Aspects of information support in ensuring the survivability of spacecraft under electrophysical effects

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Abstract. *In order to improve the operational efficiency of decision-making in the context of spacecraft (SC) endurance in operation, the task was set to increase the efficiency of adaptation of its control system to the environmental effects. The instruments installed on most Russian SCs in many cases do not provide for identification and timely elimination of accident sources due to delays in the identification of faults and failures. A technology is proposed that involves intellectualization of control systems. It is suggested to complement the SC control circuit with an expert system that includes a "prognostic decision support system", a "control simulation and correction module". Due to the ambiguity and common uncertainty of cosmic phenomena, it is suggested to predict the reaction of SC equipment to external effects rather than monitor such effects. The intelligence of the expert system is to be ensured through the analysis of the communication medium that defines the possibility to ensure SC survivability. The correction of control is suggested to be performed not on the basis of process parameters monitoring, but rather knowledge. This knowledge is held by experts who possess experience in SC flight mission performance. The results of the audit of external factors and development of SC functional units reactions represent the input data. After clearing, sorting and statistical analysis of data, it is suggested to regard it as information resources. The results of such resources analysis and design of messages based on expert conclusions transforms such resources into knowledge that is used in decision making and control correction. The diversity of architectures and processes of SC functional units design has defined the requirement to involve experts with diverse professional backgrounds. It was proposed to generate forecasts of SC equipment reactions development in the form of description of the dynamics of multifactor combination of the results of intersubject audit of functional units operations and subjective expert evaluations. In order to ensure agility of information analysis within the knowledge base, it was suggested to use the OLAP comprehensive multidimensional analysis technology. In particular, that regards fast analysis of shared multidimensional information that includes requirements for multidimensional analysis applications. The proposed model of systematic accumulation and processing of knowledge will enable flight control officers to timely identify inadequacies in the control inputs. The logical and statistical analysis capabilities ensured by this application will enable the delivery of analysis results to the experts within a time period sufficient for elimination of the causes of faults and failures in SC equipment operation. Multidimensional conceptual representation of data including the support of multiple hierarchies will define the capability to refer to any required information regardless of its size and place of storage. The proposed method of information support of SC equipment reactions forecasting is addressed in the light of the analysis of electrophysical effects that affect SC in near-Earth orbits. Combining the methods of computer data processing and intersubject analysis of functional units operation must insure efficient decision-making based on increased accuracy and agility of data processing and, consequently, selection of SC operation adaptation scenario subject to flight control officer's preferences.*

Keywords: *spacecraft survivability, electrophysical factors, intellectualization of controls, expert system, prognostic decision support system, simulation and correction of control, networked expert environment, knowledge management, intersubject audit, subjective expert evaluation, comprehensive multidimensional analysis technology.*

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Introduction

The experience of near-Earth activities shows that the effects of space factors, as well as the dynamics of near-object effects may significantly impact the efficiency of spacecraft operation. Therefore, along with the requirement to improve the dependability of SC design on the ground, of great relevance is the matter of operational support of its survivability under external effect in flight. This article suggests a research of mechanisms to ensure SC resilience to electrophysical effects (EPE).

Conventional electrophysical effects measurement facilities use data received from standard raw information instruments (RII)[1]. However, the instruments installed on most Russian SC do not provide for identification of faults and failures which complicates the detection of accident sources. As a result, due to low adaptability to environmental effects stable of SC operation may be disrupted.

The approach proposed in this article is geared toward the intellectualization of control and command through the introduction of an Expert system that allows compensating the development of SC reaction to electrophysical effects. It is suggested adding messages on the errors of electronic, mechanical and electromechanical equipment to the standard RII instruments information that is contained in the database and defines the control and command signals. The diagram of intellectualization of SC control systems is given in Figure 1.

Expert system functions

The system is to be built on the basis of the Prognostic decision support system (PDSS) and the Control simulation and correction module (CSCM). The coordinated operation of the Expert system and the standard control circuit is to be insured by the Database of external EPE and real-time messages regarding the compliance with technical documentation and the results of SC functional modules operation audit.

Updates to the database can be made as follows:

- automatically:

1) acquisition of information from RII and SC functional modules sensors;

2) collection of statistical data on the SC reaction to environmental effects;

3) analysis of the messages on the changes in the SC equipment put into the database;

- semi-automatically:

1) reading of the barcodes on the installed equipment;

2) by the cosmonaut responsible for the operation of a specific functional unit;

3) by control center employees.

The Control simulation and correction module is to be a unit of the Expert system intended for adaptation of the Standard control circuit signals to the SC characteristics that change under the influence of external effects. The adaptation can take the form of modification of control signals or module configuration. It is suggested to implement the second type of adaptation by introducing a new functional unit to address faults and failures of devices in the existing control channel.

In any case, shaping the signals that ensure SC resistance to external effects requires an analysis of the combination of information received from the Standard control circuit and the Expert system. An important feature of the suggested procedure of such signal generation is the information support of the SC reaction to EFE forecasts. To that effect we propose introducing the Intelligent control module to enable stable SC functional modules operation under external effects.

Due to the diversity of the internal factors that define the SC reactions to external effects, let us assume that the information received by the Expert system must be analyzed by experts in various fields. Therefore, such system can only operate using the intersubject audit technology.

Another important factor in ensuring SC survivability consists in the fact that the quality of control and command is significantly affected by the reliability of incoming information that cannot be verified directly, as well as the speed of its delivery to the decision-maker (DM). In other words, the matter of decision efficiency is closely connected with the speed of relevant information delivery to the experts. Therefore, the computer-based Prognostic decision support system (PDSS) must inevitably be part of the suggested Expert system.

In practice, in order to ensure efficient control and command the following factors must be taken into consideration:

- the distribution of PDSS, i.e. whether group or individual decision making is used;

- types of structures of external factors compensation tasks, i.e. availability of analytical models, quantitative evaluations or qualitative characteristics;

- nature of decision efficiency evaluation, i.e. possibility of objective evaluation of the results of corrective input;

- nature of the situation in which decisions are made, i.e. stressfulness, DM's experience, etc.

For the purpose of improving the agility of control and command it is suggested to ensure SC adaptivity to external effects based on predicted operating modes. The forecast is to be generated in the form of dynamics description of multifactorial situations. A situation shall be understood as a SC survivability characteristic under the chosen strategy of corrective inputs generation.

Strategic model of a multifactor situation

The mission tasks define the requirements to SC survivability. However, this task is ill-posed, as SC design usu-

[1] This regards, for example, electrical and magnetic field sensors, energetic particle flow of solar and galactic source sensors, etc.

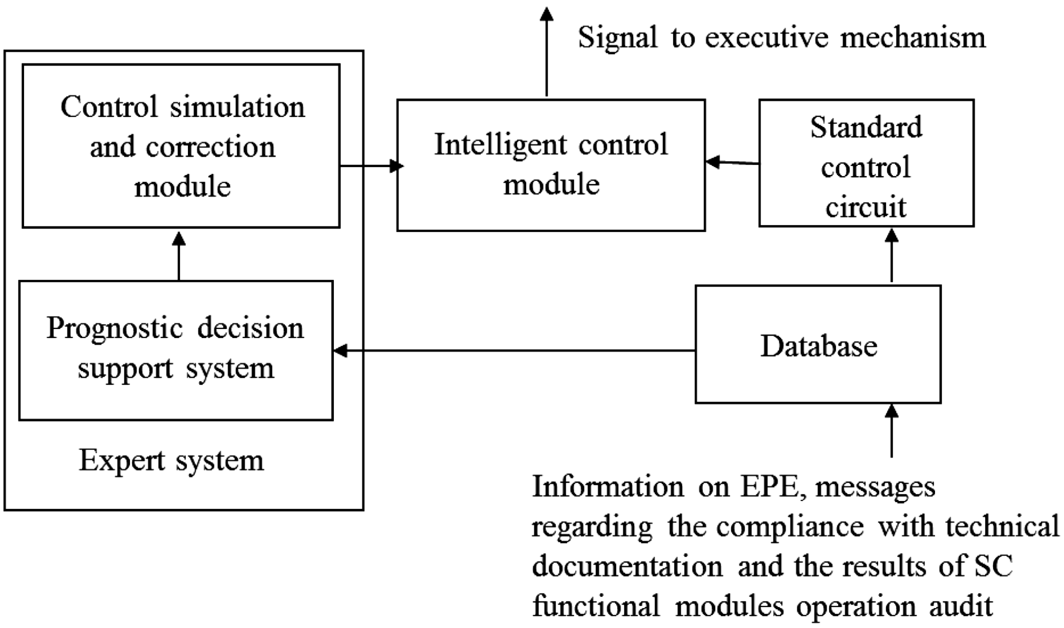

Figure 1. Diagram of intellectualization of SC control

ally allows for a multitude of possible solutions for control adaptation under identical external factors. To that effect we propose evaluating the operational stability of a functional module using the following model (1):

$$<S, k_1, \dots, k_m, R> \quad (1),$$

where $S=\{s_i, i=1,2,\dots, m\}$ is the set of strategies for generating corrective inputs that are defined by the characteristics of the hardware and software included in the considered module. It is assumed that such signals would enable SC survivability under environmental effects. Hereinafter we shall name the EFE adaptivity processes the multiple choices and confine them with the conditions of mission survivability.

$k_1, \dots, k_m$ are expert evaluations of the probability of SC module operation without deviations from parameter values as per the mission task in case the i-th strategy has been adopted;

R is the preference-indifference relation.

Let the SC survivability strategy be chosen by experts[1]. In model (1), the value of each variant s_i out of the set S of all (possible) variants is characterized by the values of expert evaluations k_i.

Evaluation k_i should be understood as the value defined on set S and taking on the value out of set X_i that is called the scale. The the considered task such scale is defined by the set of levels of productivity of the means to ensure adaptivity of SC operation to external effects.

Without loss of generality, we suggest that all evaluations are expressed numerically and larger values are preferable to smaller ones. Thus, each variant s_i is characterized with values $k_i(s)$, that form the evaluation vector of this variant $x(s)=(k_1(s), \dots, k_m(s))$. In the model the variants are compared based on the preferability through comparison of their vector evaluations. The set of all evaluation vectors: $X = x_1 \dots x_m$.

It is assumed that the evaluations are homogenous, i.e. they have an identical (common) scale $x_0 = x_1 = \dots = x_m$. If the evaluation k_j is replaced with $\xi(k_j)$, where $\xi$is an allowable transformation defined by the type of scale, then all the other evaluations k_i should be replaced with $\xi(k_i)$. Let us also assume that the set x_0 finite: $x_0 = \{1, \dots, q\}$. Elements of this set will be called scale gradations.

Expert preferences are modeled by the relation of preference R by X: xRy. *That* means that the evaluation vector x is not less preferable than y. The relation R generates the indifference relation I and (strict) preference P: xIy, i.e. the following exressions are true: xRy и yRx. xPy is completed when xRy, is true and yRx *is not true.*

For generality, we will use the preference relation accepted for the modeling of the weighted total R^V [1]. For modeling of preferences defined using the value function we will use the preference relation R^f. Additionally, it is suggested to consider not the "weights" of the evaluations as it is done in the method of weighted sums, bit the importance of their numeric values using the terminology of the evaluation significance theory. The concepts of "weight" and evaluation importance are somewhat different, but in terms of practical conclusions of this study it is insignificant.

We evaluate the significance of changes in the SC operational performance in the form of paired comparison of values *б* (importance of first evaluation) and *в* (importance of second evaluation). It is assumed that the values of evaluation importance are whole numbers from 1 to m.

Let us assume that it is easier to the expert to identify the relation of the evaluation values importance as a relation of several whole numbers. We suggest defining the value function in the additive form by comparing by each scale grade k its value $v(k)$. Let w represent the difference quotient of

[1] In this article, the experts should be cosmonauts and control center employees.

scale grades values. It shows the measure of "waning" of an expert's preference growth.

$$d_k \le \frac{\nu(k+1)-\nu(k)}{\nu(k+2)-\nu(k+1)} \le u_k, k=1,\dots,q-2.$$

It is assumed that d_k and u_k are constant for all grades and $w=u_k$, as well as that $w>1$, $\alpha=1/w$.

Due to the variety of external effects SC is considered to be a complex system, i.e. as an object that is characterized by the functions performed by by its modules, as well as those functions' relation algorithms. In this case the set $\{k_1, ..., k_m\}$ that characterizes the SC survivability will be considered as a sum of evaluations of SC functional dependability.

An important feature of the considered task is the absence of unambiguous numerical characteristics that would describe the environmental effects. Therefore, it is suggested to solve the task of ensuring SC survivability under external effects in term of fuzzy logic (fuzzy sets).

For the purpose of this study it is suggested to apply the term fuzzy to sets of ordered couples: $A=\{u, \mu_A(u)\}$ composed of elements of the ground set U coupled with the function $\mu_A(u)$, $u \in A$ that defines the measure of membership or membership function. The function $\mu_A(u_i)$ indicates the assumed measure if membership of the element u_i in the set A. The primary feature of this function consists in the fact that it characterizes an expert's subjective idea of the nature of the evolution of SC reaction to external effects. It is also assumed that another expert's function $\mu_A(u_i)$ would have another formula.

A qualitative description of such quantitative concepts within the considered task would require a linguistic variable. A linguistic variable shall be a variable defined on the qualitative scale and possessing the values of words and phrases of a natural language.

In this article the advantage of fuzzy logic over the classic approach consists in the fact that under the fuzzy approach the analytical representation of external effects can be avoided. In many cases it suffices to provide a description of the SC reaction to such effects, while under the classic approach it is required to formalize the description of the external effects and internal factors that define the SC reaction to such effects.

It should be noted that as the diversity of deviations in the SC operation under external effects grows (growth of the value m in the formula (1)) the ability of the experts to make accurate meaningful assertions decreases. There can be a threshold beyond which the accuracy and meaningfulness become almost mutually exclusive characteristics.

Identifying such threshold requires the use of the law of requisite variety. It is known [3] that in respect to our task the variety of external factors can be compensated only by the variety of the signals that adapt the SC operation. In this case let us assume that in order to choose a strategy using the model (1) an expert must have the required experience and knowledge, be able to analyze situations, predict the dynamics of SC reaction to environmental effects.

The condition of information transmission without distortion proved by C. Shannon for noise-free signals [4], is the absence of excessive power at the source over the channel capacity. In the considered systems an evaluation of information source power and channel capacity is very complicated. However, in our case the efficiency of SC adaptation to external effects can be evaluted based on the importance of errors in the messages exchanged by functional modules. Let us assume that the measure of deviation from the standard mode of controlled module operation is defined by the value of distortion of the information received from the controlling module.

With regard to the considered task let us assume that those distortions correspond to the excess of power of the information flow over the channel capacity. In this case based on the above mentioned C. Shannon's condition let us define the condition of functional dependability of the control system in the absence of interference: *If the functional dependability of the controlled module is not lower than the functional dependability of the controlling module, then in the absence of interference the operation of the system of such modules can always be organized in such a way that its functional dependability will match the functional dependability of the controlling module without additional correction and conversion.*

The understanding of the control system dependability suggested in this article is based on the evaluation of the probability of no-failure in SC operation [5]. The model (1) allows choosing the strategy of ensuring SC survavability under environmental effects. The analysis of SC modules reaction variations is the basis for forecasting the consequences in such changes.

It is assumed that the characteristics of the SC survivability systems, requirements for the evaluations of the degree of adaptivity of functional modules, as well as the requirements for the form of control input results delivery are defined by the mission task. In this case it can be believed that the efficiency of control signals correction largely depends on the efficiency of computer support of forecasting.

Prognostic decision support system (PDSS)

There are over two hundred known software suites that can be used in forecasting the changes in the condition of complex objects or processes [6]. They work comparatively well when the development is stationary, i.e. process dynamics characteristics don't significantly change over time. Those programs also work well when the characteristics change function of a process or object is known.

In this context operational decision-making is required in order to ensure functional modules adaptivity to external factors subject to SC specific reactions to effects of unknown nature and unknown intensity dynamics. In this case it is suggested preparing expert forecast of SC reactions based on intersubject audit of its functional modules operation.

Let us identify the three primary tasks related to such PDSS operation:

Search, analysis and processing of current information:

- express analysis of subject areas with identification of key changes in SC functional modules operation;
- identification of information on specific functional modules in the database;
- identification of the most significant effects that define the developments at the SC;
- clusterization of information with possibility of reducing the dimensions of correcting signal's components;

The PDSS must enable:

- automatic offloading and transformation of information into the specified format;
- separation of dynamic links to information source (technical documentation data, RII information, functional modules operation monitoring results);
- simultaneous monitoring of independent modules that provide data on the development of SC reaction to external effects;
- setting time of repeated look-up of each of the modules for new messages;
- generation of reports within the time of operation as per the mission task specifying the number of downloaded messages;
- adding the name of source and date of receipt at the beginning of each message;
- specifying the format of the output file;
- downloading new messages without operator's involvment;
- setting the download mode at request (disabling automatic lookup);
- enabling automatic download;
- notification of new messages;
- monitoring of accidents;

2. Data logging:

- document archiving and development of internal documents with elaborate information search functions;
- creation of the archive of formal profiles (with elaborate search functions) for each functional module;
- automation of regular monitoring of functional modules;
- identification of relations between module reactions, correlations between external effect;
- automation of reports and analytical notes preparation;
- capability to modify the database sructure (adding new properties and generic objects over the course of system operation);
- organization of single storage for information on monitored objects, events, data from external databases;
- automated identification of mentions of objects, connections and events;
- visualization of knowledge as a semantic network;
- capability of searching for implied (indirect) connections between modules reactions;

3. Condition analysis and providing recommendations on managerial decision-making.

PDSS must ensure the compatibility of calculated preferences and expert evaluations obtained based on conventional (or newly developed) mathematical methods implemented within software and hardware.

The first two tasks are not managerial ones, yet SC survivability depends on the efficiency of the hardware and software subsystems that perform those tasks. Those tasks are classic, therefore in order to solve them it is suggested to use software available on the market. Practice shows that the third task can be solved with existing software products, but the combination of fuzzy logics and the requirement for fast decision-making within the time limited by the development of destructive processes in SC as the result of external EPE makes for a unique situation.

It is suggested to design PDSS as a distributed system. Hierarchically it is to be divided into several levels of forecasting process. *Sun Management Center* is an example of such system structure division that comprises the monitoring level, servers and agents. In our case the experts can be considered to be agents.

At the monitoring level it is required to take into consideration the interface between expert requests and the results of intersubject audit of the development of SC reactions to external effects. At this level, we can use the Java monitor, network monitor and call level interfaces. For the same server such monitors must ensure:

display of functional modules performance, e.g. in the form of tables and graphs;

capability to manage characteristics and properties that control functional modules operation, e.g. provide information on the proximity of the threshold of allowed change of operational performances;

capability to initialize control tasks, e.g. dynamic reconfiguration of modules' performance.

The server level receives requests via the monitor and sends them to a specific expert. Then it returns the expert's reply to the monitor. Additionally, by means of the interface the server provides the monitor with a secure entry point for communication with experts.

The purpose of the expert level is to collect information and generate corrective inputs to control commands. The experts shall apply the rules for defining the statuses of controlled modules. In case of rules infringements, the software automatically generates alerts and performs actions predefined by the respective rule of SC survivability.

Modern current information analysis systems widely use the concept of "knowledge management". According to this concept, in the proposed Expert system the main purpose of knowledge management (*Knowledge management – KM*) is the creation of an efficient communication medium that allows finding and using not information, but knowledge held by the experts experienced in the performance of SC mission tasks.

This approach is due to the fact that in practice the results of the audit of EPE and SC functional modules reactions development represent only the initial data. After clearing, sorting and statistical analysis they become information resources. The results of such resources analysis and design of messages based on expert conclusions transforms such resources into knowledge that is used in decision-making on control correction.

With regard to the considered task, in order to ensure agility of information analysis within the database, it is suggested to use the *OLAP* comprehensive multidimensional analysis technology. In particular, that includes the *FASMI* (*Fast Analysis of Shared Multidimensional Information*) test that includes requirements for multidimensional analysis applications:

1) provision of the analysis results to the expert within an acceptable time (usually, not more than 5 sec) even at the cost of less detailed analysis;

2) capability to perform any logical and statistical analysis specific to the given application and save its results in a form available to the end user;

3) multiple user access to data with support for mechanisms of authorized access and blocking;

4) multidimensional conceptual representation of data including full support of hierarchies and multiple hierarchies;

5) capability to refer to any required information regardless of its size and place of storage.

It should be noted that in respect to the considered task the *OLAP* functions can be implemented by various means, from the most simple data analysis tools in applications to complex distributed analytic systems [7].

Conclusion

Consideration of the opportunities presented by information technology in ensuring SC survivability under external effects has brought to light the capabilities enabled by the intellectualization of computer-based support of command. Based on forecasted development of SC functional modules' reaction to EPE, the proposed model of systematic accumulation and processing of data will enable FCOs to timely identify inadequacies in control actions.

The distinctive feature of the suggested method of information support of forecasting the development of SC functional modules' reaction to EPE is the combination of the methods of computer data processing and intersubject analysis of functional units operation. This approach must insure efficient decision making based on increased accuracy and agility of data processing and, consequently, selection of the scenario of SC operation adaptation to EPE subject to flight control officer's preferences.

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