

The arrows show the current directions in the PPM. For example, the current consumption of the RTM 30...40 mA, the area of the circuit that it covers in one cell is ~2.5 × 10^{-3} m^2. The number of RTM in the PAA, consisting of four panels, each of which has 64 modular elements containing 64 RTM, will be 16384 pcs. As a result of the calculation, the total current in the secondary power supply circuits of the RTM is ~500 ...650 A, and the total area of the circuits is ~41 m^2.

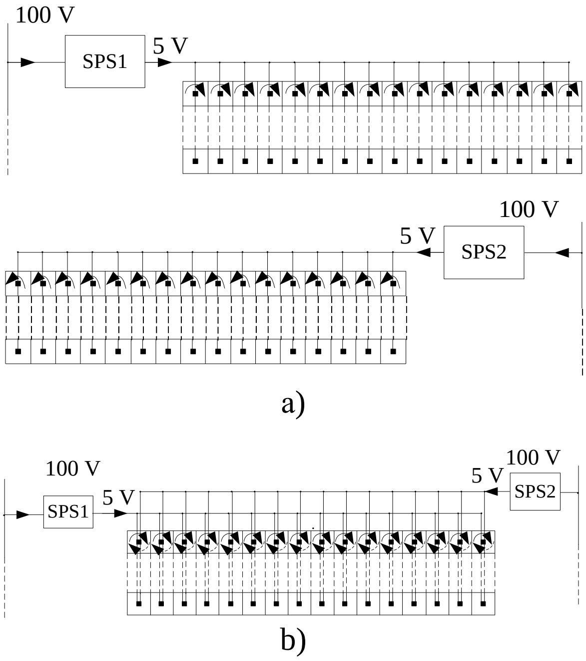

Figure 3. Scheme of current circuits of secondary power supply of transceiver modules: a-separate power supply of modules; b - with the possibility of power supply from one of the two SPS

3 Power gyroscope system as a control object

The system of power gyroscopes (PG) is designed to control the angular motion of the AS. The control is carried out according to the law of conservation of the kinetic moment for the AS as a closed system by exchanging between the kinetic moments of the AS body and the PG system. However, the system is not completely closed, since it is affected by external forces that create disturbing moments, among which the most significant are the moments of gravitational forces, light pressure and magnetic moment. In this case, the total vector of the kinetic moment of the $\vec{G}$ *(t)* is defined as the sum of the vectors of the kinetic moments of the body $\vec{K}$ (t) and the PG system $\vec{H}$ *(t)* [8]:

$$\vec{G}(t) = K(t) + \vec{H}(t),\ \vec{G}(t) = \vec{G}_0(t) + \int_0^t \vec{M}_в(t)dt,$$

where $\vec{G}_0(t$ - the initial value vector $\vec{G}(t)$; $\vec{M}_в = \vec{M}_{sd} + \vec{M}_{ge} + \vec{M}_{gm} + \vec{M}_{gs} + \vec{M}_{mm}$ - the main vector of external torque; $\vec{M}_{sd}$ – moment of force of light pressure $\vec{F}_{sd}$; $\vec{M}_{ge}$, $\vec{M}_{gs}$, $\vec{M}_{gm}$ – highlights from the gravitational forces of the Earth, Sun and moon, respectively; $\vec{M}_{mm}$ - is the magnetic moment, $\vec{M}_{mm} = \vec{L}_{cm} \times \vec{B}_E$, where $\vec{M}_{mm} = \vec{L}_{cm} \times \vec{B}_E$ - is the intrinsic magnetic moment AS; $\vec{B}_E$ - vector of the magnetic field of the Earth (MFE).

Under the action of $\vec{M}_в$, the kinetic moment accumulates in the PG system [9] to the maximum possible values ("saturation") of the region S of the available values. As an example, Figure 4 shows variants of the S region for different configurations of single-stage PG (jet flywheels).

In this case, the matrices A of the guide cosines of the kinetic moments of the rotors of the same type of flywheels are given $\vec{\Gamma}_1 ... \vec{\Gamma}_4$ and for comparative analysis, the evaluation of the regions s by an inscribed sphere with radius $R = |\vec{\Gamma}|$ carried out .

After "saturation" of the PG system, it is unloaded from the accumulated kinetic moment. One of the most common methods used for many years is the magnetic unloading method using magnetic Executive bodies (MEB) [11]. The applied methods for unloading PG from the accumulated kinetic moment using the control magnetic moment include the following actions [12]:

- measurement of the current value of the accumulated kinetic moment vector $\vec{H}$ in the PG system;
- measurement of the MFE induction vector $\vec{B}$;
- determination of the unit vector of the unloading moment $\vec{m}_r = \frac{\vec{L}_r}{|\vec{L}_r|} \times \frac{\vec{B}}{|\vec{B}|}$;
- generation of a control signal for current

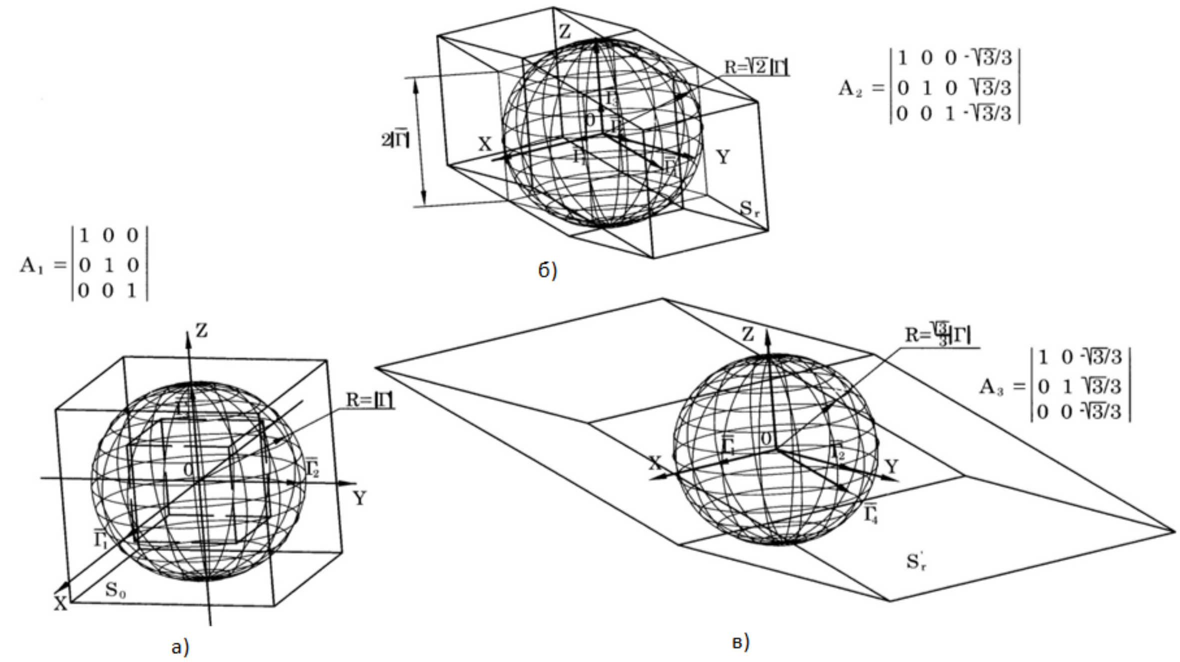

Figure 4. Options have the field values of the vector of kinetic momentum of a system of reactive flywheels with the axes of rotation of the rotors of flywheels along the three axes of the associated basis and one flywheel – diagonal of a cube with an arrangement of fins along the axes of the associated basis [10]

loops by changing the magnitude and direction of current flow in the MEB to ensure the conditions for unloading the PG from the accumulated kinetic moment

$$\vec{m}_r \cdot \vec{h} < 0, \qquad \vec{h} = \frac{\vec{H}}{\left|\vec{H}\right|}. \qquad (1)$$

4 Design of a phased array antenna with a controlled intrinsic magnetic moment

In the design of the PAA, the magnitude and direction of the current in the circuit of RTM are defined by p modes PAA – "receiving", "transmission", "reception-transmission" of radio signals of different power, where p = 1,2,...,P – number of modes of PAA, each of which is provided by the power supply in the q's of the circuits of the secondary power RTM, where q = 1,2,...,Q – the set of current circuits.

The result for each PAA module calculates the magnitude and direction of the vectors the intrinsic magnetic moments.

At the same time, they can have both positive $\vec{L}^{+}_{p1}...\vec{L}^{+}_{pn}, n = 1,2,...,N, N \subset Q$ (Figure 5) and negative directions $\vec{L}^{-}_{p1}...\vec{L}^{-}_{pm}, m = 1,2,...,M, M \subset Q$ (Figure 6).

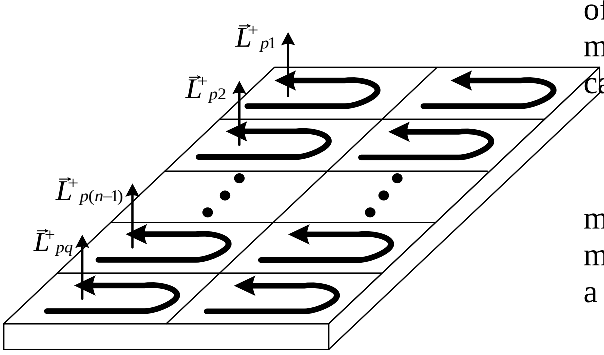

Figure 5. Positive directions of magnetic moments of current circuits

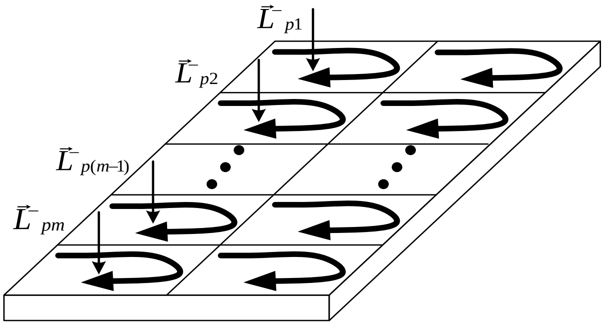

Figure 6. Negative directions of magnetic moments of current circuits

The values of the magnetic moment vectors differ due to the difference in the areas and currents of the contours. Therefore, when ground testing of the PAA in q RTM , in each p operating mode, the values of currents in the power I_{pq} circuits are measured and their areas S_{pq} are determined. To determine the area, thermographs (thermal imagers) are used. The areas are determined by images of electric (or thermal) fields of the power supply circuits of the RTM obtained from thermographs (thermal imagers) [5].

Directions normal $\vec{n}_{pq}$ to each current circuit power RTM determined on the basis of the logic of the switches of the antenna array according to the algorithm of switching of power circuit. according to these data, the magnetic moments of the RTM are calculated

$$\vec{L}_{pq} = I_{pq} S_{pq} \vec{n}_{pq}$$

According to the proper magnetic moments of each module, the magnetic moments are calculated for the PAA panel as a whole, in each p-th mode of its operation

$$\vec{L}_p = \sum_{q=1}^{Q} \vec{L}_{pq}$$

in this case, the values can take both n and m values (see figures 5,6).

Therefore, the design calculation and experimental method can determine the intrinsic magnetic moment of the PAA panel in each p operating mode. Without losing the functionality of the PAA, with the help of different variations in the switching of the power supply of the modules, magnetic moments of different signs are formed.

Due to the purposeful creation of a controlled power path for individual modules, the operating modes of the PAA panels are created, in which only positive ($\vec{L}_p := \vec{L}_\Sigma^+$) or negative ($\vec{L}_p := \vec{L}_\Sigma^-$) intrinsic magnetic moments are summed up. There are variants of operating modes in which the vectors of different signs are mutually compensated, in such cases the panel is "magnetically balanced" ($\vec{L}_p \approx O$). When the power is turned off for all the PAA modules, the grille is also "magnetically balanced".

5 Algorithm for using a phased array antenna to unload the system of power gyroscopes from the accumulated kinetic moment

The algorithm for unloading the PG from the accumulated kinetic moment using the PAA as the MEB includes the following steps:

1) measurement of the value of the kinetic moment vector $\vec{H}$ accumulated in the PG system;

2) the choice to fulfill the condition of unloading PG (1) for $\vec{m}_r = \vec{m}_p$, $\vec{m}_p = \dfrac{\vec{L}_p \times \vec{B}}{\left|\vec{L}_p \times \vec{B}\right|}$, $\vec{L}_p := \vec{L}_\Sigma^- \; \vec{L}_p := \vec{L}_\Sigma^+$ V , where $\hat{p}$ modes of operation of the PAA ($\hat{p} = 1,...,P$), providing unloading PG from the accumulated kinetic moment;

3) determining the values of the vector's $\pi_{\vec{h}}\vec{M}_{\hat{p}}$ projections unloading point on the direction vector $\vec{h}$,

$$\left|\pi_{\vec{h}}\vec{M}_{\hat{p}}\right| = \left|\vec{L}_{\hat{p}} \times \vec{B}\right|\left(\vec{h} \cdot \vec{m}_{\hat{p}}\right),$$

where $\vec{m}_{\hat{p}}$, $\vec{L}_{\hat{p}}$ – the value vectors $\vec{m}_p$, $\vec{L}_p$ for $\hat{p}$ modes of operation of the PAA;

4) selection of the $\hat{p}'$ mode of operation of the PAA at the maximum value $max\left|\pi_{\vec{h}}\vec{M}_{\hat{p}}\right|$ for unloading the PG system;

5) unloading of the PG by switching on the $\hat{p}'$ mode of operation of the PAA with the control of the condition $\vec{m}_{\hat{p}'} \cdot \vec{h} \geq 0$ (2), where $\vec{m}_{\hat{p}'}$ is the value of the vector $\vec{m}_p$ for the $\hat{p}'$ mode;

6) re-selecting the PAA mode after condition (2) is met by replaying steps 1) -4);

7) completion of PG unloading when the value $\vec{H} \approx 0$ is obtained by selecting the "magnetically balanced" mode of operation of the PAA.

Evaluating the effectiveness of the control moment.

For the case of unidirectional arrangement of magnetic moments of current circuits in the secondary power supply circuits of the previously considered PAA, the order of values of the total value of the intrinsic magnetic moment is

$$L = \left|\vec{L}_p\right|_\Sigma \sim 1\times 10^4\ A{\cdot}м^2.$$

The control moment is estimated for an AS containing a PAA and located in a geostationary orbit, where $\left|\vec{B}\right| \sim 1\times10^{-7}$ *Tl*. In this case, we consider the case of the standard orbital orientation of the AS on the GSO, when the vectors $\vec{L}$ and $\vec{B}$ are mutually perpendicular. Then the order of values of the control moment M_L modulo will be equal to

$$M_L = \left|\vec{L} \times \vec{B}\right| \sim 1\times 10^{-3}\ H{\cdot}м.$$

Comparative estimates have shown that the magnetic control moment has the same order of magnitude as the total moments of gravitational forces and light pressure forces acting on the AS [13].

6 Conclusions

Based on the cognitive-synergetic system approach to AS flight control, a new principle of synergetic - variable design of control systems have been developed. the variable control system designed according to this principle contains a control subsystem that has the ability to regulate the operation of several on-board systems, which allows: to reduce the weight of the on-board flight controls of the AS; to reduce the on-board power consumption by eliminating additional consumers; to obtain an additional functional reserve on board the AS.

The synergetic energy relationship between the phased array control system (PAA CS) and the power gyroscope system (PG CS) is considered. Thus in CS PAA control object is a PAA, and a control subsystem - chain primary and secondary power transmit-receive modules (RTM). In CS PG, the object is PG, and control subsystem the kinetic moment in PG - magnetic Executive body (MEB) system of orientation AS.

The synergistic energy relationship between the two control systems in the form of magnetic moments of current circuits in the power supply circuits of the RTM interacting with the MPZ and the kinetic moment in the PG system allowed for the design revision of the CS PAA for its use as MEB. Thus, CS PAA is endowed with the property of variability, which allows it to become a regulatory system for two physical processes at once: control of radio signals of satellite communication in the PAA and control of the kinetic moment in the PG system. An additional functional resource was obtained on Board the AS for unloading the PG from the accumulated kinetic moment, which can replace or Supplement the existing one.

Application of *the principle of synergetic-variable design of control systems makes it possible to solve the problems* of additional resource provision of the AS and increase its survivability.

The technical solution is protected by a patent of the Russian Federation [14].

Acknowledgments

Research carried out on this topic was carried out with partial financial support from RFBR grants (No. 17-29-07073, 18-07-01272, 18-08-01505, 19–08–00989, 20-08-01046), under the budget theme 0073–2019–0004.

References

[1] Kovtun V.S. Cognitive aggregative-streaming metamodel of the automatic spacecraft flight control process // West. Samar. State. UN-TA. Ser. Technical Sciences. 2020. Vol. 28. No. 3 (67). Pp. 35-60.

[2] Akhmetov R.N., Makarov V. P., Sollogub A.V. Bypass as an attribute of survivability of automatic spacecraft in abnormal flight situations // West. Samar. State. UN-TA. 2015. Vol. 14, No. 4, Pp. 17-37.

[3] Okhtilev M.Yu., Sokolov B.V., Yusupov R. M. Intelligent technologies for monitoring the state and managing the structural dynamics of complex technical objects. M. 2005. 291 p.

[4] Patent US 6019319 A. IPK7 B 64 G 1/28 / device with a flywheel in a magnetic suspension accumulating energy. Hughes Electronics Corporation // Inventions 2001. No. 2.

[5] Vendik O.G., Parnes M.D. Antennas with electronic beam movement / Ed. Bahrakha L. D. St. Petersburg, 2001, 252 p.

[6] Gabrielyan D.D., Zvezdina M.Yu., Cyprina I.G., Shatsky V.V., Shatsky N.V. The beamforming flat active phased antenna array with arbitrary aperture boundary // Journal of Radioelectronics. No. 12. 2012. P. 40-58.

[7] Vorobyov S.N. The choice of components for the secondary power supply transceiver modules AFAR // Components and technologies. 2014. No. 10. Pp. 36-40.

[8] Raushenbach B.V., Tokar E.N. Control of spacecraft orientation. - Moscow: Nauka, 1974. 594 p.

[9] Kovtun V.S., Platonov V. N. Patent RU 2112713 C1. MKI B 64 G 1/24 / Method for controlling a spacecraft using reactive Executive bodies while maintaining a given orientation // Inventions 1998. No. 16.

[10] Kovtun V.S. Methods of controlling a geostationary satellite using flywheels and electric rocket plasma engines //

Cosmonautics and rocket science. 2009. No. 55. P. 60 – 68.
[11] Sheremetyevsky N. N., Bikhman R. I. Simple reliable system of kinetic moment reset for artificial Earth satellites oriented in the orbital coordinate system // In the collection "Management in space" Vol. 1. M. - "Science". 1976. P. 110-118.
[12] Kovalenko A.P. Magnetic control systems for space aircraft. - Moscow: Mashinostroenie, 1975. 320 p.
[13] 13. Kovtun V.S., Banit Yu.R. Patent RU 2176972 C1. MKI B 64 G 1/24 / Method for determining the magnetic moment of solar batteries of a spacecraft with a system of power gyroscopes // Inventions 2001. No. 35.
[14] Kovtun V. S., Platonov V.N., Frolov I. V., Ermakov P.N. Patent RU 2604268 C2 B64G 1/36/ Method for forming control actions on a spacecraft with a phased antenna array // Inventions 2016. No. 34.