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S.N. Firsov
O.A. Pishchukhina

Assessment of Functional Sustainability of Computer-Integrated Technological Systems

Department of Electrical Engineering, National Aerospace University
Department of Social Informatics Kharkiv National University of Radio Electronics

This paper puts forward formation of quantitative complex indexes and criterion as the key points for assessment of computer-integrated technological system sustainability. The offered assessment goes beyond classical approach as it takes into account incomplete aprioristic information about the technical state of the system and conditions of its operation. The developed assessment method contributes to the effective analysis of functional sustainability of computer-integrated technological systems; comparative evaluation of the two or more computer-integrated technological systems; synthesis of technological systems with specified property of functional sustainability. This solution will also lead to optimal use of available resources for system recovery and increasing operability level of the system.
Keywords: Computer-integrated technological system, functional sustainability, assessment, quantitative indexes.

Introduction

Retention of functional characteristics of the computer-integrated technological systems (CITS) by introduction of redundancy is an important aspect of the reliability problem while the emergence of abnormal situations associated with the presence of failures, malfunctions, faults and other technical anomalies. Increase of interest to this issue contributed to the emergence of a new research trend of functionally sustainable management of CITS, which takes its roots in the writings of Moore and Shannon [1], further it was developed by Zakrevskiy [2] in the context of the reliability of redundant computing systems. Mashkov defined it as a new scientific direction [3], which subsequently was developing with the support of his followers in the direction of ensuring a functional sustainability of complex technical systems, such as automated traffic management systems, management information systems, etc.

Property of the system’s functional sustainability is the ability to maintain the performance of its basic functions over given time, within the limits established by applicable regulatory requirement in terms of either countering or impact of the flow of failures, malfunctions and faults [4-5]. The presented definition reflects the close relationship of the concept of "functional sustainability" with such concepts as "reliability", "survivability" and "fault tolerance". However, the fundamental difference between them is that the methods for ensuring functional sustainability should be focused not on reducing number of emergency situations (as traditional methods of increasing reliability, survivability and fault tolerance of technical systems), but on ensuring fulfillment of the required functions when abnormal situations have been occurred. Therefore, ensuring the functional sustainability of systems goes beyond the traditional and classical control theory, as it implies the presence of incomplete aprioristic information about the technical state of the system and conditions of its operation. This puts forward operative formation of movement parameters management corresponding to the system's technical condition and the optimal use of all available resources [6-8].

Formation of the set of functional sustainability indexes of CITS is an important and crucial stage in the creation of theoretical foundations of this property introduction. This process is associated with the necessity to meet a number of contradictory requirements for such indexes. Resolution of these contradictions is possible by application of reasonable compromise, as well as by using of system of partial indexes (for which the area of application is limited) while solving a number of the specific tasks. That is why the formation of functional sustainability indexes of CITS is cutting-edge problem requiring relevant analysis, consideration and practical implementation.

1. Problem statement

The next basis of the requirements for the functional quality indexes comes from the investigated operating experience of CITS:

selection of indexes under the semantic content should correspond to the definition of the property of functional sustainability of systems;

index should provide a sufficiently high level of systematic research;

index should allow developing models of functional sustainability of CITS available for conducting research and performing calculations;

index should be sensitive to changes at the level of performance of functional sustainability.

On the basis of the considered requirements, it is necessary to develop indexes of functional sustainability of either designed or operated systems, reflecting in a greater or lesser degree compliance with the specified requirements.

2. Problem solution

In this paper, devoted to research in the thematic area, emerged failures are considered as the probable events, and probabilistic indexes dominate for reliability characteristics. However, due to the fact that a failure is characterized by uncertainty associated with the time, fault’s location, its class and type in the framework of the functionally sustainable management concept, the probability theory does not provide an appropriate mechanism to determine the level of functional sustainability. Therefore, there is a necessity to introduce other indexes, which take into account the above specifics, as well as characterizing the quality of the functionally sustainable management.

The next indicators can be attributed to general indexes, characterizing the quality of the use of models and toolkit of technical diagnostics and recovery of system functionality:

– operational efficiency of diagnosing functional state of CITS;

– efficiency of recovery operability CITS’s elements;

– accuracy of the technical diagnosis, i.e. the degree of diagnosing results compliance with the actual functional state of CITS;

– mean value of recovery efficiency, i.e. the arithmetic mean of the effectiveness of recovery after failure by each type of resource;

– complexity of recovery (costs of energy, time, resource, etc. for recovering);

– ratio of efficiency restoration;

– complexity of the software diagnostics;

– level of functional sustainability(complex characteristic given by indicating the reliability, depth of diagnosis, efficiency of recovery and time for diagnosis and recovery):

$$L=f(D, \lambda, E_{ср}, t_д, t_в), \quad (1)$$

where D – reliability of technical diagnosis;

λ – depth of diagnosis;

E_{cp} – arithmetic mean of the effectiveness of recovery;

$t_д$, $t_в$ – time for diagnosis and recovery respectively;

– period of active use, i.e. duration of operation from the beginning of CITS's operation and its renewal after renovation before moving to the ultimate state.

General indexes, in most cases, are complex and comprise some specific ones, allowing to characterize more accurately the quality of functional sustainability.

The specific indexes of functional sustainability comprise:

– maximum time of diagnosis of the CITS's functional state (the expected maximum time of diagnosis of the CITS's functional state for a given set of failure modes. This set is determined by the required depth of diagnosis);

– depth of diagnosis defined by specifying a stage, up to which the diagnosis is performed. The stages are: detection of malfunction, locating a point of a failure, determining its class and type;

– coverage factor (ratio of the number of elements, for which the redundancy has been introduced, to the total number of elements);

– coverage ratio of abnormal situations (ability of self-eliminating the certain anomalies, provided that there is an abnormal situation belonging to a given set of failures);

– adequacy of diagnostic models;

– maximum time for recovery of the functional state of CITS's elements;

– residual resource (a number of resources from the moment of recovery of the functional state before the emergence of a new abnormal situation);

– ultimate resource (a number of resources at the presence of which the maintenance and (or) recovery of the functional state is impossible or impractical).

The required numerical values of functional sustainability indexes are determined by the following factors:

– type of the abnormal situation and its characteristics;

– possible effects and the amount of damages arising as a result of anomalies;

– achieved level of functional sustainability of similar CITS;

– possible ways to enhance and ensure the functional sustainability.

For example, the rate of efficiency of diagnostics of CITS's functional state is a complex index, characterized by such indicators as the maximum and minimum time of diagnosis. The value of the maximum and minimum time of diagnosis depends on the type of a dichotomous diagnostic tree and the required depth of diagnosis:

$$t_{min} = \sum_{i=1}^{G} t_{i1} = \sum_{i=1}^{G} \left(t_{op} N_{op}\right)_{i1}; \; t_{max} = \sum_{i=1}^{G} t_{iq} = \sum_{i=1}^{G} \left(t_{op} N_{op}\right)_{iq}, \quad (2)$$

where t_{i1} – time of movement on dichotomous tree with the depth G and tree's branches with the minimum length;

t_{iq} – time of movement on dichotomous tree with the depth G and tree's branches with the maximum length;

t_{op} – the execution time of an operator in the diagnostic procedure; Nop – number of operators.

The index of recovery efficiency of functional properties of CITS's elements is also a complex index, characterized by such indicators as the maximum and minimum recovery time. The value of indexes of the maximum and minimum recovery time depends on the type of the selected resource and required quality of recovery:

$$t_{min} = t_{i1} = t_{pd\_i1} + t_{kom\_i1} + t_{pp\_i1};\ t_{max} = t_{iw} = t_{pd\_iw} + t_{kom\_iw} + t_{pp\_iw}, \quad (3)$$

where t_{i1} – time of operability recovery by the first resource;

t_{iw}– time of operability recovery by the w-th resource;

t_{pd} – time of resource run-up;

t_{kom} – time of resource commutation; tpp – parameter passing time.

Indicator of diagnostic adequacy represents the actual degree of diagnosis compliance with the functional state of CITS. It depends on adequacy of diagnostic models.

Average index of recovery efficiency is defined as follows:

$$E_{cp} = \frac{1}{N}\sum_{i} E_i, \quad (4)$$

where E_i – recovery efficiency by the i-th resource, $E_i = y_{i\_vost} / y_{i\_nom}$.

Dynamic complexity includes such indicators as computational complexity, complexity of data preparation, analysis and computational complexity. Computational complexity is the compound index which includes the following indicators: time of solving the problem, memory size, capacity of storage devices, etc.

Criteria for the functional sustainability of CITS. ll existing categories of criteria designed to assess the quality of the functional components of sustainable systems can be reduced to the three groups: eligibility criteria, criteria of the comparative evaluation and optimality criteria.

Eligibility criterion is formed as the next inequality:

$$L \ge L_{ag} \quad (5)$$

where L_{ag} – a given value of the index of functional sustainability.

This criterion is intended to substantiate the requirements for the functional sustainability of CITS with consideration of a predetermined level.

Criterion of the comparative evaluation is formed as the inequality:

$$L_i \ge L_j \quad (6)$$

where L_i, L_j – indicators of the level of functional sustainability of the i-th and the *j*-th variants of CITS.

The above criterion is used for selection of the certain CITS amongst alternative ones with the best index of the level of functional sustainability.

Optimality criterion is formed as the equality:

$$L = \max_{\{L_i\},i=1..n} L. \quad (7)$$

The above criterion allows to synthesize the system in the way, that the index of the level of functional sustainability gains the maximum value within the certain bounded set.

Assessment of complex index of the functional sustainability level of CITS. n some cases, assessment of a complex index of the functional sustainability level of CITS by conducting testing of the system becomes very difficult or requires large material costs. At the same time, there is a possibility of experimental processing of independent subsystems, making up the CITS. In this regard, the problem of estimating the functional sustainability level of CITS arises as a problem of estimating the functional sustainability level of its independent subsystems. In this case, the index of functional sustainability level of CITS can be written as:

$$L = \prod_{i=1}^{l} L_i, \tag{8}$$

where L_i – index of the functional sustainability level of the i-th element of system;

l – a number of elements, making up the system.

When solving the problem, values of indexes of the functional sustainability level of the system components are assumed to be known. These values are obtained as a results of experimental tests: $\underline{L}_i$ the lower limit of the confidence interval of the functional sustainability level of the *i*-th element, corresponding to the accepted level of trust γ; $\hat{L}_i$ –point estimation of the functional sustain ability level of the i-th element.

Then, point estimation of the functional sustainability level of all system in accordance to (8) is equal:

$$\hat{L} = \prod_{i=1}^{l} \hat{L}_i \tag{9}$$

Obviously, the definition of the lower limit on the ratio defined as follows is too rough:

$$\underline{L} = \prod_{i=1}^{l} \underline{L}_i. \tag{10}$$

This is because joint getting of indexes of the functional sustainability levels of all elements into the lower boundary of the confidence intervals is very unlikely. That is why, application of equality (10) can result in too small values of $\underline{L}_i$.

Result that is more accurate is based on the use of the approximate equation:

$$\underline{L} \cong \hat{L} - t_\gamma \sigma_{\hat{L}}, \tag{11}$$

where t_γ –coefficient corresponding to the accepted level of trust γ;

$\sigma_{\hat{L}}$ –point deviation, for example in the form of root mean square deviation.

To specify the relation it is necessary to find expression for $\sigma_{\hat{L}}$. The deviation for the function (11) is obtained by the following equation linearization:

$$\sigma_{\hat{L}} \cong \sqrt{\sum_{i=1}^{l} \left(\frac{\partial \hat{L}}{\partial \hat{L}_i} \right)^2_{\hat{L}=L} D_{\hat{L}_i}} \cong \hat{L} \sqrt{\sum_{i=1}^{l} \left(\frac{1}{\hat{L}_i} \right)^2 \sigma^2_{\hat{L}_i}} \; . \qquad (12$$

For determining $\sigma_{\hat{L}}$ equality (11) should be applied to the *i*-th element:

$$\underline{L}_i \cong \hat{L}_i - t_\gamma \sigma_{\hat{L}_i}. \tag{13}$$

After completing a series of transformations with (13) the next formula arises:

$$\sigma_{\hat{L}_i} = (\hat{L}_i - \underline{L}_i)/\, t_\gamma \cong \hat{L} \frac{1}{t_\gamma} \sqrt{\sum_{i=1}^{l} \left(1 - \frac{\underline{L}_i}{\hat{L}_i} \right)^2} \; . \tag{14}$$

With considering (13) equality (1) assumes the form:

$$\underline{L} \cong \hat{L}\left[1-\sqrt{\sum_{i=1}^{l}\left(1-\frac{\underline{L}_i}{\hat{L}_i}\right)^2}\right]. \qquad (15)$$

Equality (15) helps to estimate easily the L system on the given $\underline{L}_i$ and $\hat{L}_i$.

More rigorous assessment of the lower level limit of the of CITS's functional sustainability one can gain, using general methods of interval estimation of many parameters functions, such as represented in the writings [9-10].

Integrated assessment of efficiency of functionally sustainable CITS. So far as emergency situations are reliably identified and counteracted in functionally sustainable CITS, this system belongs to the class of functional systems that have property of survivability [6]. Quantitative index of use efficiency of such systems can be defined as the ratio between the complex parameters of quality of the computer-integrated system with the functional sustainability, and the system, which does not possess any properties of functional sustainability. Integrated quality indexes reflect the degree of influence to abnormal situations on the basic characteristics of the computer-integrated technological system. For assessment of complex indexes of CITS the most essential indexes are used.

These indexes characterize the quality of system's functioning, for example, capacity, sustainability, accuracy, controllability. Quality indexes of system's functioning can be presented as follows:

$$Pk = \{Pk_1, Pk_2, Pk_3, Pk_4, Pk_5\}, \qquad (16)$$

where Pk_1 – quality index, characterizing the accuracy;

Pk_2 – quality index, characterizing the performance;

Pk_3 – quality index, characterizing the sustainability;

Pk_4 – quality index, characterizing the capacity;

Pk_5 – quality index, characterizing the controllability.

To determine the complex quality indexes for different technological systems the pivot tables are formed, reflecting the influence of abnormal situation ($d_j \in D_{CITS}$) to the corresponding quality indexes. The value of table cell is determined by the following equation:

$$S_{ij} = \begin{cases} 1, d_j \in D_{CITS}, \Delta Pk_i = 0; \\ 0, d_j \in D_{CITS}, \Delta Pk_i \neq 0, \end{cases} \qquad (17)$$

where S_{ij} – value of a cell located at the intersection of the i-th row and the j-th column.

On the basis of expression (17) the cell S_{ij} is assigned the value "0" if the type of failure $d_j \in D_{CITS}$ modifies the value of the quality index of CITS for the worse and the value "1"in the contrary case.

For further calculations, the matrix s_{CITS} is made, it consists of rows and columns of tables of anomalies influence on the quality indexes of system.

The value of the complex quality index for different variants of CITS is defined as follows:

$$J = \sum_{i=1}^{M} \sum_{j=1}^{L} S_{ij} / ML \qquad (18)$$

where J – complex quality index;

M, L – the number of rows and columns in the matrix s_{CITS} respectively.

Complex quality index (18) is an integrated quality assessment of the CITS's functioning while emergence of abnormal situations. In the case, when a set of abnormal situations do not influence on quality indexes, that corresponds to the presence of only"1" in the pivot table cells, then complex quality index is equal to "1". If all types of abnormal situations influence on quality indexes of CITS's functioning, that corresponds to the presence of only"0" in the pivot table cells, then complex quality index is equal to "0".

Assessment of the level of functional sustainability of CITS. One of the specific characteristics of the functionally sustainable CITS, operating in real time, is that it is able to recover the quality of management after the emergence of abnormal situations. The system, having the property of functional sustainability, performs its functions with the required quality (even if emergencies arises in its functional elements), as well as providing a gradual deterioration of its performance with an increasing number of types of anomalies. Such system remains operational until it gains abnormal situations of a certain multiplicity, after which its characteristics do not allow it to perform assigned tasks with the required quality [14].

The developed quantitative assessment methods for determining the survivability allows: (i) the analysis of functional sustainability of computer-integrated technological systems; (ii) the comparative evaluation of the two or more computer-integrated technological systems; (iii) the synthesis of technical systems with specified properties of functional sustainability [15].

The method is based on the fact, that in the system a failure of arbitrary multiplicity may be present, and increase of failure multiplicity in system emerges gradually from a failure of smaller multiplicity to a failure of higher multiplicity.

Failure's state of the i-th multiplicity for all possible combinations of system's state is called generalized failure of multiplicity q^i. When studying the functional sustainability of computer integrated technological system, the generalized failures have been introduced, and states of the system have been determined.

The coefficient of functional sustainability of computer integrated technological system for the generalized failure $G(q^i)$ is the ratio of a number of operable states of the system to the entire aggregate of its states [6]:

$$G(q^i) = M_i / C_p^{\,i}, \qquad (19)$$

where $C_p^{\,i}$, M_i – the total number and the number of operable states for the generalized failure of multiplicity q^i respectively.

The dependence of the functional sustainability coefficient from the multiplicity of the generalized failure is a function of the system's functional sustainability: $G = f(q^i)$.

The denominator of function (19) has been determined by the multiplicity of the generalized failure and the number of failure modes:

$$C_p^{\,i} = p!/i!(p-i)! \qquad (20)$$

The numerator of function (19) depends on the type of CITS. So in the case of a single failure, CITS without the property of functional sustainability remains operational only if the failure emerges in the one of its elements. In the case of multiplicity of the generalized failure q^i, $2 \le i \le p$ CITS without functional sustainability is operational only if all the failures emerge with respect to one element. At the same time, the system with a functional sustainability retains its functionality, as part of the failure can be parried by other types of redundancy relating to other elements of CITS.

Conclusion

The results of conducted research contain the integrated assessment, i.e. formed complex indexes of functional sustainability of CITS to assess the level of system's functional sustainability. The method of assessment of the introduced complex quality index allowing to determine the functional sustainability level of CITS has been offered. Criteria allowing quantitative evaluation of the functional sustainability level have been formed as for promising, as for classical CITS. After series of experiments in simulation mode it has been proved, that the use of the proposed methodology for the functional sustainability allows:

(i) to improve the complex quality index of system by 2.4 times compared with the same system without the property of functional sustainability;

(ii) to increase the integral value of functional sustainability by 2.8 times compared with the system, in which traditional methods for ensuring operability are used.

Besides, conducted practical experiments and evaluation of functional sustainability prove, that the application of the methodology to ensure the functional sustainability of CITS increases the operability level for both its typical elements and the whole system.

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Оценка функциональной устойчивости компьютерно-интегрированных технологических систем

Статья посвящена проблеме формирования количественных комплексных показателей и критериев, которая является ключевой при оценке устойчивости компьютерно-интегрированной технологической системы. Предлагаемая оценка выходит за рамки классического подхода, поскольку учитывает неполную априорную информацию о техническом состоянии системы и условиях ее эксплуатации. Разработанный метод оценки способствует эффективному анализу функциональной устойчивости компьютерно-интегрированных технологических систем; позволяет реализовать сравнительную оценку двух или более компьютерно-интегрированных технологических систем; осуществить синтез технологических систем с указанным свойством функциональной устойчивости. Предлагаемое решение также приведет к оптимальному использованию имеющихся ресурсов для восстановления системы и повышению уровня работоспособности системы.

Ключевые слова: компьютерно-интегрированные технологические системы, функциональная устойчивость, оценка, количественные показатели.

Оцінка функціональної стійкості комп’ютерно-інтегрованих технологічних систем

Стаття присвячена проблемі формування кількісних комплексних показників і критеріїв, яка є ключовою при оцінці стійкості комп'ютерно-інтегрованої технологічної системи. Пропонована оцінка виходить за рамки класичного підходу, оскільки враховує неповну апріорну інформацію про технічний стан системи та умови її експлуатації. Розроблений метод оцінки сприяє ефективному аналізу функціональної стійкості комп'ютерно-інтегрованих технологічних систем; дозволяє реалізувати порівняльну оцінку двох або більше комп'ютерно-інтегрованих технологічних систем; здійснити синтез технологічних систем із зазначеною властивістю функціональної стійкості. Пропоноване рішення також призведе до оптимального використання наявних ресурсів для відновлення системи і підвищення рівня працездатності системи.

Ключові слова: комп'ютерно-інтегровані технологічні системи, функціональна стійкість, оцінка, кількісні показники.

Сведения об авторах:

Фирсов Сергей Николаевич – д-р техн. наук, доцент, зав. каф. 305 «Электротехники и мехатроники», Национальный аэрокосмический университет им. Н.Е. Жуковского «ХАИ», Украина.

Пищухина Ольга Александровна – канд. техн. наук, доцент, доцент кафедры СИ ХНУРЕ, Украина.