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SOME ASPECTS OF AUTONOMOUS CYBER-PHYSICAL SYSTEMS DIAGNOSTICS BY THEIR QUALITATIVE STATE

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Summary. *Recent trends in the development of cyber-physical systems are aimed at their autonomy and self-organization. In this context, the question of monitoring and diagnosing possible evolutionary changes that carry certain risks is very important. This study aims to analyze and determine the approach to monitoring and diagnosing autonomous cyber-physical systems according to their qualitative state. The work of monitoring and diagnostic systems and their interaction with autonomous cyber-physical systems in different scenarios in making decisions about evolutionary transformations by the latter are considered. The ways of further development of monitoring and diagnostic systems based on the assessment of the qualitative state of the studied system are determined.*

Key words: *cyber-physical system, autonomy, self-organization, evolutionary transformations, monitoring and diagnostic system, quality assessment, algorithms for evaluating the results of transformations.*

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Problem statement. The concept of Industry 4.0, whose essence lies in the fact of total automation of all spheres of life, has been developed intensively since 2016, and it is based on intelligent technology use. Such an approach, first of all, is caused by the increasing complexity of modern automation systems, big volumes of information that have to be processed, the requirements for decision-making under real-time conditions, the flexibility of industrial processes, and the quality of work under any circumstances. The adopted technologies of cyber management and artificial intelligence, which were implemented in cyber-physical systems, have been a driving force of Industry 4.0 that has to solve the specified and other problems. According to scaling, all cyber-physical systems are classified as classical: the level of a device, «smart house», etc.; industrial: the level of an enterprise, and distributed systems, for example, management in the field of energy supply, transport flows, etc.; cyber-physical world: integral level providing the merging of other levels into the System of systems. Henceforth, we mark all cyber-physical systems as CPS. Though the levels differ considerably in scale, technologies of data processing, and decision-making, they all have the main common feature, i.e. their autonomy (at least, the intention to be autonomous at the present stage). In this case, autonomy means operation without human participation based on its own «vision» of the ways the specified functions are performed. Moreover, one of the most important opportunities of CPS is work taking into account «customer order» which involves the ability to interact with its environment, adapt its own behavior, and alter the functions of constituents.

Self-organization of technical (including cyber-physical) systems according to the laws of evolutional development has been paid great attention to in scientific literature lately, which means the possibility of autonomous improvement of their functional and organizational structure taking into account the previous working experience and interaction with the external environment. Autonomy, self-organization, totality and extensiveness of cyber-physical systems implementation have enabled us to formulate one of the problems that involve possible harm of artificial intelligence that manages CPS caused to people, the environment, or some infrastructure

Taking into account the previous abstracts, one should pay the attention to the fact, that the defined purpose to be achieved due to the operation of cyber-physical systems has been the same despite all transformations. All possible transformations aim only at the improvement of the ways of the purpose achievement. We do not speak about any available consciousness that artificial intelligence has, let alone any intention to cause damage, we can only speak about possible CPS behavior according to the results of self-study.

Analysis of the well-known research results. The conducted analysis of literary sources has proved that in recent years the development of automation systems has reached a new level of construction and control in functioning. The problem has become especially important as the developed cyber-physical systems are controlled by artificial intelligence, and due to their complexity and the tasks solved complexity they need to be autonomous in decision-making [1], [2], [3], [4]. One of the aspects of autonomy is the self-organization of the systems, i.e. the evolutional development that enables them to adapt to external and internal changes [5], [6]. Among new assignments arising due to the growth of cyber-physical systems are the control over their transformations and the possible damage risk prevention [7], [8], [9].

The urgency of the investigated problem. Taking into account the above-mentioned context, the problem of evaluation of behavior, state, and diagnostics of operation quality of the cyber-physical systems capable of self-organization has been quite urgent.

The purpose of the study is to analyze and determine the approach to monitoring and diagnostics of autonomous cyber-physical systems by their qualitative state.

Main material. The term and general definition of the concept of self-organization for complex systems were introduced by William Ross Ashby in 1947 [10]. Regarding CPS, we have introduced the following definition: a self-organized cyber-physical system is a cyber-physical system, which is open and which is capable, under changing external or internal conditions, to store, improve and develop its functional and organizational structure on the basis of previous experience. Nevertheless, any cyber-physical system is artificial and technical, it is created according to the specific rules, requirements, and standards specified by the national standards series [11]. V-model of the life cycle of a cyber-physical system according to [12] is presented in fig. 1. As we can see, CPS creation has been rationed, and according to the results the system performance is checked (experimental operation in particular), and the correction is made at certain stages if necessary.

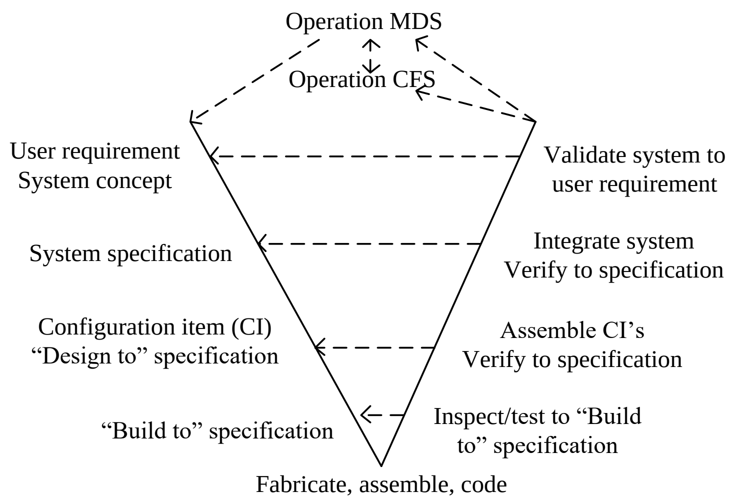

Figure 1. Example of a V-model of the life cycle CPS with the location of the MDS city

According to the presented life cycle, the autonomy foundation of a cyber-physical system is laid when created and can be implemented at the stage of operation (Operation/Utilization), when the system performs the specified functions. It enables us to determine the ways of self-organization (evolutional development) which can take place in CPS:

- functional changes (changes of functions which are implemented, a change of the function specification).
- process changes (changes of processes which are implemented, a change of the process specification).
- technical changes (a change of hardware-software components, a change of the hardware-software components specification).
- structural changes/system reconfiguration (adding or removing some hardware components, a change of general system and special software, a change of intersystem and functional connections).

It should be admitted, that the defined evolutional development can take place only in case of redundancy of all CPS components specified at the design stage, and the available knowledge base. The basis is created during experimental operation, after that, it is adjusted and formed by artificial intelligence (AI) of a cyber-physical system on the basis of the gained experience, and by the developers of the system by norms and connections (fig. 1) following the principles of an open system.

Let's examine CPS operation from the synergetic approach position. According to [13], synergy is the theory of structures' self-organization in open systems that is based on the definition of a structure as a state created due to its components' functioning. During CPS operation some deviations in the current operating parameters from the expected values take place. The system state, when it becomes critical due to stored deviations or one serious failure, is defined as a bifurcation point. Passing across this point means CPS transition to a new qualitative level.

Let's study some possible prerequisites of the CPS evolutional development on the basis of its state assessment: good state – an object is able to perform the required function; up state – an object is able to perform the required function, but the stable operation can be guaranteed; down state – an object is not able to perform the required function [14]. Obviously, some evolutional transformations should start when the last two states are identified, they are defined as the bifurcation points.

Since the purpose of the study deals with the systems of monitoring and diagnostics (MDS), further materials under consideration will describe the assessment of self-organization and CPS behavior from the MDS position, when the latter was defined as an intelligent expert system able to make a decision at the level of an expert-professional.

First of all, we have characterized a complex system < system of monitoring and diagnostics > $\rightarrow$ < cyber-physical system > as a complex modeled system regarding the behavior. The established hierarchy of the specified complex system defines MDS as a supersystem relative to CPS, it does not matter if it is separated or integrated. The place of MDS relative to CPS is shown in fig. 1. Supersystems are easy to notice if we analyze the classical approach to designing and defining the main functions and requirements for the monitoring and diagnostic system, according to [14]: automatic real-time monitoring of CPS state; definition, preferably in real-time, reasons of failure or the critical state of the CPS; lack of MDS impact on the CPS operation quality.

Let's accept the definitions dealing with the purpose of the study and representing the «vision» of a cyber-physical system by the monitoring and diagnostics system assessing its qualitative state. Taking into account all the above-mentioned, we will further rely on the definition of Anokhin P.K. where he defines a system as a combination of mutually beneficial components arranged to achieve one or several purposes, with the hierarchical structure, multiple connections, and the possibility of numerous changes of its state. According to [15], the most successful assessment of the components' mutual benefits takes place when the categories of quality are taken into consideration, namely qualitative assessment of the current state, which makes it possible to evaluate the compliance of components to the specified requirements regarding quality and detect any abnormal behavior.

The next definition deals with information operated by the MDS. As it is shown in [15], [16] the hierarchical structure of the CPS construction according to [17] is transformed into a sensor architecture of information where CPS is created by sensors, and data collection is performed through simplex information channels. Now, it should be quite reasonable to specify the definition of a sensor (detector) as any data source, physical or virtual (for example, the tables of databases are referred to as table sensors).

A simplified structural model of the MDS $\rightarrow$ CPS is given in fig. 2.

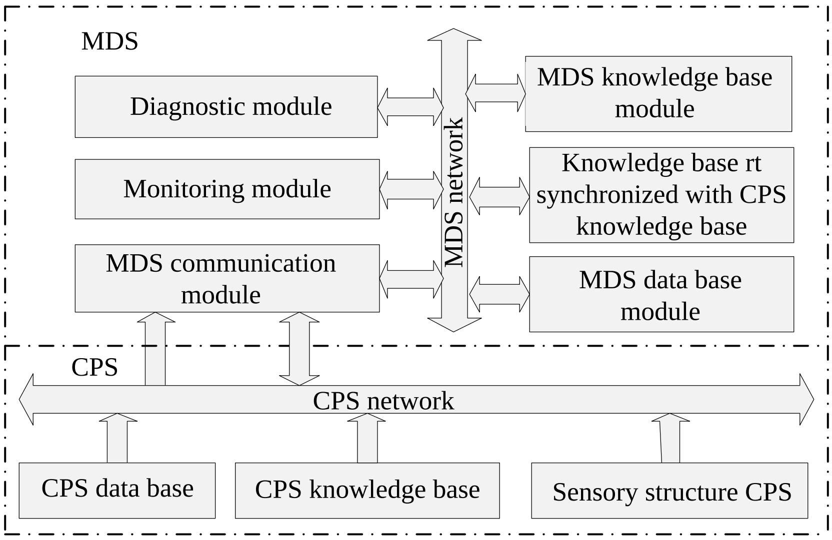

Figure 2. Simplified structural model of the MDS $\rightarrow$ CPS system

Data collection from sensors CPS is provided by an MDS communication module, for example, it can be a network of syntactic analyzers (parsers) [18], [19]. Moreover, the MDS communication module provides the data exchange between databases MDS and CPS.

Taking into consideration the definition of an artificial system, we can see, that the above-mentioned states of the CPS can be analyzed by the degree of their components' mutual benefits, i.e by their quality value. According to the three-aspect model of assessment of technical systems quality state, the CPS sensor architecture can be represented by the structures created by functional, process, and technical hardware-software) specifications by their quality indicators [20]. The quality condition of the CPS and its components is estimated by the following expression:

$$Q_{CPS} = \left\{ Q_{i^1} \left\{ \dots \left\{ Q_{i^\alpha} \right\} \right\} \right\} = \left\{ \bigcup_{i^1=1}^{m^1} \left\{ Q_F, Q_T, Q_P \right\}_{i^1} \left\{ \dots \left\{ \bigcup_{i^\alpha=1}^{m^\alpha} \left\{ Q_F, Q_T, Q_P \right\}_{i^\alpha} \right\} \right\} \right\}$$

$$Q_{\langle \cdot \rangle} = \frac{\sqrt{\left(Q_T\right)^2 + \left(Q_F\right)^2 + \left(Q_P\right)^2}}{\sqrt{3}} , \qquad (1)$$

where Q_F, Q_T, Q_P is the quality condition of functional, process, and technical hardware-software) specifications of the components, respectively; $Q_{\langle \cdot \rangle}$ – the resulting quantitative value of the quality of the specification; $i = \left(\overline{1, m}\right)$ – a random index of a component by the hierarchical level. Quantitative assessment of CPS quality state, or CPS structures by specifications (simple and complex indicators of quality) can be obtained by the qualitative assessment and a scale accepted by the system developers, for example: $Q_{GS} - \delta < Q_{Rec} \le Q_{GS}$, $Q_{US} - \delta < Q_{Rec} \le Q_{US}$, $Q_{Rec} \le Q_{DS}$, where Q_{Rec} is the obtained quality value, Q_{GS}, Q_{US}, Q_{DS} – the expected quality values of states CPS, δ – the possible range of deviation.

The monitoring of the CPS quality current state compliance with the expected one is performed by the Monitoring module on the basis of real-time data from the CPS sensors. The construction of structures, both expected and current, as well as their qualitative assessment are provided by the common rules according to (1). All possible options of a cyber-physical system functioning and the expected states specified at the stages of development with all amendments made within the process of operation are stored in the MDS knowledge base. Knowledge for monitoring includes the general structure, the sequence of functions and processes performed, as well as the involved hardware-software. Each of the above-listed components (their specifications) has its own identification code owned by the developers and their expected use is also reflected in the CPS quality state. All states $Q_{CPS} \le Q_{US}$ (bifurcation points) will be recorded by the Monitoring module as state shots whose quality does not correspond to the expectations and transferred to the Diagnostic module as data packages.

The main task of diagnostics is to determine the place and the reasons for deviation in the quality state of the system under investigation from the expected one, i.e. the reasons of bifurcation points appearance. We must admit, that according to standards, the concept of diagnostics includes the prediction of possible state of the system in time. Nevertheless, taking into account some possible risks of self-organization, the new task of MDS is the prediction of the ways of the CPS evolutional development before the transformations start. This problem can be a matter of a separate scientific investigation, so we haven't considered the prediction in the paper under discussion.

The source of knowledge for the diagnostics is the MDS knowledge base containing the shots of the CPS states whose quality does not meet the level of «good state». The base is filled at the stage of development and experimental operation, whereas the changes are made at the stage of operation. The general knowledge structure in the MDS knowledge base can be described by a set: {state shot, marks {component, marks {possible reasons of quality state reduction, marks {options of the cause elimination, marks}, {the variant is applied by artificial intelligence, marks}.

According to the accepted algorithm, the Diagnostic module operation involves both the comparison of the obtained shot of the state with the shots which are stored in the MDS knowledge base and searching for the nearest one by the quality characteristics. For example, due to the calculation of Euclid metrics minimum in n-dimensional vector space created by the quality indicators of the components $d\left(q_k, q_c\right) \to \min \in \left(d_l, d_r\right)$, where $q_{k,} q_c$ are the vectors of quality indicators from the database and the current ones, respectively, d_l, d_r are the confidence interval. After that, the Diagnostic module records the data to the synchronized database according to the specified multiple structures of knowledge, in this way providing the AI CPS with recommendations on the possible reasons for any abnormal situations and the ways of their elimination, simultaneously these data are transferred to the professionals-experts. For the case when no analog is found for the state shot, the Diagnostic module records it and specifies the reasons in the MDS knowledge base, and the synchronized database, after that transfers it to the experts and AI CPS to make a decision regarding a possible way to eliminate the failure.

In all cases, AI CPS on the basis of the gained experience (study at the stages of tests and operation) makes a decision regarding an option of the evolutional transformation, puts it in a field {an option used by the artificial intelligence, marks} of the knowledge set structure in the CPS knowledge base. In its turn, the Diagnostic module on the basis of a change in the synchronized database records an option into the analogous field of the MDS knowledge base and modifies knowledge for monitoring. There are several scenarios for further assessment and actions regarding the performed evolutional transformations:

1. The CPS state has a status «good state» (evolutional changes have positive results).

- Cyber-physical system continues performing the specified functions.
- The experts test different operation modes of the components and the whole system (including possible correlations) using the model of the system under study. It the state of high quality is proved, the decision made by the AI CPS and fixed in the subset { an option used by the artificial intelligence, marks} is transferred by the experts (if it is absent) into the field {options of the causes elimination, marks} of the MDS knowledge base. Simultaneously, in the similar subset of the synchronized base the correspondent mark is activated for the AI CPS informing. After that, the MDS operates according to the standard algorithm.

2. The CPS state does not meet the status «good state» (evolutional changes have negative results).

- The previous state of the system quality is stored, or its degradation is fixed. Diagnostic module disavows the changes made in the MDS knowledge base, then returns the knowledge base of the monitoring to the previous state (the part of the knowledge base dealing with the state shot under study) and transfers the data to the experts. Simultaneously, in the subset {an option used by the artificial intelligence, marks} of the synchronized base, a mark is activated for the AI CPS informing regarding the cancellation of the decision made concerning evolutional transformations.
- MDS operates according to the standard algorithm.
- AI of a cyber-physical system makes the next decision, and in case of several unsuccessful transformations, it can block the corresponding components. In its turn, the Diagnostic module modifies knowledge for monitoring, and if the transformation is positive, a corresponding mark is activated for the AI CPS informing. Here, a part of the CPS functions cannot operate.
- The experts are searching for some possible solutions to the problem using the model of the system under study, and after that, they transfer new tested options to the MDS so that the decision is made by the AI CPS. It should be mentioned, that the experts do not work under real-time conditions.

We have taken into consideration the ways of evolutional development based on a change, specification of the components, and the components themselves until now, and we have also admitted that one of the main conditions of the CPS evolution is redundancy. Nevertheless, there is one more way of transformation dealing with structural transformations. Obviously, it is the most radical and expensive way of self-organization, moreover, any redundancy is involved in this case. It is also clear, that it is very difficult to gain enough AI CPS experience for such large-scale transformations, and the main source for decision-making is the options obtained from the developers.

The MDS operation algorithm differs a little from the above-mentioned ones under such evolutional development direction conditions, if the AI CPS decision gives a positive result, it is accepted. The very difference is that artificial intelligence only «announces» the transformations, and it is specified in the subset {options of elimination of the cause, marks}, whereas the experts are responsible for the transformation acceptance. Moreover, such a large-scale evolution, according to the experts' decision, can lead to the system changes in the MDS itself.

Conclusions. Some tendencies of cyber-physical systems development, autonomy and self-organization aspects in particular, have been considered briefly in the paper under discussion. Great attention is paid to some possible risks of this approach. Some possible ways of self-organization and bifurcation points appearance have been determined which resulted in the evolutional development of autonomous cyber-physical systems. The tasks and functions of monitoring and diagnostic systems have been stated for the cyber-physical systems state. The use of the three-aspect model of the quality state assessment has proved to be the most successful one when dealing with the categories of quality. The operation of monitoring and diagnostic systems as well as their interaction with autonomous cyber-physical systems under different scenarios of decision-making conditions regarding evolutional transformations by the latter have been taken into consideration and analyzed. Great attention is also paid to the fact, that the concept of diagnostics also involves the prediction of possible ways of the cyber-physical systems evolutional development, that is the matter of further research together with the improvement of diagnostics.

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ДЕЯКІ АСПЕКТИ ДІАГНОСТИКИ АВТОНОМНИХ КІБЕРФІЗИЧНИХ СИСТЕМ ЗА ЇХ ЯКІСНИМ СТАНОМ

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Резюме. *Стисло розглянуто тенденції розвитку кіберфізичних систем у контексті концепції Індустрії 4.0. Показано, що основою концепції є всеосяжне впровадження штучного інтелекту при прийнятті рішень щодо керування технічними системами на всіх рівнях. Зростаюча складність таких систем призводить до поняття їх автономності й далі до самоорганізації та еволюційного розвитку. В цьому контексті досить гостро постає питання оцінювання поведінки, стану та діагностування якості роботи автономних кіберфізичних систем. Поставлена в дослідженні мета – це аналіз та визначення підходу до моніторингу й діагностування автономних кіберфізичних систем за їх якісним станом. У ході дослідження визначено поняття самоорганізуючої кіберфізичної системи, можливі шляхи її самоорганізації й стани, які призводять до виникнення точок біфуркації та еволюційних перетворень. Розглянуто питання протиріччя між самоорганізацією кіберфізичних систем заснованих на досвіді штучного інтелекту й вимогами стандартів до технічних систем. Сформульовано завдання та функції систем моніторингу й діагностики стану кіберфізичних систем. Показано, що найбільш вдалим є оперування в категоріях якості засноване на визначенні штучної системи як комбінації взаємосприяючих складових та триаспектної моделі оцінювання якісного стану. Наведено вираз для оцінювання якісного стану кіберфізичної системи та її складових. Розглянуто й проаналізовано взаємодію системи моніторингу й діагностики та кіберфізичної системи як складної системи. Обґрунтовано ієрархічне положення системи моніторингу й діагностики. Наведено спрощену структурну модель складної системи та загальну структуру бази знань. Досліджено завдання й роботу системи моніторингу й діагностики при взаємодії з автономними кіберфізичними системами за різними шляхами самоорганізації та алгоритмами при прийнятті рішень стосовно еволюційних перетворень останніми. Розглянуто алгоритми роботи складної системи, коли прийняття рішення штучним інтелектом кіберфізичної системи дає позитивний і негативний результати. Зазначено, що остаточне рішення щодо затвердження перетворень в обох випадках дають експерти після тестувань згідно зі стандартами. Визначено шляхи подальшого розвитку систем моніторингу й діагностики, засновані на оцінювання якісного стану досліджуваної системи.*

Ключові слова: *кіберфізична система, автономність, самоорганізація, еволюційні перетворення, система моніторингу й діагностики, оцінювання якісного стану, алгоритми оцінювання результатів перетворень.*

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