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Spacecraft Emergency Situations Automated Scenarios Design within the Framework of FDIR Concept and Dynamical Neural Networks Technique

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Abstract: The space complex is considered as a Socio-CyberPhysical System (SCPS) in order to point out that the human factor is one of the most important ones in the analysis of emergency situations using spacecraft telemetry in the conditions of the current level of software development, information and technical resources of the space complex to ensure its functional stability. Functional stability of the system means its functionality under the influence of destructive factors of the external or internal environment. The concept of Fault Detection, Isolation, and Recovery (FDIR) is described, its advantages and drawbacks are pointed out in the context of the current problem. Based on the FDIR concept, decision support systems will be developed in future. In the framework of FDIR, spacecraft telemetry data is proposed to be used to design the monitor, the task of which is to identify and register emergency situations, based on modern data processing tools, namely, Dynamical Neural Networks (DNNs).

Keywords: FDIR concept, dynamical neural networks, telemetry, socio-cyberphysical system

1. INTRODUCTION

A space complex may be considered as a Socio-CyberPhysical System (SCPS) due to the increased influence of the human factor on the functional stability of the system in the context of modern trends in increasing software and hardware implementations in space technology. *Functional stability* is understood as the ability to preserve and/or restore the performance of system functions, as well as to adapt information communication channels when changing system elements under the influence of destructive factors of the external and/or internal environment (Korolev, 2018). Thus, along with technical, informational, and software processes and resources, a set of technical experts can be represented as human resources, taking into account the importance of their daily participation in ensuring the functional stability of the entire system. Increasing of personnel interaction efficiency with software and hardware is carried out, among other things, by developing decision support systems. In this paper, a new concept for operability diagnostics of a spacecraft using telemetry data from its service and target systems is proposed and presented. Based on this methodology, decision support systems are planned to be developed in future.

One of the modern methods of ensuring functional stability is the application of the concept of Fault Detection, Isolation, and Recovery (FDIR). The main tasks of FDIR are the automatic switch of the spacecraft to a safe mode of operation, logging, and localization

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of emergency situations. This methodology makes it possible to increase the reliability of the target application without using excess reserves, therefore it is widely used in the rocket and space industry (Akhmetov, Makarov, & Sollogub, 2014; Eickhoff, 2012).

To construct and implement the mentioned concept above during the system design and after the start of the flight mission, it is necessary to classify the nature of possible faults. To do this, methods of probability theory, reliability theory, and expert evaluation are currently used in engineering practice. Another way is to process the telemetry information coming from the spacecraft, to analyse and classify it, using classical and modern concepts of data processing: the method of support vectors (Azevedo, Ambrosio, & Vieira, 2012), self-learning Kohonen maps (Talalaev & Fralenko, 2018), artificial neural networks, one of the extensions of which are Dynamical Neural Networks (DNNs) (A. S. Poznyak, Oria, & Poznyak, 2019), which will be used further in the current research.

DNNs have the aim of approximating uncertain systems represented by differential or difference equations or measuring (telemetry) information. In case of dynamical representations, both unknown parameters in the right-hand side of the system or its unknown form may be recovered, meanwhile, if the system is represented by time series, omissions or errors in the input sequence can be restored due to the flexible structure of DNNs. The main difference between dynamical neural networks and well-known data processing methods is time-dependence of their coefficients (weighting matrices), which allows them to be used in approximation problems for dynamical plants. DNNs have proven to be efficient approximate representations of different classes of uncertain models (A. Poznyak, Sanchez, & Yu, 2001; Wu, 1998; T. Poznyak, Chairez, & Poznyak, 2019). They can also use their internal memory to process arbitrary sequences of inputs. When analyzing time series, this property is important not only to recover the missing data, but also to detect non-standard behavior, that can lead to faults and emergency situations.

The following main contributions of this study are:

1. The space complex is considered as a SCPS and the concept of its functional stability is introduced and explained;
2. The telemetry data of the spacecraft is analyzed from the point of view of detecting and classifying anomalies;
3. In the FDIR concept, DNNs are proposed to be used as a monitor on telemetry data.

The rest of the paper is organised as follows. In Section 2, components of the space complex are described as well as a SCPS and its functional stability are defined. Section 3 analyzes the spacecraft telemetry data, introducing two types of anomalies and emergency engine start, that can occur the system. In Section 4, basics of FDIR concept are given and its modification for the current problem is discussed. Section 5 introduces theoretical background for DNN identification, using telemetry data. Section 6 presents some concluding remarks and ideas for future work.

2. THE SPACE COMPLEX AS A SOCIO-CYBERPHYSICAL SYSTEM

This section describes the main components of the space complex and their functions, as well as definitions of functional stability and telemetry. The necessity of transition from a cyberphysical system to a socio-cyberphysical one is justified when describing the space complex and ensuring its functioning.

The structure, characteristics, and operational standards of the equipment for a particular spacecraft are directly related to its purpose as part of the *Space Complex* (SC) defined as a set of interconnected orbital and ground-based technical devices that provide solutions to various tasks based on the use of outer space.

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Out of all the variety of SC components, only the following will be used in the current research:

- *Satellite Constellation* (SCon) as a set of spacecrafts located on the orbits in accordance with the ballistic structure and united by the commonality of the problems to be solved as part of the SC;
- *Ground Control Complex* (GCC) as a set of technical devices and structures designed to control the functioning of the spacecraft of SCon from the moment of launching to orbit;
- *Mission Control Center* (MCC) as structures with technical systems and technological tools of command-software, telemetry, and ballistic-navigation support, external information exchanges, trunk and special communications, mapping, designed to ensure the activities of service personnel for the formation, transmission, reception, processing, storage, documentation of information during the continuous process of spacecraft flight control;
- *Payload Data Management Center* (PDMC) as a set of interconnected ground-based technical devices with software designed to provide the customer and its consumers with target information obtained on the basis of space data (Piro et al., 2018).

Due to the concept of telemetry, the space complex may be represented and described as a single system. *Telemetry* is defined as a field of science and technology that deals with the development and operation of automated devices complex that ensures the receipt, conversion, transmission via a communication channel, reception, processing, and registration of measuring information and information about events in order to monitor at a distance the state and functioning of technical and biological systems of various objects and the study of natural phenomena. Thus, there is necessarily a telemetry system as a part of any spacecraft, considered as an automated system. A typical model of a telemetry system functionating is shown in Figure 2.1.

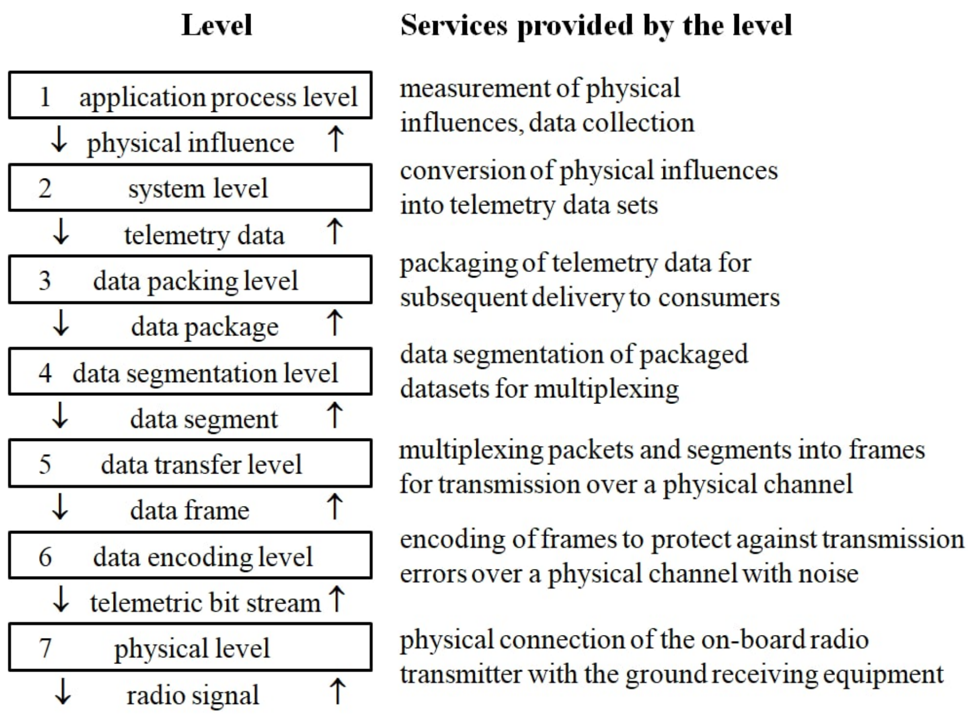

Fig. 2.1. Hierarchical model of a telemetry system using CCSDS (the Consultative Committee for Space Data Systems) recommendations

Functional stability is understood as a necessary condition for ensuring the fulfillment of the SC and its components objectives. For correct operation of the concept of functional stability, the SC should be considered as a complex object, represented by a *CyberPhysical System* (CPS), meaning an intelligent system based on engineering interacting networks of physical and computational components.

Taking into account the interaction of the SCon ballistic structure features and the geography of Ground-based Communications (GC), the unity of the information space for a particular spacecraft and the entire SC is possible only within a time-limited communication session over a physical connection via a radio signal, by establishing a communication channel. Usually, the communication channel between the spacecraft and the GC is considered as the basic level when presenting the SC as a CPS. With this approach, all resources and processes in the CPS belong to one of the categories: information, software or technical.

However, in this paper, this functionality is proposed to be extended by adding the category "personnel", designed to reflect the knowledge, experience, intuition, and ability to improvise of the personnel teams of the GCC, MCC, and PDMC in the form of expert assessments described by weight functions. Thus, in this paper it is proposed to consider a SC as a SCPS. The idea of considering a human (social) factor in automatic control systems is not new, associated with increasingly complex control and navigation tasks. For example, a concept of control subject has been introduced by V. Lefebvre (Lefebvre, 1977) and developed by V.E. Lepskiy (Lepskiy, 1998), D.A. Novikov (D.A. & E., 2012). According to this new general statement of control problems, control subject and control object should always be considered as integral parts. In (Sleptsov & Andrianova, 2021), the control subject's goals are described as follows: "Control subjects task is to ensure the required state of the system from its point of view, taking into account information about external disturbances. Naturally, the control system functioning this way is closed-loop as control object and control subject form a closed cycle."

Consideration of SC as a SCPS will make it possible to introduce into the control process a human factor not as a statistical disturbance, but as one of the vectors determining the development of SC. To solve this problem, methods of scenario tree construction are used to develop emergency situation scenarios. However, this method requires a sufficient amount of accumulated event statistics, i.e. recorded facts of qualitative or quantitative changes in the parameters of the internal and/or external environment of the spacecraft, which is directly related to the level of wear of the spacecraft systems components and contradicts the trend of high functional stability of the spacecraft for short periods of its operation. Thus, in this paper, the scenario tree method will not be directly applied.

3. SPACECRAFT TELEMETRY AS AN INFORMATION ENVIRONMENT FOR CONSTRUCTING THE SCENARIOS

Consider the communication channel between the spacecraft and the GCC as the only way for a single information space existence between the spacecraft and the SC. Characteristics of the communication channel under this consideration act as boundary conditions, and the main limitation of information exchange is the duration of the communication channel stable existence, mainly due to the mutual radio visibility of the spacecraft and the GSS.

Figure 3.2 shows the telemetry data of an element of the Spacecraft Orientation and Stabilization (SOS) system for 14 days: from 305 to 319. The SOS data are selected because the functional stability of the entire spacecraft directly depends on the operation of this system, as well as the quality of its target tasks: in this example, the telemetry information from the Earth remote sensing satellite is used.

The color of plots in Figure 3.2 shows the change of day in the considered interval. From the color change, it can be seen that the oscillation of the plots is cyclical: the data of the first days differ qualitatively from the last by the presence of a shift equal to about 17 minutes,

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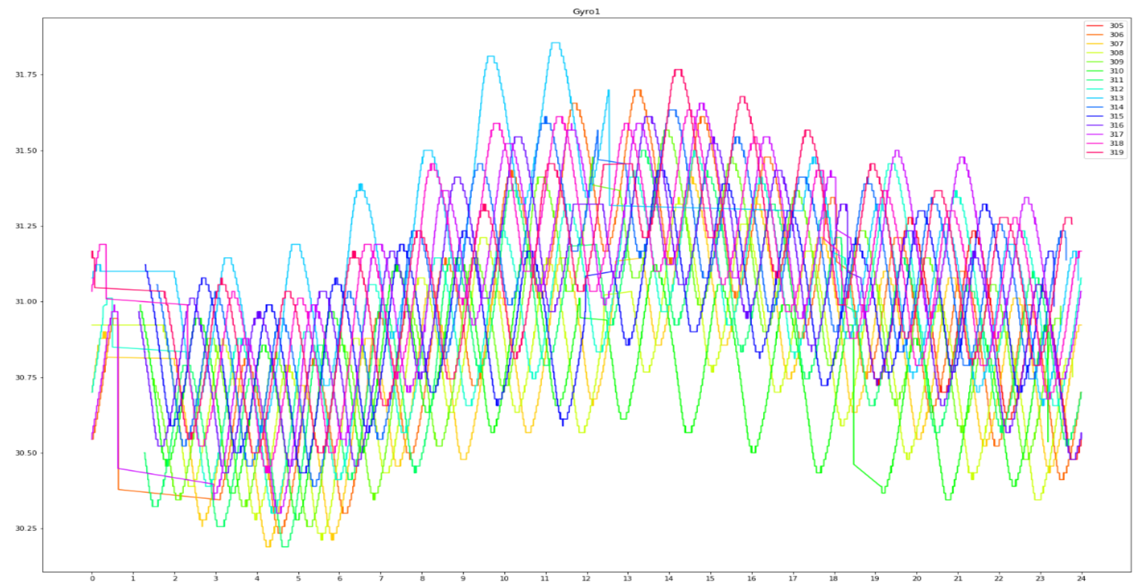

Fig. 3.2. Telemetry data from the element of SOS system

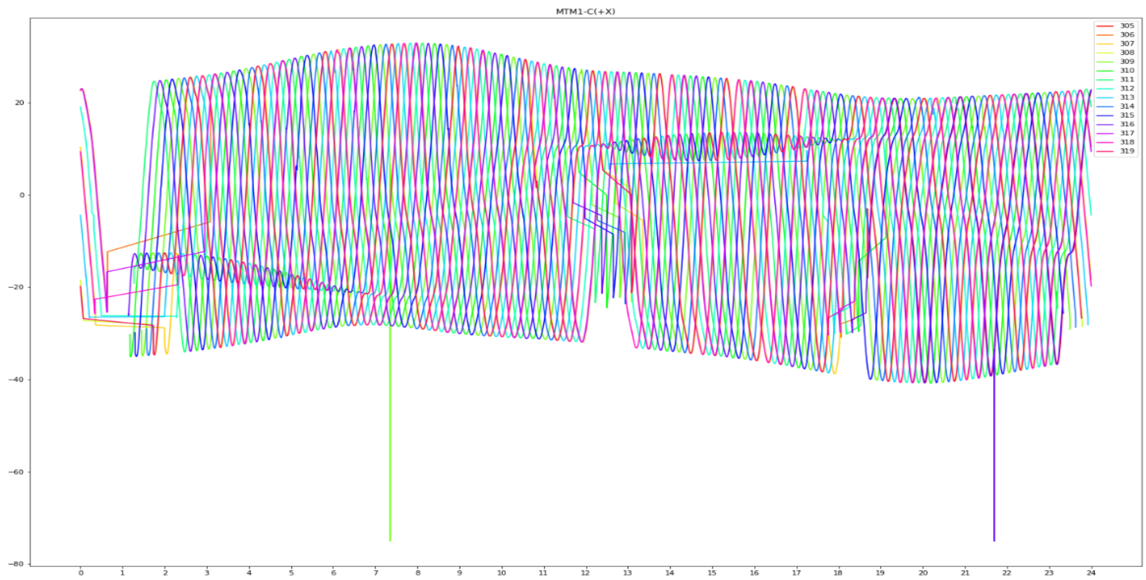

Fig. 3.3. Telemetry data from the magnetometer: X axis

which corresponds to the natural precession of the orbit for this spacecraft. This pattern can also be traced for other elements. Thus, Figures 3.3, 3.4, and 3.5 show telemetry data from one magnetometer along three axes, but the tendency to cyclicity persists here, despite the difference in the nature of the recorded characteristic.

In each of Figures 3.2–3.5, a characteristic area of data dominance is clearly visible, and it is not difficult to find mathematical functions to describe its boundaries. Denote this statistical area by the "norm" for the time period of observations under consideration. Two types of anomalies in relation to the "norm" can be distinguished.

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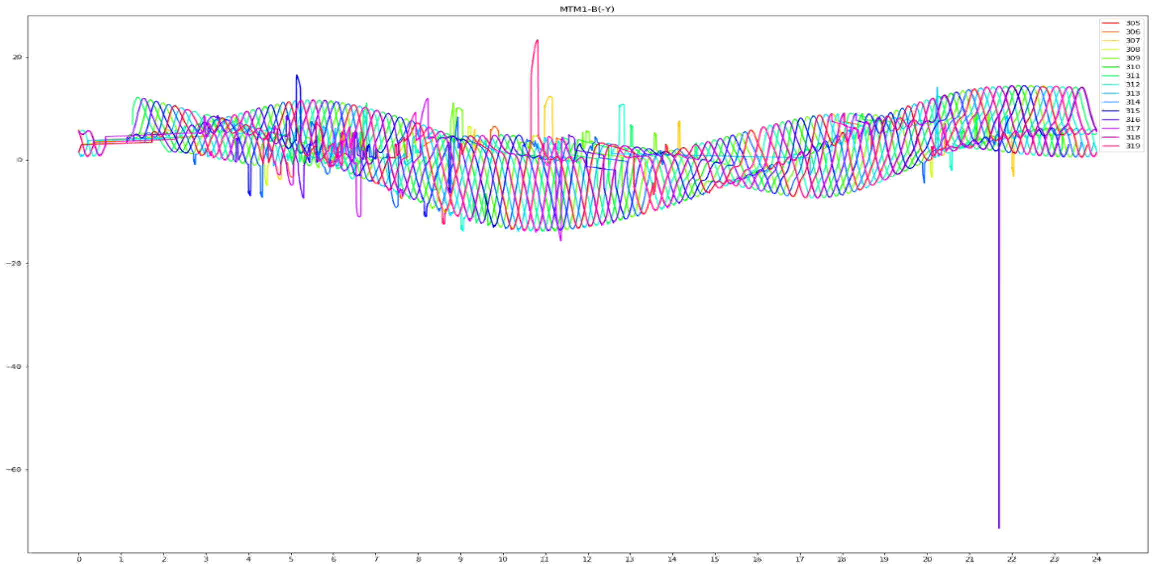

Fig. 3.4. Telemetry data from the magnetometer: Y axis

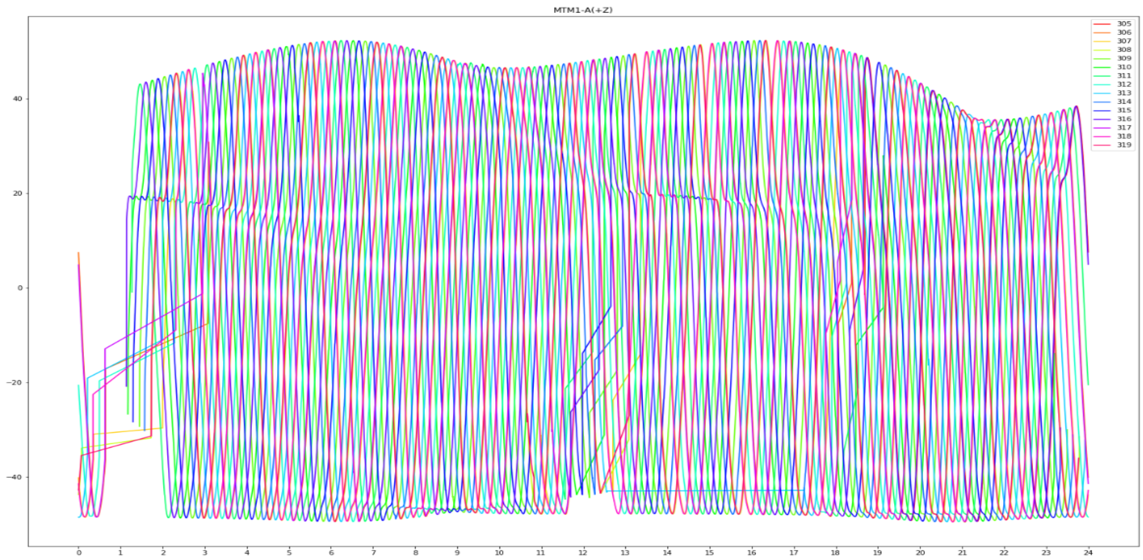

Fig. 3.5. Telemetry data from the magnetometer: Z axis

The first type of anomalies are long straight lines in the near-horizontal plane of the plot. These anomalies are nothing but gaps in the data. These gaps indicate the presence of problems in the recording equipment on board of the spacecraft and/or in the data transmission over the communication channel. In any case, the analysis of possible reasons for the presence of these gaps is the prerogative of specialists and experts, and not automatic tools, due to the lack of data on which it is possible to make a mathematically sound forecast about the cause of this phenomenon.

The second type of anomalies are vertical bursts that go beyond the boundaries of the "norm". These situations can be either single values as in Figure 3.3, or blue indications similar in nature in Figure 3.2. In the future, the anomalies of the second type will be called events, i.e. the occurrence of conditions or disturbances.

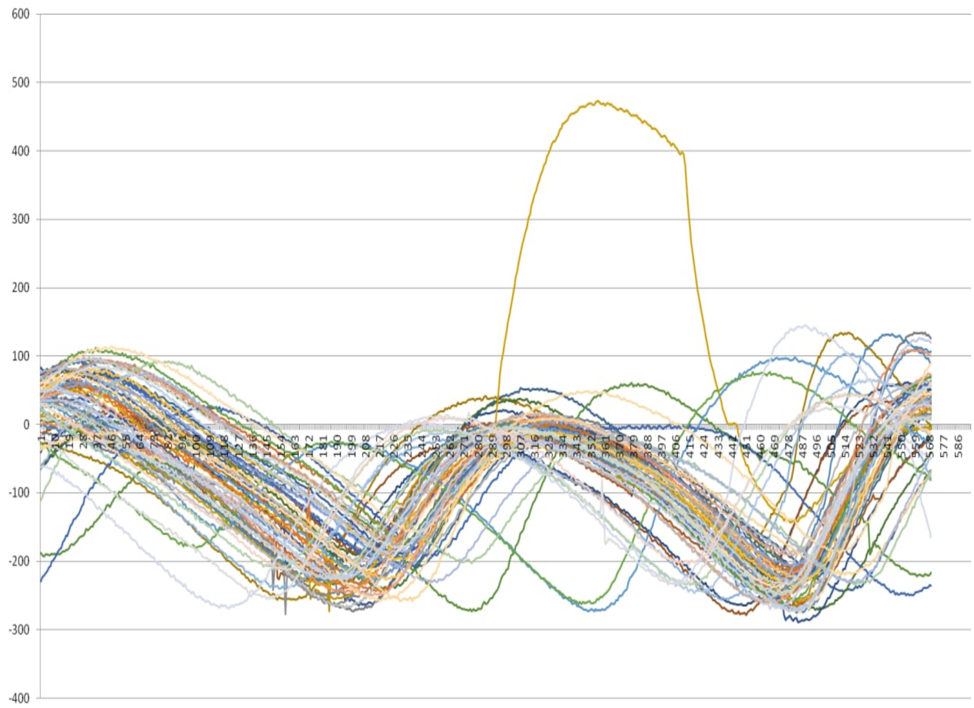

Fig. 3.6. Example of telemetry with an emergency engine start

Figure 3.6 shows a fragment of telemetry, which represents the emergency activation of the spacecraft engine (orange color), which can be classified as an emergency situation. The sequence of events in the telemetry of various spacecraft systems leading to an emergency situation will be called an *emergency scenario*. The development of automated software tools for localization and relief of the emergency situation consequences, followed by the recovery of the spacecraft operability, is one of the main tasks, solved in the framework of the FDIR concept.

4. DESCRIPTION OF FDIR METHODOLOGY

The FDIR concept is based on the principles that emergency situations of varying criticality occur with a certain probability. The probability and criticality of the occurrence of an emergency situation is determined from previous experience, the results of game-theoretic modeling, expert knowledge. The parrying of emergency situations depends on its criticality and can be carried out with the help of predefined scenarios developed on the basis of expert opinion and experience, see Figure 4.7.

The FDIR also provides for the possibility of parrying single emergency situations. This is achieved through the use of watchdog timers. A watchdog timer is an electronic timer that is used to detect and recover faults. During normal operation, this timer is constantly restarted to prevent the entire system from restarting, while in case of a software or hardware fault, this timer stops restarting and initiates system restart.

This concept is based on the following principles (Akhmetov et al., 2014; Eickhoff, 2012; Wander & Förstner, 2013; SalarKaleji & Dayyani, 2013):

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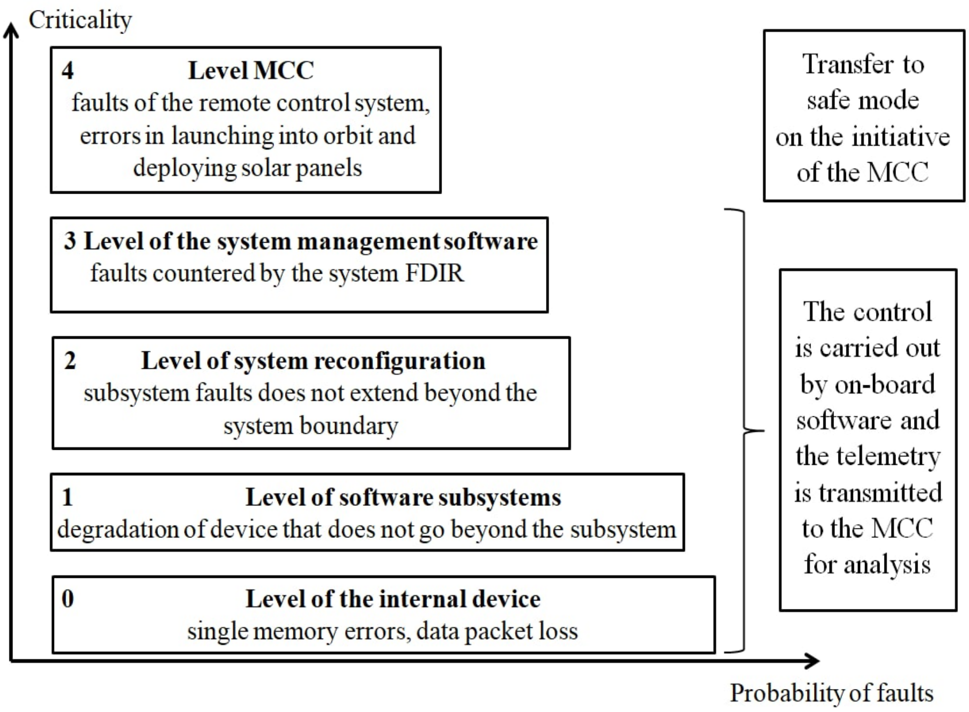

Fig. 4.7. Levels of FDIR

- design a precise hierarchy of types of faults, determination of the level of software and hardware that ensures the elimination of every fault;
- construction and implementation of algorithms for automatic transfer of the system to the safe mode;
- exploitation of autonomous onboard radio command and information-telemetry systems in the design of the spacecraft, providing reliable control and guaranteed receiving of telemetry information;
- ensuring the protection of the issuance and realization of potentially dangerous commands;
- providing the possibility of full or partial cleaning of the onboard RAM and restoring the original state of the onboard software;
- identification of the faults using explicit and implicit characteristics;
- usage of flexible configuration of software and hardware in system design.

The safe mode of operation of the spacecraft assumes:

- automatic transfer of the spacecraft to the orientation mode, which provides guaranteed power from solar panels, disconnection of the electrical load associated with the intended use and with other energy-consuming processes;
- ensuring the operation of the thermal regime system, onboard control system;
- use of redundancy: functional and/or substitution;
- the ability to restore onboard software using a new configuration of onboard hardware and software, which provides a mode of restoring normal functioning.

FDIR has several levels of settings:

1. The settings that are embedded in ROM during the preparation of the spacecraft on the ground;
2. Software settings in RAM that are implemented and changed during flight tests;

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3. Flexible and adaptive settings, laid down according to certain cycles: year, month, decade.

The advantages of this concept include:

1. Adaptability and flexibility of spacecraft systems;
2. Autonomous and prompt elimination of emergency situations or automatic transfer to safe mode for further actions of the MCC;
3. The FDIR concept implies the use of the onboard computer resource, and, accordingly, the analysis of telemetry information on board, which, on the one hand, reduces the load on the MCC, allows for the analysis of information promptly and allows you to make decisions during a communication session with the Earth, and on the other hand, selectively record the most interesting fragments of telemetry information for long periods of time.

Accordingly, the disadvantage is the complication of the onboard hardware and software complex, which requires:

1. complication of initial design;
2. increased requirements on the reliability of the electronic component base;
3. increased requirements on the quality of the program code.

As an implementation of the FDIR concept, the presence of the Automatic RecOnfiguration (ARO) mechanism in the onboard software can be considered. The essence of the work of this software mechanism is that each working element of all spacecraft systems is expertly assigned with weight values, which are summed up in the ARO indicator. When the value of the ARO indicator due to faults in the operation of the spacecraft elements falls below the expert-defined value, the procedure for changing the orientation mode of the spacecraft is automatically started, aimed at stabilizing the functioning of the spacecraft. The telemetry data of the ARO software mechanism is shown in Figure 4.8.

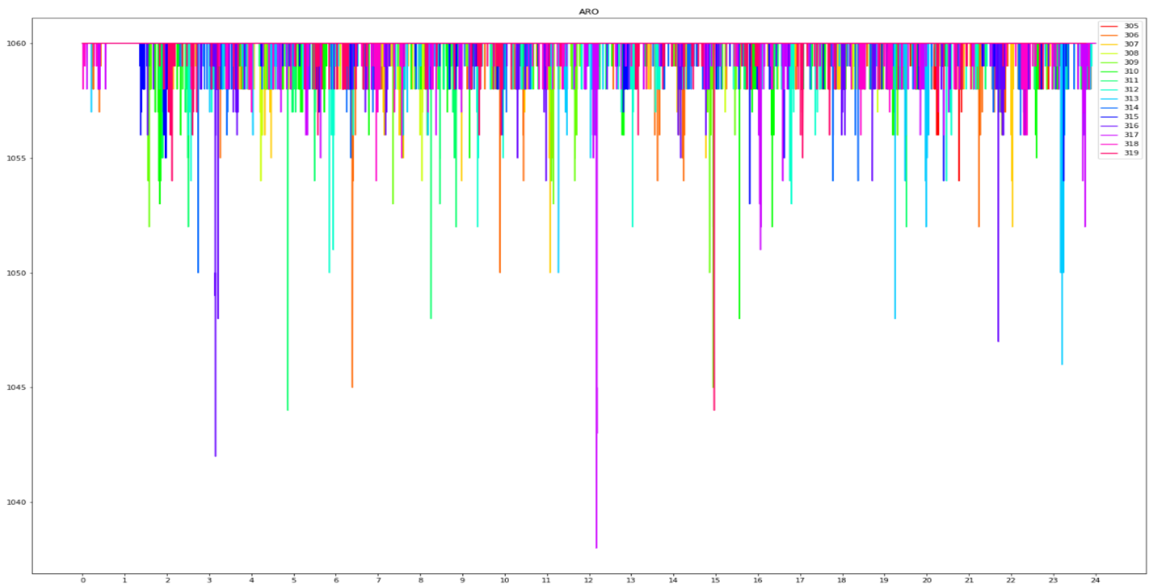

Fig. 4.8. Telemetry data from ARO

The FDIR concept involves the use of several execution units: a monitor, a script block, and a logging block. They can be both software and hardware. Later in this article, the design of the software monitor will be described. Monitor's task is to identify and register emergency situations.

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The main tools for monitoring used in the aerospace industry are various types of Kalman filters (Pontuschka & da Fonseca, 2014; Lu, Eykeren, Kampen, Chu, & Yu, n.d.; Zolghadri, 2017), and also time series (Troiano, Tipaldi, Hoping, De Pasquale, & Bruenjes, 2012). Time series have no predictive power. Kalman filter makes it possible to predict, but it can diverge. DNNs that will be described in the next section have predictive ability, and their convergence is proved using Lyapunov methods. The speed of their convergence depends on the selection of parameters.

5. DNN IDENTIFICATION FOR ELECTRO-MECHANICAL PART OF THE SPACECRAFT SYSTEM

DNNs have the aim of approximating the right-hand side of uncertain systems represented by dynamical equations. For continuous-time systems, differential neural networks have proven to be efficient approximate representations of different classes of uncertain models (A. Poznyak et al., 2001; Wu, 1998; T. Poznyak et al., 2019), meanwhile up to now recurrent neural networks with time-dependent weighting matrices have not been used much to represent discrete-time systems.

Measurements from the spacecraft sensors are received discretely, which is why in the development of this study it is planned to consider the electro-mechanical part of the measured data as a discrete-time system of the “black box” type, i.e. with unknown motion laws, and based on the available sensors data to approximate this system using recurrent neural networks. Generalization of existing methods to discrete-time systems is not a difficult task, since the mathematical basis for the approximate representation of systems using DNN is the Lyapunov stability theory, which is sufficiently developed for both continuous and discrete-time cases. Move on to the description of the system under consideration.

5.1. Problem description

In Figure 5.9, the spacecraft is represented by an unknown electro-mechanical model, which has the following input and output signals: α_i, being the spacecraft rotation angle; ω_i, being the angular velocity of the spacecraft; ω_i^M, being the angular velocity of the wheel; $u_i = u_i\left(\omega_i^M(kT)\right)$, being the control signal; ξ_i, being the norm-bounded disturbances, $i = \overline{1,3}$.

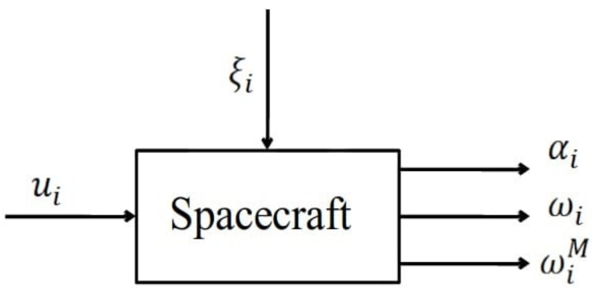

Fig. 5.9. Spacecraft as a black box representation

Dynamical representation of the system, given in Figure 5.9, may be proposed in the following form:

$$\alpha_i(kT) = f_i\left(\alpha_i((k-1)T), \omega_i((k-1)T), \omega_i^M((k-1)T)\right) + \xi_i(kT), \tag{5.1}$$

$$\omega_i(kT) = g_i\left(\alpha_i((k-1)T), \omega_i((k-1)T), \omega_i^M((k-1)T)\right) + \tag{5.2}$$

$$u_i\left(\omega_i^M((k-1)T)\right) + \xi_i(kT),$$

$$\omega_i^M(kT) = h_i\left(\alpha_i((k-1)T), \omega_i((k-1)T), \omega_i^M((k-1)T)\right) \tag{5.3}$$

where functions $f_i\left(\alpha_i, \omega_i, \omega_i^M\right)$, $g_i\left(\alpha_i, \omega_i, \omega_i^M\right)$, and $h_i\left(\alpha_i, \omega_i, \omega_i^M\right)$ are unknown and should be approximated; k is a non-negative integer value; $T > 0$ is a time step.

5.2. Dynamical (recurrent) neural network identifier

Denoting the state vector of system (5.1)–(5.3) by $x = \left[\alpha_i,\, \omega_i,\, \omega_i^M\right]$, supposing that the right-hand side of the system is unknown or partly known, represent system (5.1)–(5.3) in the form

$$x(kT) = Ax((k-1)T) + W_1^*\sigma_1(x((k-1)T)) + \\ W_2^*\sigma_1(x((k-1)T))u_i\left(\omega_i^M(k-1)T)\right) + \tilde{f}(x((k-1)T))$$

where $A \in \mathbb{R}^{9\times 9}$ is a Hurwitz matrix, $W_1^* \in \mathbb{R}^{9\times 9}$ and $W_2^* \in \mathbb{R}^{9\times m}$ are time-invariant (unknown) weighting matrices (m can be chosen), $\sigma_1(x((k-1)T)) \in \mathbb{R}^{3\times 1}$ and $\sigma_2(x((k-1)T)) \in \mathbb{R}^{m\times 1}$ are activation functions (for example, sigmoidal ones).

DNN identifier takes the following form:

$$\hat{x}(kT) = A\hat{x}((k-1)T) + W_1(kT)\sigma_1(\hat{x}((k-1)T)) + \\ W_2(kT)\sigma_2(\hat{x}((k-1)T))u_i\left(\omega_i^M(k-1)T)\right).$$

By means of the Lyapunov stability theory for discrete systems and using the concept of ultimate boundedness, difference equations for the weighting matrices may be found in the form

$$W_i(kT) = \Sigma_i(x((k-1)T), \hat{x}((k-1)T), u(\omega_i^M(k-1)T)),\ i = \overline{1,2}.$$

The values of $W_1(kT)$ and $W_2(kT)$, obtained from the solution of the minization problem, connected with Lyapunov inequality, starting from some moment k_0T do not or slightly change, that is why these values may be fixed and used further for solving the prediction problem. The main task of prediction is not only to restore the future dynamics of the system using previous states and fixed weighting matrices, but also to detect possible faults in the system in the future and prevent them.

6. CONCLUSION

The purpose of this work was to explain the necessity of representation of SC in the form of SCPS and, in this context, to describe the tools that will be used for detection and localization of anomalies and emergency situations in the system. For this purpose, the experience of controlling the spacecraft SCon was used, in particular, the analysis of telemetry and the application of the FDIR concept, as an example of the introduction of expert participation of the MCC, GCC, and PDMC teams in controlling the spacecraft during the communication session. In order to achieve the goal in the mentioned operating conditions of the spacecraft, it was proposed to consider the use of DNN as a mechanism for automated analysis of telemetry for constructing emergency scenarios, which in the future will become the basis for creating a decision support system that allows increasing the functional stability of the entire SC and saving the limited time of the spacecraft communication session for detection, localization, and recovery of the consequences of an emergency situation on board the spacecraft by creating an automated archive of emergency scenarios.

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