НЕЙРОІНФОРМАТИКА ТА ІНТЕЛЕКТУАЛЬНІ СИСТЕМИ

НЕЙРОИНФОРМАТИКА И ИНТЕЛЛЕКТУАЛЬНЫЕ СИСТЕМЫ

NEUROINFORMATICS AND INTELLIGENT SYSTEMS

UDC 681.5.015:629.7.05

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FAULT TOLERANCE OF SPACECRAFT ORIENTATION AND STABILIZATION SYSTEM

Formed the structure of the orientation and stabilization system for ensuring its active fault tolerance. Parameterized types of failures of the system functional elements, characterized by changes in the properties of the conversion elements. Received diagnostic functional models for solving problems of detection, search the place and establish a class of failure for system. Developed models and methods of systematic approach to fault tolerance in the direction of the effective use of the signal, parametric and structural redundancies and selection of parrying tools. Performed experimental researches of the sample model of the automatic attitude control and stabilization the properties of active fault-tolerance in emergency modes of operation.

Keywords: stabilization and orientation spacecraft system, fault tolerance, reaction wheel, angular velocity sensor.

Analysis of priority and future space programs shows that the actual is the establishment and maintenance of small satellites with operation period over 15 years [1]. The solution of this problem involves various difficulties, including the fault of spacecraft blocks and systems. One promising avenue is to create a fault-tolerant spacecraft orientation and stabilization systems.

Small spacecraft conditions of use involves a high precision working off program reversals with high accuracy stabilization of the angular position. These conditions with acceptable energy and mass-dimensional characteristics are able to ensure reaction wheels (RW) as the executive bodies [2]. An increase in resources of such systems is achieved by applying the minimally redundant system schemes of RW [3].

Since any deviation of the spacecraft system parameters can lead to a deviation from stated rigid requirements for their work, it is impossible to use traditional approaches to fault tolerance associated with redundancy of its con-stouten elements [4]. Therefore, necessary to adopt the application methods and models associated with providing of an active fault tolerance.

Significant contribution to the development of models, methods and means of active fault tolerance was made by such scientists as R. Isermann, R. Patton, P. Frank, R. Beard, V. Y. Rutkowski, A. V. Mozgalevskaya, I. V. Kuzmin, B. I. Dotsenko, J. E. Eisenberg, D. V. Lebedev, A. S. Kulik, V. S. Blintsov, L. G. Raskin. However, the proposed models, methods and tools to ensure the active fault-tolerance are predominantly fragmented and they do not reflect the dynamics of the control processes, do not con-sider the possibilities of diagnosing the operational state of the functional elements, as well as fault parrying through the effective use of existing and the introduction of additional redundancies. Consequently, the development of diagnosing models and methods, as well as failure parrying to provide an active fault-tolerance of the spacecraft attitude determination and control in real-time is an important scientific and applied problem.

PROBLEM FORMULATION

To achieve this purpose the authors have solved the following problems:

1. Determined the structure of the spacecraft attitude determination and control system, set of its functional elements failures types and developed diagnostic models that connect direct and indirect features.

2. The models and methods for in-depth diagnosis of the spacecraft orientation and stabilization system with depth to failure type are developed.

3. The models and methods for parrying failures in the spacecraft attitude determination and control system through effective use of the signal, parametric and structural redundancies are designed.

4. The experimental procedures for the testing of active fault-tolerance model sample of spacecraft attitude determination and control system are held. Also evaluated its comprehensive indicator of the quality and fault tolerance level.

DETERMINATION OF THE SPACECRAFT ORIENTATION AND STABILIZATION SYSTEM STRUCTURE

Consider the generalized block diagram of the perspective spacecraft orientation control system (Fig. 1).

A typical control system of the perspective spacecraft includes in the structure the spacecraft as a control object, RW for generating control moments, complex of angular velocity gauges (CAVG) for measuring angular velocity, data spacecraft subsystem for generating control signals applied to all blocks of the system. To orient the spacecraft and CAVG data correction at the system uses celestial navigation system (CNS) and combined orientation sensor (COS). Electromagnetic drives driven by signals from the magnetometers installed on spacecraft in order to unload RW.

The initial configurations of accommodating RW on the spacecraft with minimum redundancy were selected following variants [5]:

– scheme provided for NASA standards within the project multipurpose modular platform MMS, shown in Fig. 2, *a*;

– the scheme of the executive drives installation of the company General Electric, with RW kinetic moments directed from the middle of the cube (Fig. 2, *b*).

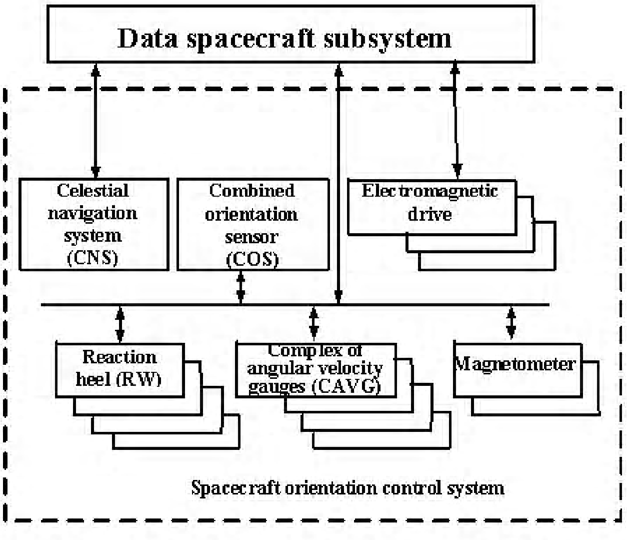


Fig. 1. Structural diagram of the perspective spacecraft control system

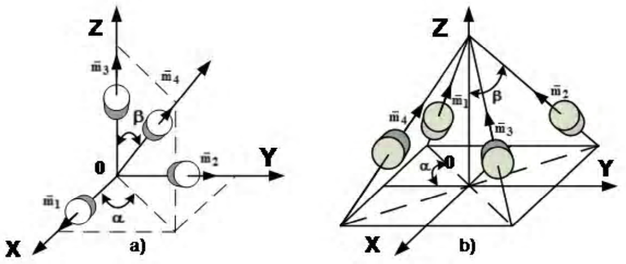


Fig. 2. Minimally redundant RW installation schemes on the spacecraft

It is known that when comparing different configurations that satisfy the technical requirements, preference is given to those who provide the field of formation control torque to the ellipsoid of the following form:

$$\left(\frac{M_x}{I_x\dot{\omega}_x}\right)^2+\left(\frac{M_y}{I_y\dot{\omega}_y}\right)^2+\left(\frac{M_z}{I_z\dot{\omega}_z}\right)^2=1. \qquad (1)$$

where M_x, M_y, M_z are projections of the total required reactive RW torque on the axis of the coordinate system associated (CSA); I_x, I_y, I_z are spacecraft axial moments of inertia; $\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z$ are projections of the desired angular acceleration on the axis of the spacecraft CSA.

Analysis of the shape of the area under consideration for the minimally redundant set of schemes for the cases of the use of all four RW and a failure of one of them showed that in both modes shape of the control torque for the pyramid scheme is closer to the required one. Thus, this scheme is preferable. Also identified the optimal angles of installation RW by analyzing projections of the trace of the correlation matrix of the errors (AS Kulik Saturday AM, Reznikov OV).

The result was that the optimal setting angles for the selected scheme are $\alpha = 45°$ and $\beta = 54,7°$.

At the block diagram of the spacecraft control system also contains a gauges block, changing the dynamics of the system. As the gauges on this object were selected angular velocity sensor (AVS), combined in a block. In this case the AVS scheme of installation that enables the CAVG deep diagnosing with depth to failure mode has been selected the following way: setting of three main AVS vector directed along the axes of the CSA and the installation of additional AVS vector collinear to them (Fig. 3).

The analysis of such a setting scheme performed in the works [6–8], who showed that it provides a CAVG diagnosable with depth to failure mode.

SPACECRAFT DIAGNOSING SYSTEM DEVELOPING

In this paper, the spacecraft system of orientation and stabilization is considered as a combination of automatic control devices (ACD) and the object of automatic control (OAC) (Fig. 4), and diagnosing problem reduces to determining the functional state of the OAC, including the executive bodies of the spacecraft and the feedback sensors.

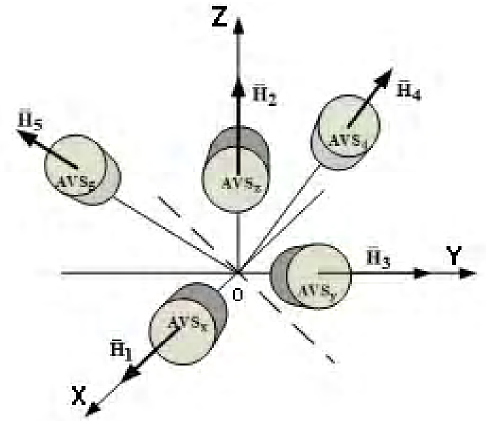


Fig. 3. The installation scheme of AVS on the spacecraft

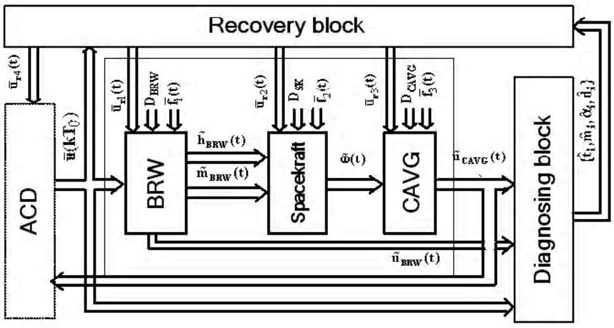


Fig. 4. Functional scheme of spacecraft orientation and stabilization system with active fault tollerance

Many types of failure for the spacecraft orientation and stabilization system D_{SOSS} can be separated into many types of failures of the block of reaction wheels (BRW) D_{BRW}, spacecraft D_{spa} and complex of angular velocity gauges D_{CAVG}.

In this paper, we do not consider the set of ACD failures, which is the microcontroller. Fault tolerance of controllers described in many papers, the current trend – is to use a spacecraft centralized controllers with a three-or five-fold redundancy of the main computer unit. Therefore, consider that the failures of the ACD are parried by switch of reserve units.

Many types of BRW failures consists of sets of RW failure modes, and each RW incorporates the PA, contactless DC motor and tacho, respectively, considered to be 60 kinds of BRW failures.

Many types of failures for CAVG contains multiple failure modes each of the AVS separately, total 30 kinds of failures.

In this paper, we also consider the many types of failures related to the change the moments of inertia of the spacecraft $D_{spa_{IM}}$.

One cause of this failure is the spacecraft incomplete or asymmetric disclosure of solar panels. As shown in various reports incomplete disclosure may occur due to a structural defect in the mechanism of the disclosure, a surface tear of solar cell, mounting damage one of the solar panels at start, etc.

When used as an unloading the jet engine, is possible asymmetrical consumption of fuel and as a result a change in one of the spacecraft moment of inertia.

Many types of spacecraft failures also includes a variety of failure modes associated with the inaccuracy of the external disturbances mathematical model $D_{spa_{dist}}$.

Diagnosing these failure modes will be carried out on two levels: the block and the system. There are only three levels of the hierarchy of diagnostic software (Fig. 5).

First, the lower level is the block level. Here formed diagnostic software (DS) for units of sensors, actuators, calculators not autonomous, but on the basis of their functioning conditions in a closed loop.

The second level is system. Diagnostic software is developed for the entire closed-loop control system of orientation and stabilization. Here is diagnosed how the system runs its functions under the conditions of space flight. The third level of the hierarchy is oversystem. At this level formed diagnostic software for a space mission as a whole.

Block level will form the diagnostic software for CAVG and BRW based on the conditions of their operation in the contour of spacecraft orientation and stabilization system. It allows to provide orientation and stabilization system by blocks of sensors and actuators with the properties of fault tolerance when single failures occurred.

At the system level, we will develop diagnostic software for many types of spacecraft failures to ensure fault tolerance using systemic connections. Also at the system level, we will solve the problem of spacecraft orientation and stabilization system restore functionality in catastrophic failure in one of the blocks – BRW or CAVG through the use of auxiliary control devices (magnetometers, jet engines), and measuring devices (star trackers, GPS, etc.)

Failure modes were grouped into classes defined by the change of one of the system mathematical model parameters because of the failures parameterization. Set of failures classes contains 46 elements that are direct diagnostic features of failure.

Motion model of system in the presence of it failures obtained based on the equations system describing the dynamics of the stabilization and orientation system of the spacecraft and set of straight diagnostic features. In this case, is made the transition to a mathematical description in

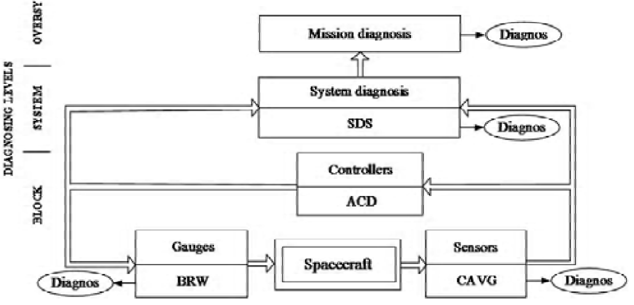


Fig. 5. Functional scheme of the hierarchy of diagnostic software

recurrence-matrix form of the system motion equations linearized at the operating point.

Analysis of the structural and signaling systems diagnosable relative to this set of failures classes showed that the complete diagnosable system is provided on transitive operating modes of RW and spacecraft in general and to differ PA and RW failures is necessary to introduce additional control point between them. Spacecraft is the object with a known input. Diagnosing its functional state based on the difference signal of measurement vector and the reference model output. Since all state variables of spacecraft (angular speed velocity of the spacecraft and RW) are directly measurable, as a function of diagnostic models that connect direct and indirect failure indications, selected models species

$$\begin{gathered}\Delta x(k+1)=A\Delta x(k)+\Delta A(\Delta\gamma_q)\tilde{x}(k)+\Delta B(\Delta\gamma_q)u(k)+\\ +\Delta F(\Delta\gamma_q)f(k)+\tilde{B}u_0(\Delta\gamma_q);\\ \Delta y(k)=C\Delta\, x\big(k\big)+\Delta\, C(\Delta\gamma_q)\tilde{x}(k)+\tilde{C}u_0(\Delta\gamma_q).\end{gathered}\tag{2}$$

where $\Delta A(\Delta\gamma_q)$, $\Delta B(\Delta\gamma_q)$, $\Delta F(\Delta\gamma_q),\Delta C(\Delta\gamma_q)$, are deviations respectively state matrices of control, disturbance, and output due to the presence of a direct indication of failure $\Delta\gamma_q$ in system; $\tilde{B}u_0(\Delta\gamma_q)$, $\tilde{C}u_0(\Delta\gamma_q)$ are matrix characterizing the influence of drift in the elements of the control object on its state variables and output signals.

Based on the obtained models developed procedures for processing indirect diagnostic fault features for block and system levels. They allow to consistently remove the uncertainties associated with the moment of a failure, its location, class, and the type. It was taken into account following. When establishing the facts failure, finding its place and the class definition is used dichotomous tree that represents the production knowledge base of diagnosing process. The nodes of this tree are used predicate constructions of double type

$$z=S_2\left\{f\left[\Delta y\left(k\right)\right]-\delta\right\}=\begin{cases}1, & \text{if } f\left[\cdot\right]\geq\delta;\\ 0, & \text{if } f\left[\cdot\right]<\delta;\ \forall k\in T,\end{cases}\tag{3}$$

where δ is threshold; $f\left[\Delta y_i\left(k\right)\right]$ is nonlinear function of measurement vector $\Delta y\left(k\right)$.

So, as the argument of double predicate uses discrete deviation of the output signals measurement of the system, placed in the vector $\Delta y\left(k\right)$, functional relationship of these measurements and the threshold value that determines function allowable change $f\left[\cdot\right]$. Nonlinear function $f\left[\cdot\right]$ formed via diagnostic models, connecting specific for each of the main diagnosing problem the direct feature $\Delta\lambda_i$ with indirect – the calculation results $\Delta y\left(k\right)$.

To provide diagnosability of the system with a depth to the RW functional element and differences between failures in spacecraft and AVS, for all operating modes introduce additional diagnostic features formed on the basis of the hypothesis of quasi-stationary direct feature of failure in the diagnosis interval:

$$\begin{gathered}\Delta\hat{\gamma}_i(k)=\text{const}\bigcap\Delta\hat{\gamma}_j(k)=\text{var, if }\left(\Delta\hat{\gamma}_i\neq 0\right)\cap\left(\Delta\hat{\gamma}_j=0\right);\\ z_{Di}=s_2\left(\left|I_{CTi}\right|<\Delta I_{CTi}\right),\ I_{CTi}=\frac{d(\hat{\gamma}_i)}{dt};\\ i,j=\overline{1,N_\gamma},i\neq j.\end{gathered}\tag{4}$$

Fig. 6, 7 and 8 are fragments of search algorithms for place and the class definition of failure.

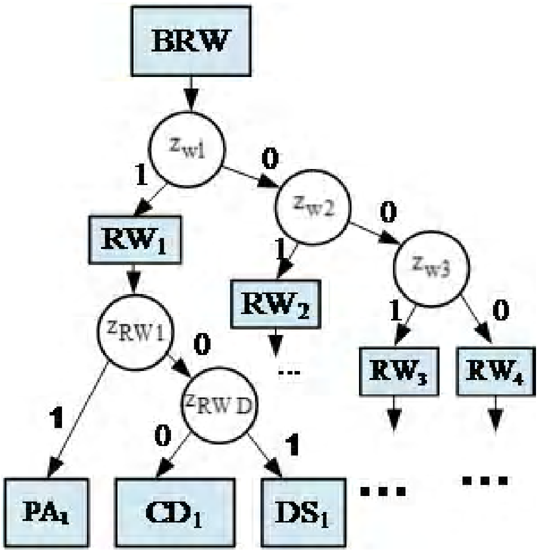


Fig. 6. Dichotomous tree search for a place of failure in the BRW

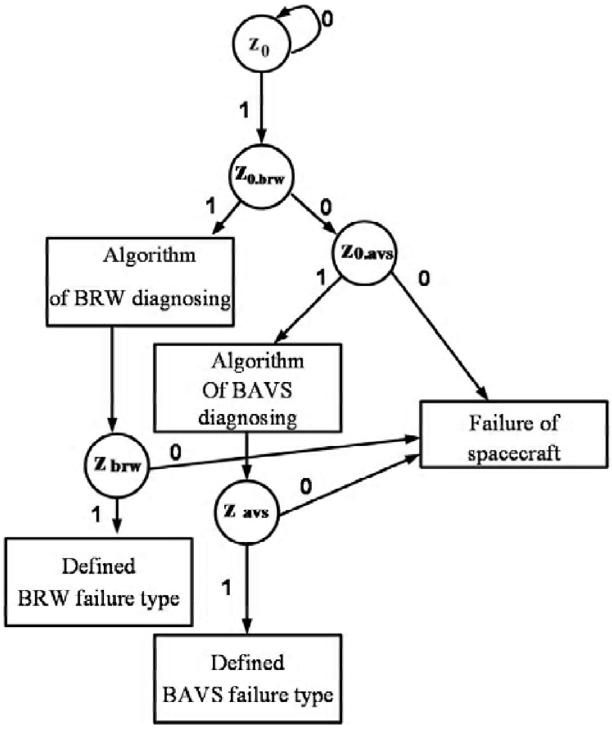


Fig. 7. Dichotomous tree search for a place of failure in the spacecraft orientation and stabilization system

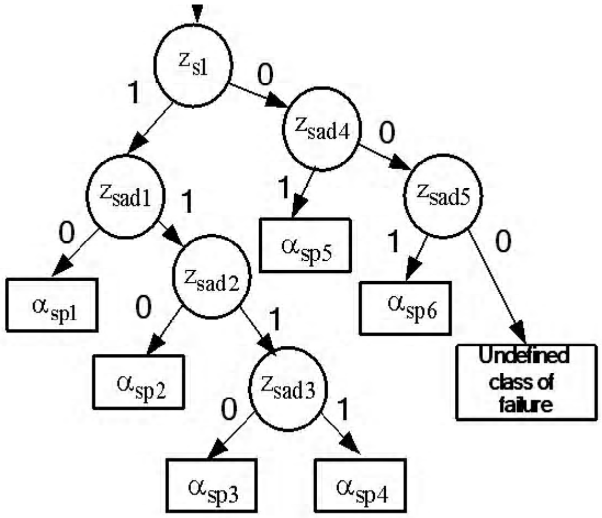


Fig. 8. Fragment of the dichotomous branch of the failure class definition in the spacecraft

To determine the failure mode are used functional dependencies, linking a particular failure type with direct diagnostic features. Final estimate of the parameter deviations value from the nominal system performed at the last stage of diagnosis procedure as a result of the evaluation characteristic values choice, calculated on the steps of determining the place and class of failure characterizing the detected type of failure

$$\Delta\hat{\gamma}_i(k)=\begin{pmatrix} CA_{\gamma_i}C^{-1}\tilde{y}(k-1)+C_{u0_{\gamma i}}+ \\ +CB_{\gamma_i}u(k-1)+CF_{\gamma_i}\,f(k-1)+ \\ +CB_{u0_{\gamma i}}+C_{\gamma i}C^{-1}\tilde{y}(k) \end{pmatrix}^{-1}\Delta y(k). \quad (5)$$

RECOVERY SYSTEM DESIGN

Developed diagnostic software is a foundation for the development of tools for the spacecraft orientation and stabilization system functional state automatic recovery in emergencies.

Consider the recovery of functional state of spacecraft orientation and stabilization system on block level. The starting point for this task is complete diagnosis of the function block. Based on this information, depending on the block construction, the principle of its action, the failures set are selected recovery tools – signal and parametric adjustment or possible hardware and control algorithms reconfiguration of the block.

Selection of recovery tools is produced by bases there control system functioning history, the current type of failure, the excess resources remaining and future challenges of the space mission. In this case, the recovery procedure related to the signal and parametric tuning often have the highest priorities, and procedures relating to the reconfiguration of the hardware and control algorithms are called only after all the resources associated with the adjustment have been exhausted.

After restoring the damaged unit is produced its diagnosis of the functional state. As a result:

– fully restored functionality of the block and it can be used in the orientation and stabilization system of spacecraft as intended;

– working capacity of the unit is not restored and detected another type of failure, and the previously described cycle is repeated until complete recovery the functional properties of the emergency unit.

After a complete recovery, the emergency unit on the system level signal is transmitted and produced parry of system failure effects in the blocks for the subsequent implementation of the flight mission.

However, such situation is possible when failures on block level can produce such abnormal situation, which is not possible to parry at this level because of the lack of excess capacity. In this case, the recovery procedure of the functional state of spacecraft occurs at the system level, using the connection between the block and the additional devices that are not intended directly for the tasks of orientation and stabilization of the spacecraft, but allowing performing tasks for space missions.

At the system level are also solved problem of flexible parry abnormal system situations associated with failures in the spacecraft construction or significant perturbing effects.

After the spacecraft orientation and stabilization system recovery are also produced diagnosing of the restored system. The full diagnosis allows make a decision to continue parry the effects of failures, or about the further implementation of the mission, or about the need parry on oversystem level (Fig. 9).

EXPERIMENT

Debugging algorithms of diagnosing functional state and recovery of the orientation and stabilization system of the spacecraft performed on a specialized hardware-software complex (HSC), presented in Fig. 10 and Fig. 11.

Functional structure of HSC allows you to enter into the system failure modes from the considered set, and to investigate the behavior of the system in the nominal and emergency modes.

HSC consists of the following elements: a platform with minimally redundant BRW, established by pyramid scheme and CAVG, fixed in gimbals, automatic control device and the PC with specialized software.

The complex software includes low-level software that provides execution in the control microcontroller module and the peripheral microcontroller module developed procedures control of and provide the active fault tolerance. On the upper level, there is software for performing the

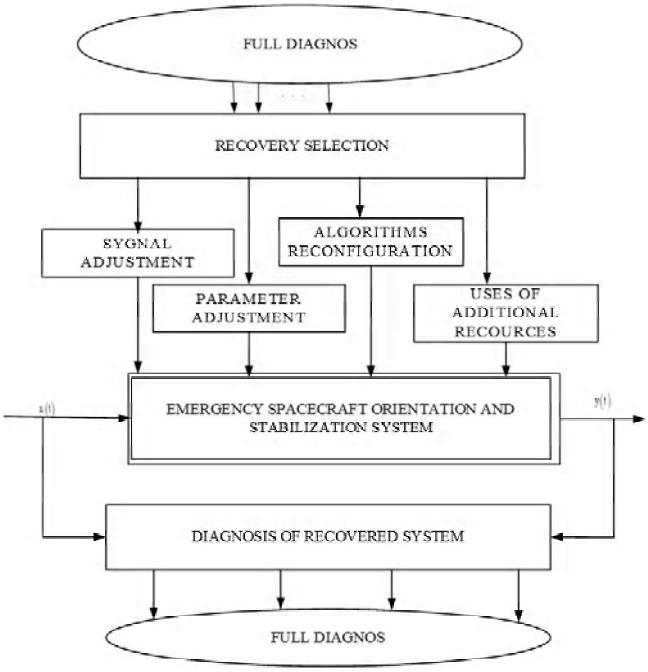


Fig. 9. Parrying tools of orientation and stabilization system of the spacecraft failures at the system level

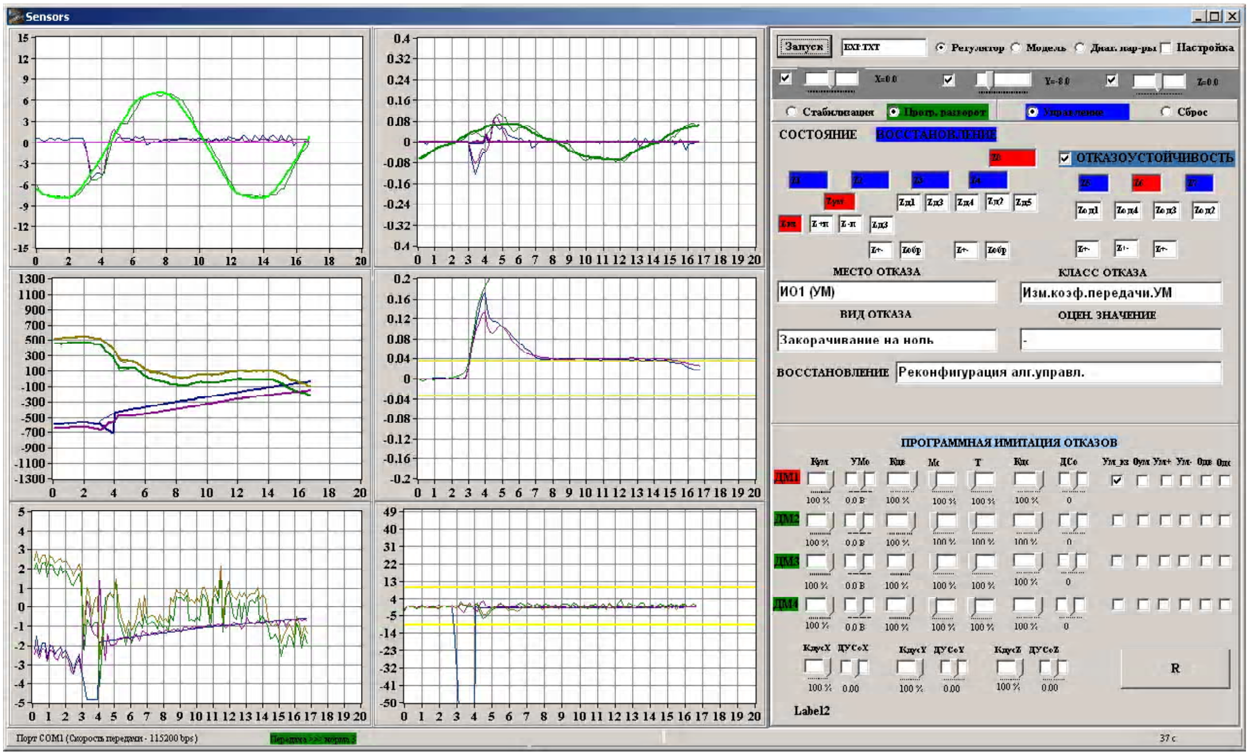
following functions: information exchange with automatic control device, setting modes of the system, visualization and storage of the experimental results.

In order to simulate effect of the considered set of failure modes on the system using developed HSC, uses software simulators. They are used because of the fact that they have essential advantages such as the possibility of rapid modification, imitation of wide variety operating conditions, ease of the results interpretation, small power consumption, a good adaptability. At this distortion of measured and control signals of the system performed so that the response to it was analogous reaction to input types of failure.

Fig. 10. Exterior view of HSC for research models and methods of maintenance the active fault-tolerance spacecraft attitude control and stabilization

Fig. 12 shows the functional diagram of RW with software simulators of failure modes.

Fig. 13 and 14 shows the results of the spacecraft stabilization control system simulation without active fault tolerance (dotted line) and with an activated diagnosis and recovery system (solid line) at the mode of the angular reorientation of the platform along the OZ axis by predetermined path.



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☑ X=0.0 ☑ Y=-8.0 ☑ Z=0.0

СОСТОЯНИЕ ВОССТАНОВЛЕНИЕ

☑ ОТКАЗОУСТОЙЧИВОСТЬ

МЕСТО ОТКАЗА: ИО1 (УМ)

КЛАСС ОТКАЗА: Изм.коэф.передачи.УМ

ВИД ОТКАЗА: Закорачивание на ноль

ОЦЕН. ЗНАЧЕНИЕ: -

ВОССТАНОВЛЕНИЕ: Реконфигурация алг.управл.

ПРОГРАММНАЯ ИМИТАЦИЯ ОТКАЗОВ

	Кум	УМо	Кдв	Мс	Т	Кдс	ДСо	Ум_кз	Оум	Ум+	Ум-	Одв	Одс
ДМ1	100 %	0.0 В	100 %	100 %	100 %	100 %	0	☑	☐	☐	☐	☐	☐
ДМ2	100 %	0.0 В	100 %	100 %	100 %	100 %	0	☐	☐	☐	☐	☐	☐
ДМ3	100 %	0.0 В	100 %	100 %	100 %	100 %	0	☐	☐	☐	☐	☐	☐
ДМ4	100 %	0.0 В	100 %	100 %	100 %	100 %	0	☐	☐	☐	☐	☐	☐

КдусX	ДУСоX	КдусY	ДУСоY	КдусZ	ДУСоZ
100 %	0.00	100 %	0.00	100 %	0.00

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Fig. 11. The main window of the program results visualization and setting a system operation for spacecraft attitude control and stabilization

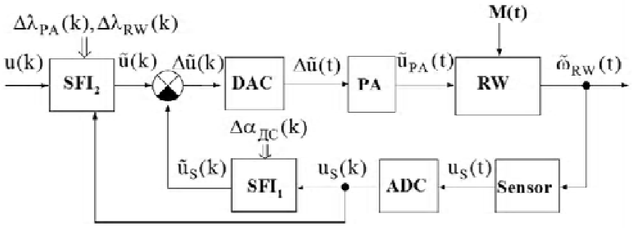

Fig. 12. The functional diagram of RW with software simulators of failure modes

Similarly, research has been done in the modes of attitude control and stabilization object functioning on the whole parrying failure modes set. All types of failure were observed by diagnostics subsystem, found their place, set the class and defined failure mode.

Average failure detection time was 0,07 s with the average total time of diagnosis – 0,32 s, and the average time failure parrying – 1,35 s. Thus, the average time spent on diagnosis and parry of spacecraft stabilization control system failures was 1,74 seconds. This time less than time t_{pp}= 9 s for transient system in normal mode in 5,17 times

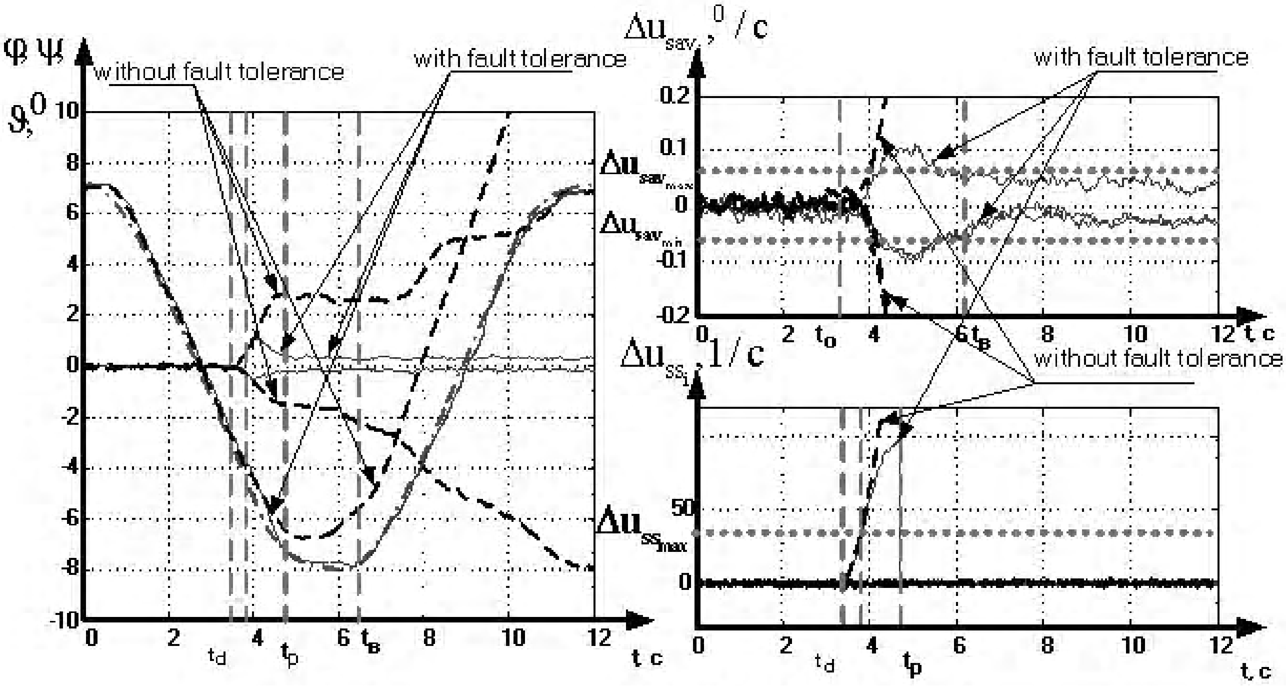

Fig. 13. The results of the spacecraft stabilization control system at break RW with a fourth serial number

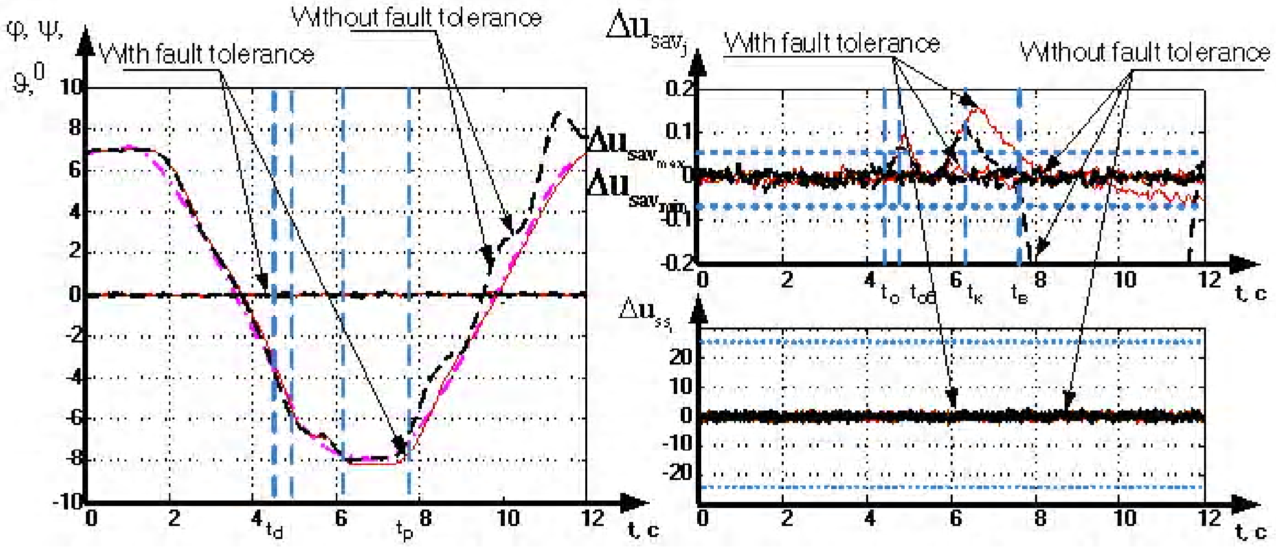

Fig. 14. The results of the spacecraft stabilization control system with a decrease in gain Kz

CONCLUSIONS

Thus in this paper identified the main trends in modern space technology that is in reducing the weight and size, power and cost characteristics, function of space vehicles, as well as increasing the time of their active life. There was formed the structure of the orientation and stabilization system for ensuring its active fault tolerance feature, defined a set of standard and parameterized types of failures of the system functional elements, characterized by changes in the properties of the conversion elements. There was received diagnostic functional models for solving problems of detection, search the place and establish a class of failure, which provide unique analytical relation between direct and indirect diagnostic features for each diagnosing problem, take into account the dynamic features of the object, as well as systemic linkages between its elements. There was developed diagnostic logic models for detection, finding a place and establish a class of failure in the system of automatic orientation and stabilization, the expressions for the calculation of direct and indirect diagnostic features, and formed their processing rules that al-low to solve problems of analytically develop procedures for deep diagnosing. Further developed models and methods of systematic approach to fault tolerance in the direction of the effective use of the signal, parametric and structural redundancies and selection of parrying tools when there are multiple connections between the means of parrying and failure modes. Experimental researches of the sample model of the automatic attitude control and stabilization the properties of active fault-tolerance in emergency modes of operation which have shown operability of the developed models and methods of deep diagnosing and failures flexible parrying and fundamental possibility maintain operability of the object in the event of failure modes in it from the finished set.

SPISOK LITERATURY

1. Проектирование и экспериментальная отработка систем управления объектов ракетно-космической техники. Т. 2. Проектирование систем управления космических аппаратов и модулей орбитальных станций [Текст]: учебник в 3 т. / Ю. С. Алексеев, Е. В. Белоус, Г. В. Беляев и др. / под общей ред. Ю. С. Алексеева, Ю. М. Златкина, В. С. Кривцова, А. С. Кулика, В. И. Чумаченко. – Х. : Нац. аэрокосм. ун-т им. Н. Е. Жуковского «Харьк. авиац. ин-т», НПП Хартрон-Аркос, 2012. – 680 с.
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Стаття надійшла до редакції 16.09.2013.

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ОБЕСПЕЧЕНИЕ ОТКАЗОУСТОЙЧИВОСТИ СИСТЕМЫ ОРИЕНТАЦИИ И СТАБИЛИЗАЦИИ КОСМИЧЕСКИХ АППАРАТОВ

Сформирована структура системы ориентации и стабилизации, обеспечивающая ее активную отказоустойчивость. Параметризированы виды отказов функциональных элементов системы, характеризующиеся изменением свойств преобразовательных элементов. Получены диагностические функциональные модели для решения задач обнаружения, поиска места и определения класса отказа системы. Разработаны модели и методы системного подхода к отказоустойчивости с целью эффективного использования сигнальной, параметрической и структурной избыточностей и выбраны инструменты парирования. Проведены экспериментальные исследования макетного образца автоматической системы ориентации и стабилизации для исследования свойств активной отказоустойчивости в аварийных режимах работы.

Ключевые слова: система стабилизации и ориентации космических аппаратов, отказоустойчивость, двигатель маховик, датчик угловой скорости.

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ЗАБЕЗПЕЧЕННЯ ВІДМОВОСТІЙКОСТІ СИСТЕМИ ОРІЄНТАЦІЇ ТА СТАБІЛІЗАЦІЇ КОСМІЧНИХ АПАРАТІВ

Сформована структура системи орієнтації та стабілізації, яка забезпечує її активну відмовостійкість. Параметризовані види відмов функціональних елементів системи, що характеризуються зміною властивостей перетворювальних елементів. Отримано діагностичні функціональні моделі для вирішення задач виявлення, пошуку місця та визначення класу відмови системи. Розроблено моделі і методи системного підходу до відмовостійкості з метою ефективного використання сигнальної, параметричної та структурної надлишковості та обрані інструменти парирування. Проведено експериментальні дослідження макетного зразка автоматичної системи орієнтації та стабілізації для дослідження властивостей активної відмовостійкості в аварійних режимах роботи.

Ключові слова: система стабілізації та орієнтації космічного апарату, відмовостійкість, двигун маховик, датчик кутової швидкості.

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