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Technology elements of behavioral energy testing of distributed information systems

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ABSTRACT

Early testing of the reliability of functioning, performed before the occurrence of critical emergency situations, plays an important role in the theory and practice of monitoring and diagnosing various technical systems, including computer distributed information systems. Many checking and diagnostic methods directly or indirectly use the energy characteristics of systems, that are directly related to the work they execute, that is, their performance. The proposed elements of the technology of behavioral energy-consumption testing are based on the corresponding models and methods, supplemented by the registration and analysis of inertial temperature and operational volt/ampere characteristics of the test behavior of systems, at the model level represented by extended energy-consumption Petri nets. The elements of behavioral testing technology, proposed in this work, are distinguished by an additional set of calculated and empirical boundary temperature and volt/ampere characteristics of both systems and their components. These characteristics represent states/vertexes, positions/transitions, fragments and scenarios of operation, that are critical in terms of energy consumption, which gives grounds for their monitoring. A feature of these elements of the technology is also the possibility of determining and using natural identifying properties of energy characteristics in behavioral testing, which allows them to be used in check and recognition experiments for the reliability of functioning, both independently and in conjunction with behavioral analysis. The use of additional analysis of energy consumption by temperature and volt/ampere characteristics, as part of complex testing technologies and automatic systems of technical diagnostic, based on them, makes it possible to increase the efficiency, completeness and flexibility of behavioral online and offline testing for computer distributed information systems.

Keywords: Network information system; behavioral energy testing; extended energy-loaded Petri net; energy-loaded identifier

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INTRODUCTION

Existing and prospective computer systems, including distributed information systems (DIS) [1, 2], are characterized by high complexity, a wide variety of architectures, technologies, diversity and ubiquity of application, high importance and criticality of the tasks being solved [3, 4]. Moreover, these properties develop exponentially [5]. In this regard, the need for advanced development of means to ensure the reliability of functioning [6, 7] of DIS, including testing methods [8, 9], [10], technologies and automated systems for technical diagnostics [11, 12], [13], is obvious.

There are and continue to appear various methods of offline [14, 15] and online testing [16, 17] computer systems, which significantly take into of account the features of architecture, technology, level, decomposition. Their methodological division into two basic classes is preserved: structural [18, 19] and functional [20, 21] classes, and, as a rule, complexes [22, 23] of different methods are used in implementations. The rapid growth in the degree of integration of technological components of DIS often does not give an idea of their internal structure, being limited to the functional and information specifications of certain presentation levels [24]. As a result, both the design of DIS and testing in its composition, with rare exceptions, for example, FPGA [25, 26], are significantly shifted from logical-electrical to architectural, system-functional levels [27, 28] and use complex technologies [29, 30] based on models and calculi of different classes.

A natural characteristic of the reliability of the functioning of the DIS component is temperature or energy costs, volt/ampere characteristics, which have,

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respectively, inertia and efficiency [31, 32]. Recently, these characteristics of DIS, often left without due attention, due to the growing interest in "green" technologies and energy saving [33, 34] are included among the most important for design and testing. Moreover, the emphasis is primarily on dynamic modes and transient states/processes of DIS components, including switching [35, 36], [37], which is typical for both structural [18, 19] and functional [20, 21] design and testing methods.

As noted, for real large systems, complex design and testing technologies are the most effective [29, 30], various interrelated methods of which take into account as much as possible all the information available in the input specifications about the architecture, technologies, operation, information structures of DIS and their components. In this case, it becomes possible to use information about the calculated and empirical energy characteristics of the DIS components in the most complete, diverse, in statics and dynamics.

The generality and compatibility of energy-loaded structural and functional models and methods of upper levels in complex technologies make it possible to expand them both for offline and online testing [38, 39]. This significantly expands the methodological basis for building design and testing tools, including automatic systems of technical diagnostics.

Thus, it is of interest to further develop just such a complex technology of behavioral energy-loaded testing of DIS components, based on methods for checking and recognizing their reliable functioning, taking into account energy consumption and extended energy-loaded Petri nets [40, 41].

1. GOAL, PROBLEM TASKS

The goal of the work is to increase the efficiency, completeness and flexibility of the basic elements of the complex technology of behavioral testing of DIS, extended by checking energy consumption and performed in experiments for checking and recognizing the functioning of extended Petri nets (EPN).

To achieve this goal, the following tasks are solved:

1) preprocessor, spatio-temporal decomposition of DIS models of distribution of behavior between components and in scenarios;

2) preprocessor analysis of energy consumption of boundary (upper and lower) and averaged for reference DIS, both calculated and experimental;

3) preprocessor analysis of identification of reference behavior for check and recognition in testing;

4) processor early behavioral testing of energy consumption for compliance with the reference ones during the main functioning of DIS;

5) processor, behavioral offline testing of energy consumption, as a check experiment for compliance with the reference ones outside the main functioning of DIS;

6) processor, behavioral online testing of energy consumption, as a recognizing experiment for compliance with the reference ones during the main functioning of DIS

7) post-processor, behavioral statistical, expert and fuzzy analysis and forecast of energy consumption and reliability of DIS functioning after early, online, offline testing.

2. DEFINITION OF TECHNOLOGY ELEMENTS OF BEHAVIORAL ENERGY TESTING

The resources required for this or that testing of DIS, the trade-off between its completeness and efficiency in specific applications, as a rule, determined by the criticality of the use of DIS, allow you to choose both the type of search and optimization in the testing itself, and the type of analysis of results and prediction of the reliability of functioning of DIS and choosing the necessary actions to ensure it.

All the preprocessor, processor and postprocessor testing elements of technology presented below, performing synthesis, control and recognition, search for intermediate and final solutions. The basic types of search are possible in the analysis of the behavior of DIS, testing, analysis and prediction of the reliability of the functioning of DIS can include depth-first search, breadth-first search, deterministic, pseudo-random, evolutionary, associative search, etc. Most often, the specific features of DIS and the conditions for their use determine the combined approach to the choice of search and the criterion for its optimization.

The elements of testing technology of DIS, presented below, focus on the special properties and actions of behavioral energy and energy-loaded testing, without considering the choice and description of the search mechanisms, built into them, and its optimization, which does not reduce the special completeness of the presentation of the testing technology itself.

2.1. Preprocessor elements of technology of testing

The solution of three preprocessor tasks involves the analysis and synthesis of DIS models and its components in the form of EPN (1) with the introduced and selected network and hierarchical structure, energy-loaded positions, transitions, chips [40,41].

$$S(f) = (P, T, Ev, Ac, X, Y, Ep, Et, F, S, M_0). \quad (1)$$

Preprocessor complex, spatio-temporal, in the general case, multi-level decomposition of EPN of the distribution of behavior between its components and in scenarios, respectively, is performed (2) [40,41]:

$$nS = (X, Y, S(f)^S, \alpha),$$
$$IS = (S(f), \cup_{i\in I} S(f)_i^p, \cup_{j\in J} S(f)_j^t, Sg_{iS}), \quad (2)$$

a) in the spatial network structure of DIS between its interacting components, in the structure of each component between its subcomponents, etc. with subsequent multi-level detailing of the elements of network structures of interaction;

b) in the temporal asynchronous-event structure of DIS behavior scenarios between its functional, conditional, communication states/vertices of diagrams and positions/transitions of EPN, graph-topological fragments based on them, in the temporal asynchronous-event internal decomposition structure of functional, conditional, communication states/vertices of diagrams and positions/transitions of EPN introduced using superposition, etc. followed by multi-level detailing and synchronization (3) [42] of the elements of hierarchical structures of behavior.

$$\psi^{\dagger} = \psi \cup (\cup_{i\in I} \psi_i^p) \cup (\cup_{j\in J} \psi_j^t)$$
$$\xi^{\dagger} = \xi \cup (\cup_{i\in I} \xi_i^p) \cup (\cup_{j\in J} \xi_j^t). \quad (3)$$

Preprocessor analysis of energy consumption as part of determining: boundary (upper and lower) and average characteristics of energy consumption in monogenic environment for reference DIS and their components (Fig. 1), both calculated and experimental, is performed with reference to:

a) states in state diagrams, to vertices in activity diagrams, to positions and transitions in EPN for behavior scenarios;

b) basic topological fragments of behavior scenarios, both for and EPN, taking into account the performed binding to their states/vertices and positions/transitions (in CPN, taking into account the mechanisms of transport and accumulation of values in recorder chips [40, 41]) of reference characteristics of energy consumption;

c) reference extrema and infima of energy consumption, both for states/vertices of diagrams and positions/transitions of EPN, basic graph-topological fragments of behavior scenarios based on them.

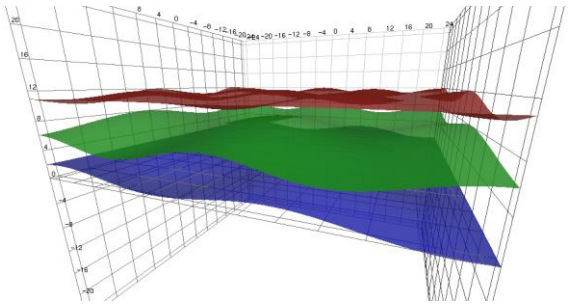


Fig. 1. **Continuous space for monitoring the characteristics of energy consumption of DIS components in monogenic environment: z-axis –components; y-axis – energy consumption; x-axis – time**

Source: **compiled by the authors**

Preprocessor analysis of the energy-loaded identification of the reference behavior on base testing model (4) [40, 41]:

$$CS=(W^{\wedge}, \{Pr, inPr, mPr\}, \{Ci, inCi\}, \{Cp, inCp\}, Sg_{ca}, Ce_c), \quad (4)$$

during subsequent check and recognition in testing is performed through the definition:

a) behavioral identifiers (characteristic graph-topological behavioral neighborhoods) for states/vertices of diagrams, positions/transitions of EPN and fragments of behavior based on them;

b) energy identifiers (characteristic graph-topological energy neighborhoods) for states/vertices, positions/transitions of EPN (taking into account the mechanisms of transport and accumulation of values in tokens-registrators (5)) and fragments of behavior based on them;

$$leaf_{ij}(p)=M(p)=pr_2(K(p,ev',ep'))=ep,$$
$$leaf_{ij}(t)=pr_2(K(t,ac',et'))=et. \quad (5)$$

c) complex energy-behavioral identifiers, compatible at the level of common states/vertices of diagrams, positions/transitions of EPN and fragments of behavior based on them (Fig. 2).

Decomposition allows one to polynomially reduce the dimension of the solution of energy-loaded testing problems, that is, to increase its efficiency, with an acceptable loss of its functional completeness and generality. Analysis of energy consumption and energy-loaded identification, by determining the reference energy consumption and test 0-primitives, in turn, ensure the implementation of check and recognition experiments of energy-loaded online and offline testing of DIS.

2.2. Processor elements of technology of testing

Processor early signal energy and energy-behavioral event-current and cumulative online testing of the ranked energy consumptions for compliance with the reference ones is performed in the background for achieved during the main operation of DIS:

a) states/vertices of diagrams, EPN positions/transitions;

b) basic graph-topological fragments of behavior based on them.

Energy and energy-behavioral event-current testing involves ensuring the conditions for controllability and observability of energy consumption through check points in the process of the main functioning of DIS and its components, and, first of all, refers to the energy extrema and infima identified during the ranking (Fig. 3). Energy and energy-behavioral testing of states/vertices and positions/transitions included in the constructed graph-topological fragments, in addition to event-current

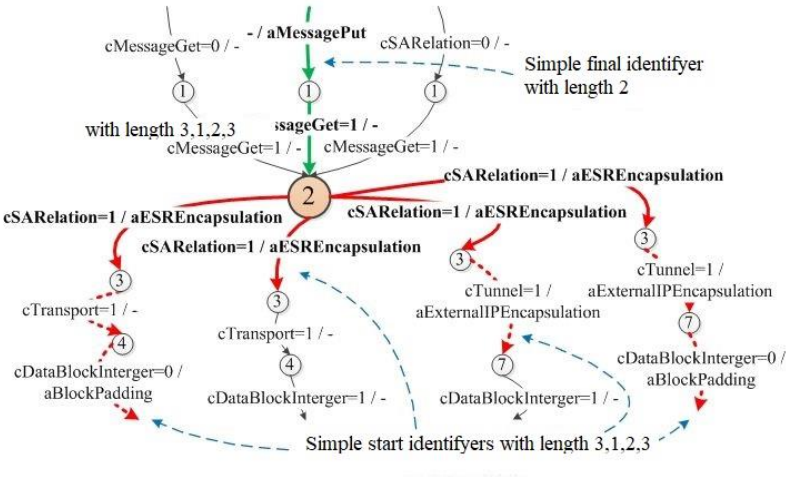


Fig. 2. **Identifiers of states/vertexes for behavior diagram**
Source: **compiled by the authors**

testing, includes accumulative testing for the fragment as a whole, represented in its nodal and output states/vertices and positions/transitions with using energy-loaded chips-recorders [40, 41].

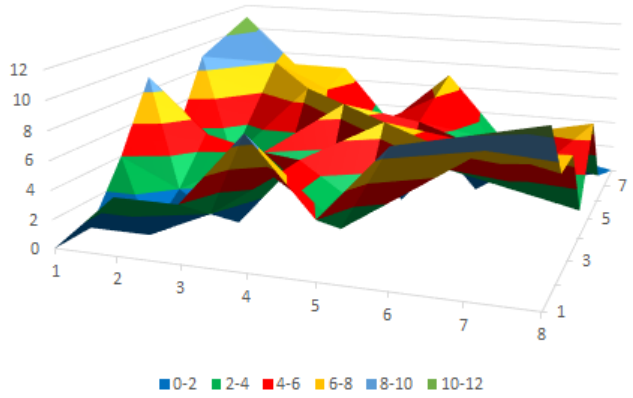


Fig. 3. **Discrete space for monitoring the extrema/infima of energy consumption of DIS components in heterogenic environment: z-axis – components, y-axis – energy consumption, x-axis – time**
Source: **compiled by the authors**

Processor, energy and energy-behavioral offline testing, as a special check experiment for compliance with the reference energy consumption and behavior outside the main operation of DIS and its components, includes the construction of tests for the reference EPN and their application to the tested model/implementation of DIS.

Offline testing is performed as part of:

a) synthesis of indivisible (primary) test energy (without explicit inclusion of the main behavior, but based on it) primitives based on the corresponding, preprocessor defined energy identifiers (0-primitives);

b) active formation, as an assembly of a set of test energy fragments (without an explicit inclusion of the main behavior, but on its basis) based on the adjacency relation and the shortest attainability of the reference behavior, checked in this test at the previous steps, with the current assessment and ranking of the achieved completeness, length and time (complexity), multiplicity, controllability and observability, heritability for use in a special test mode of operation of DIS;

c) energy offline testing of DIS with its withdrawal from the main operation to a special test mode of operation, performed unconditionally (until the test is completed fully) or conditionally until the first energy anomaly, with subsequent transfer of the results to post-processor statistical, expert and fuzzy analysis and prediction of the reliability of operation of DIS;

d) synthesis of indivisible (primary) test energy-behavioral (with explicit inclusion of the main behavior) primitives based on the corresponding, preprocessor-defined energy-behavioral identifiers (0-primitives);

e) active formation, as an assembly, of a set of explicitly proposed test energy-behavioral fragments (with an explicit inclusion of the main behavior) based on the adjacency relation and the shortest reachability of the reference behavior, checked in this test at the previous steps, with the current assessment and ranking of the achieved completeness, length and time (complexity), multiplicity, controllability and observability, heritability for use in a special test mode of operation of DIS;

f) energy-behavioral offline testing of DIS with its withdrawal from the main operation to a special test mode of operation, performed unconditionally (until the test is completed fully) or conditionally until the first energy-behavioral anomaly, with subsequent transfer of the results to post-processor statistical, ex-

pert and fuzzy analysis and prediction of the reliability of operating of DIS.

One of the methods of offline testing, which realizes the strategy of parallel evolution search for test cover, is presented on Fig. 4.

For the majority of well-established manufacturing technologies, modes and scenarios of operation of DIS components, the construction and use of energy identifiers outside the explicit consideration of behavior, therefore, offline construction and use of energy primitives, fragments and tests based on them, in general, is problematic due to the use of balanced energy-saving technologies. This in no way excludes the event-current and cumulative test monitoring of the reference energy consumption of states/vertices of diagrams, positions/transitions of EPN, energy fragments based on them for models of DIS, in their processor early signal behavioral online testing, which mentioned above.

Processor, energy and energy-behavioral online testing, as a special recognition experiment for compliance with the reference energy consumption and behavior in the background during the main operation of DIS and its components, based on the preprocessor determination of energy and energy-loaded identifiers, includes background recognition of test primitives, fragments and tests based on the relation of adjacency and shortest reachability of the reference behavior, tested in this recognition at the previous steps for the reference EPN with simultaneous application to the tested model/implementation of DIS.

Online testing is performed as part of:

a) background recognition of indivisible (primary) test energy (without explicit inclusion of main behavior, but based on it) primitives based on corresponding, preprocessor-defined energy identifiers (0-primitives);

b) recognition as a background assembly of a set of test energy fragments (without an explicit inclusion of the main behavior, but on its basis) based on the adjacency relation and the shortest reachability of the reference behavior, checked in this test at the previous steps, with the current assessment and ranking of the achieved completeness, length and time (complexity), multiplicity, controllability and observability, heritability with immediate operational application in the background mode to the main functioning of DIS;

c) energy online (background) testing of DIS without removing it from the main functioning, performed as recognition unconditionally (until the test is completely recognized) or conditionally until the first energy anomaly, with subsequent transfer of the results to post-processor statistical, expert and fuzzy analysis and prediction of the reliability of functioning of DIS;

d) background recognition of indivisible (primary) test energy-behavioral (with explicit inclusion of the main behavior) primitives based on the corresponding, preprocessor-defined energy-behavioral identifiers (0-primitives);

e) recognition, as a background assembly, of a set of explicitly recognized test energy-behavioral fragments (with an explicit inclusion of the main behavior) based on the adjacency relation and the shortest reachability of the reference behavior, tested in this test at the previous steps, with the current assessment and ranking of the achieved

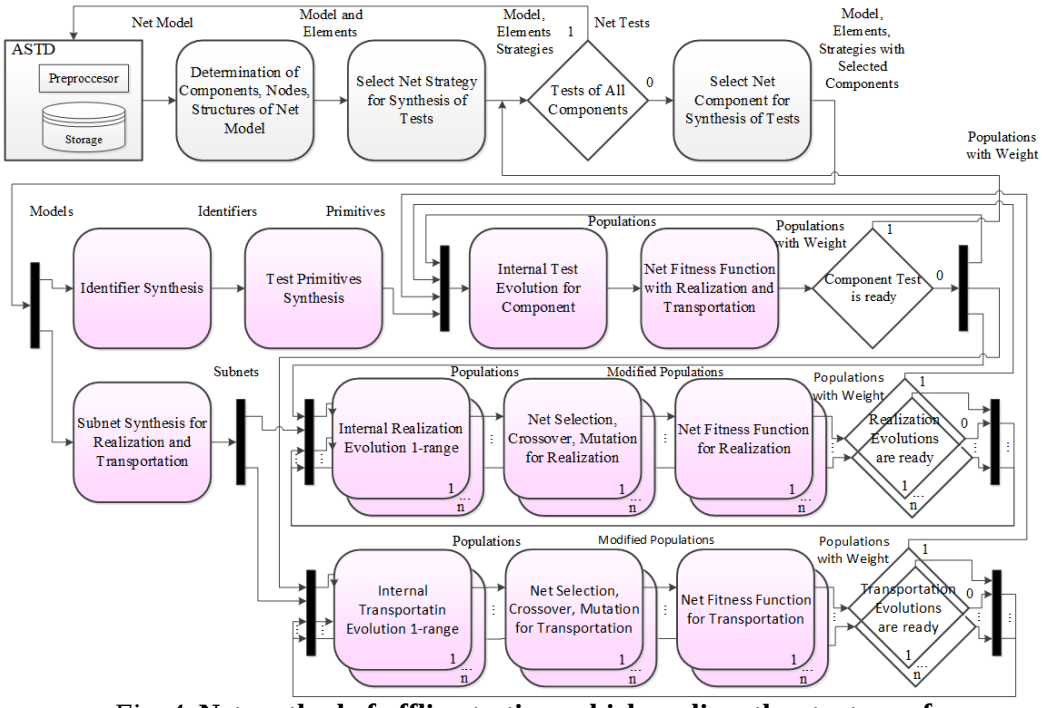


Fig. 4. **Net method of offline testing, which realizes the strategy of parallel evolution search for test cover**

Source: **compiled by the authors**

completeness, length and time (complexity), multiplicity, controllability and observability, heritability with immediate operational application in the background mode to the main functioning of DIS;

f) energy-behavioral online (background) testing of DIS without removing it from its main functioning, performed as recognition unconditionally (until the test is fully recognized) or conditionally until the first energy-behavioral anomaly, with subsequent transfer of the results to post-processor statistical, expert and fuzzy analysis and prediction of the reliability of functioning of DIS.

One of the methods of online testing, which realizes the strategy of parallel evolution search for test cover, is presented on Fig. 5.

As well as for offline testing, for well-established manufacturing technologies, modes and scenarios of operation of DIS components, the construction and application of energy identifiers is outside the explicit consideration of behavior and, therefore, based on them, online recognition of primitives, fragments and tests is problematic. This also does not exclude the event-current and cumulative online test monitoring of the reference energy consumption of states/vertices of diagrams, positions/transitions of EPN, energy fragments based on them for models of DIS, in their processor early signal behavioral online testing mentioned above.

2.3. Postprocessor elements of technology of testing

After early signal, online and offline testing, postprocessor, energy and energy-behavioral analysis and forecast are performed to determine the reliability of the functioning of DIS and its components to determine subsequent actions. Analysis and forecast is carried out in several forms, individually or in combination in a multi-criteria space of metrics of energy and energy-behavioral reliability of functioning of DIS, as well as completeness, length and time, multiplicity, controllability, observability and heritability for the performed and expected testing of DIS, namely, analysis and forecast:

a) probabilistic-statistical, with accumulation, statistical generalization and probabilistic approximation of experience and evaluation of the functioning of DIS in conjunction with the results of all types of testing, as well as a probabilistic-statistical conclusion about subsequent actions, including testing;

b) expert, based on an expert knowledge base formed on the basis of selected production, frame and semantic nets knowledge models, replenished in one way or another in the course of experience and evaluation of the functioning of DIS in conjunction with testing results, as well as an expert conclusion on subsequent actions, including number of tests;

c) fuzzy; formally generalizing probabilistic-statistical and expert in fuzzy relationships, knowledge and inference, with a knowledge base formally fuzzy replenished, in particular, in the process of fuzzy inference and evaluation for the functioning of DIS in conjunction with testing results, as well as the fuzzy conclusion itself about subsequent actions, including testing, as a sequence of syntactic fuzzy transformations and proofs;

d) combined, optimally, taking into account the complexity, modes of operation, criticality, combining the three previous types in accordance with the spatio-temporal structure of behavior for the functioning and testing of DIS and its components.

Performing analysis and forecasting allows you to make decisions about the continuation of the functioning of DIS and its components, signal testing, more detailed online testing located in the main functioning and, as a result, extended in time, and, finally, more detailed offline testing performed outside the main functioning and, as a result, the most compressed in time.

3. ESTIMATES OF THE DIMENSION AND RESULTS OF APPLICATION OF TECHNOLOGY

The dimension of the model is estimated using the representation of the Petri net digraph *S(f)* by list structures. The upper bound for the number of conditional fields of representation of EPN is [40, 41]:

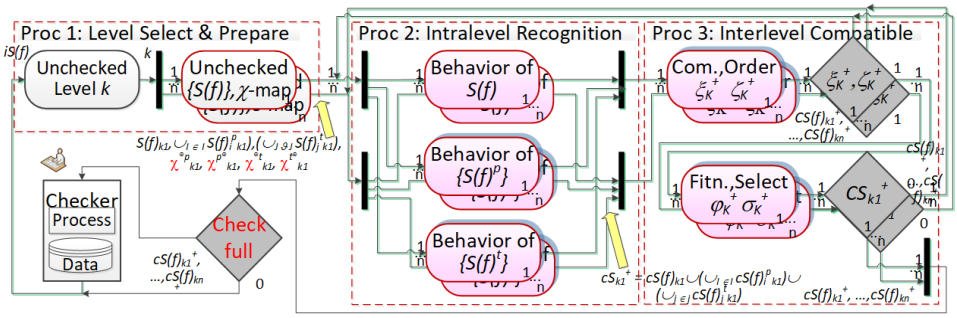


Fig. 5. **Hierarchical method of online testing, which realizes the strategy of parallel evolution search for test cover**

Source: **compiled by the authors**

$$c_{S(f)}=n_t(2n_p+1_t+1_a+2_m+2_{Addr})+n_p(2n_t+1_p+1_e+2_m+2_{Addr})=$$
$$=4n_pn_t+(2_m+2_{Addr})(n_t+n_p)+1_tn_t+1_an_t+1_pn_p+1_en_p\cong$$
$$\cong 4n_pn_t+6(n_t+n_p). \quad (6)$$

Total estimate of fields for testing model does not exceed:

$$c_{RSS(f)pet\text{-}n}= (2n_p+1)*min(min((2^{np}-1), n_t),$$
$$(2^{nt}-1))+\Sigma_{i=0}^{np}(3n_p*n_t^i). \quad (7)$$

For fields of positions/transitions, labels, events and actions for the number of conditional cells of the maximum length and the search estimate becomes:

$$c_{AS(f)}= d_{AS(f)}= 2*6n_tn_p(n_t)+2*6n_pn_t(n_p)=12n_pn_t(n_p+n_t),$$
$$c_{AS(f)multi}= d_{AS(f)multi}= 6n_t(n_p2^{nt+1}-1)+6n_p(n_t2^{np+1}-1)=$$
$$=3n_t(n_p2^{nt+2}-2)+3n_p(n_t2^{np+2}-2). \quad (8)$$

Estimates show the limits of applicability of the energy-loaded testing model and characterize the problem as NP-hard. Polynomial decrease of estimates is possible by network and hierarchical decomposition of the EPN and the testing model.

The experimental energy testing was held for real DIS, in particular, multiagent systems, of monitoring, control and video surveillance showed in table.

Table. **Experimental degree of energy testing**

Intelligent MAS Systems	Decomposition Degree k	Input reduced complexity 50	Input reduced complexity 500
1 MASMC Module	8	14296	1.43E+17
MASMC Module (Energy Testing)	8	10073	6.38E+14
2 MASVS Module	10	1825	1.09E+11
MASVS Module (Energy Testing)	10	1392	8.21E+9

The comparison of not energy and energy testing for original and energy modified monitoring/control (MASMC) and video surveillance (MASVS) confirmed decrease in computational complexity of check.

CONCLUSIONS

The paper presents the basic elements of the technology of behavioral energy-loaded testing of DIS and its components, based on the corresponding models and methods of testing, supplemented and differing by the analysis of energy characteristics of networks, which can be boundary and average temperature, volts/ampere markings of elements of extended Petri networks. The features of the analysis of energy consumption include its display in the states/vertices of diagrams and positions/transitions of extended Petri nets, fragments of behavior, as well as energy reference identification in behavioral tests. As a result, it becomes possible to increase the efficiency, completeness and flexibility of offline and online behavioral testing of various DIS.

It should be noted, that the possibility of operational temperature monitoring is present in most DIS components of medium and, moreover, high level of complexity - controllers, processors. However, the development of means of accumulation and analysis of energy consumption, especially in conjunction with behavioral analysis, as a rule, requires additional resources, which is not always possible.

Post-processor energy-behavioral analysis and forecast itself are a much more difficult task, requiring development of models and methods, that are effective in conditions of incomplete/fuzzy information.

These limitations determine the directions for the development of energy-behavioral testing.

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Елементи технології поведінкового енерго навантаженого тестування розподілених інформаційних систем

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АНОТАЦІЯ

Завчасна перевірка надійності функціонування, що проводиться до виникнення критичних надзвичайних ситуацій, відіграє важливу роль у теорії та практиці моніторингу та діагностики різних технічних систем, у тому числі комп'ютерних розподілених інформаційних систем. Багато методів перевірки та діагностики прямо чи опосередковано використовують енергетичні характеристики систем, які безпосередньо пов'язані з роботою, яку вони виконують, тобто їх продуктивністю. Запропоновані елементи технології поведінкового тестування енергоспоживання базуються на відповідних моделях і методах, доповнених реєстрацією та аналізом інерційної температури та оперативних вольт/амперних характеристик тестової поведінки систем, на рівні моделі, представленої розширеними енерго-навантаженими мережами Петрі. Запропоновані в цій роботі елементи технології поведінкового тестування відрізняються додатковим набором розрахункових та емпіричних граничних температурних та вольт/амперних характеристик, як систем, так і їх компонентів. Ці характеристики представляють критичні з точки зору споживання енергії стани/вершини, позиції/переходи, фрагменти та сценарії роботи, що дає підстави для їх моніторингу. Особливістю цих елементів технології є також можливість визначення та використання природних ідентифікаційних властивостей енергетичних характеристик у поведінковому тестуванні, що дозволяє використовувати їх у дослідах перевірки та розпізнавання надійності функціонування, як самостійно, так і в поєднанні. з аналізом поведінки. Використання додаткового аналізу енергоспоживання за температурними та вольт/амперними характеристиками в складі комплексних технологій тестування та на їх основі автоматизованих систем технічної діагностики дає змогу підвищити ефективність, повноту та гнучкість поведінкового онлайн- та офлайн-тестування для комп'ютерних розподілених інформаційних систем.

Ключові слова: мережева інформаційна система; поведінкове енергетичне тестування; розширена енерго-навантажена мережа Петрі; енерго-навантажений ідентифікатор

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