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SET-THEORETIC MODEL OF THE INFORMATION STATE OF THE INDUSTRIAL CYBER- PHYSICAL SYSTEM

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***Summary**. The article presents the results of the study, which made it possible to define the concept of sensory, sensory-hardware, sensory-functional and sensory-software infrastructures of the cyber-physical system and formulate the principles of a unified approach to the identification of the current state of a cyber-physical system based on its sensory infrastructure. The set-theoretical model of formation of the information state of the cyber-physical system based on the model of its sensory infrastructure is proposed, the decomposition of which enables to determine the current state of its hardware, functional and programmatic components.*

***Key words**: information state of the industrial cyber-physical system, sensory, sensory-hardware, sensory-functional and sensory-software infrastructure of the cyber-physical system.*

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Statement of the problem. General determination of the cyber-physical systems (CPS) can be stated as the integration of the calculation and real processes, under which physical and virtual components, being tightly interrelated and working in different space-time volumes, demonstrate multiple and clear behaviorist modalities, interact between each other in many ways changeable depending on the context [1, 2]. The planned sphere of the CPS implementation is the transport, power engineering, industrial enterprises and huge infrastructures, the city infrastructure control in particular. The cyber-physical systems, which provide the total virtualization of the automation pyramid, starting from the production processes till the enterprise resources planning (ERP) and the cloud technologies (IMC – AESOP), have been called the industrial or production ones [3].

Analysis of the available results of investigation. The global automation of all spheres of the human activity is challenged by the new problems as to the quality of the cyber-physical systems, because not only the quality of human being depends on them, but the environment, the health and life of people. Unfortunately, the first experience of the industrial CPS implementation and operation has shown, that the absolute methods and means for the summarizing and processing of great amount of different measuring information for the identification and interpreting of complex events and critical states of the cyber-physical systems are not available, which resulted in the appearance of the variety of the local failures of the technological and infocommunication equipment [1, 2, 3, 4]. The most effective as to the diagnosis of the CPS state is the approach of the "tied model", which is its digital twin. The tied model is located on the cloud platform and is a mirror-image presentation of the real system, which can continuously record and track the system health. In its turn, this model is the component of the prognostics and health management, PHM, which, basing on the statistical data of the operation history and system failure, estimates its degradation and predicts its possible failures. But, the available methods ignore the life cycle (LC) data of the investigated and the similar one systems and configurations, which makes worse its prediction abilities [5].

The importance of the studied problem for the identification of the current health of the investigated industrial SPS is based on the introduction of the functional system of the quality monitoring as the component of the expert CPS LC quality system [6].

The Objective of investigation is to find the unified approach for building the model of the current state of the system.

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Description of the main ideas. Within the hardware implementation of the given functional services [3], hierarchy infrastructure of the industrial CPS consists of:

– the elements level: the level components-elements. The structural (hardware) units of the level include sensors, the function of which is to produce the measuring signals and to transform them into data (messages) suitable for the further processing;
– the nodes level: the level components-nodes. The structural (hardware) units of the level include microcontrollers and industrial computers, which process the measuring data, retrieve the management signals on the execution devices; compile data (messages) for the systems of monitoring, control and management, execution devices;
– the subsystem levels: the level components-subsystems. The structural hardware units (device) levels include computers, mainframes, or, probably, the cloud service devices, which provide the operation of systems of the enterprises dispatching and management (SCADA, DCA, MES, ERP).

The connection between the devices, each of which performs the set of independent tasks, is carried out taking advantage of the segment industrial and/or computer network.

The set determination of the hardware infrastructure of the industrial CPS can be presented by the following expression:

$$\{Sys\}=\left\{Lev_{\alpha}\left\{Lev_{(\alpha-1)}\{\ldots\{Lev_{1}\}\}\right\}\right\}=$$
$$=\left\{\bigcup_{\beta^{\alpha}=1}^{m^{\alpha}}Con_{\alpha\beta^{\alpha}}\left\{\bigcup_{\beta^{(\alpha-1)}=1}^{m^{(\alpha-1)}}Con_{\alpha\beta^{\alpha}(\alpha-1)\beta^{(\alpha-1)}}\left\{\ldots\left\{\bigcup_{\beta^{1}=1}^{m^{1}}Con_{\alpha\beta^{\alpha}\ldots1\beta^{1}}\right\}\right\}\right\}\right\}= \quad , \quad (1)$$
$$=\left\{\bigcup_{\beta^{\alpha}=1}^{m^{\alpha}}\bigcup_{\gamma^{\alpha}=1}^{n^{\alpha}}Dev_{\alpha\beta^{\alpha}\gamma^{\alpha}}\left\{\bigcup_{\beta^{(\alpha-1)}=1}^{m^{(\alpha-1)}}\bigcup_{\gamma^{(\alpha-1)}=1}^{n^{(\alpha-1)}}Dev_{\alpha\beta^{\alpha}\gamma^{\alpha}(\alpha-1)\beta^{(\alpha-1)}\gamma^{(\alpha-1)}}\left\{\ldots\left\{\bigcup_{\beta^{1}=1}^{m^{1}}\bigcup_{\gamma^{1}=1}^{n^{1}}Dev_{\alpha\beta^{\alpha}\gamma^{\alpha}\ldots1\beta^{1}\gamma^{1}}\right\}\right\}\right\}\right\}$$

where Lev_x – the levels set $\left(Lev_{x-1}\subset Lev_x\subset Sys\right)$, Con_{β^x} – components set of the corresponding level $\left(\forall Con_{\beta^x}\subset Lev_x\right)$, $Dev_{\beta^x\gamma^x}$ – the set of structural hardware units of the component (devices) $\left(\forall Dev_{\beta^x\gamma^x}\subset Con_{\beta^x}\right)$, $\{\alpha:1\}$ – the set of the hierarchy levels indexes, $\beta=\left(1:m^x\right)$ – the index of the level component x, $\left\{1:n^x\right\}$ – the index of the structural hardware units (devices) of the level component x, x – random index.

Horizontal connections between any components and level devices from (1), in accordance with the principles of building the hierarchy automation systems with the strict interrelation of the lower level objects to the upper level objects, are not available $Com_{i^x}\bigcap Com_{j^x}=\phi\ \left(i\neq j\right)$, where Com – random component or the device of the x level, (i,j) random indexes.

The sets the levels consist of, being the sets of the upper level, are specified by the characteristic vector, which correspond to the system-forming relations:

$$L_{x-1}\subset L_x\left|\exists L_{(x-1),y}\in L_{x-1},b_i=1\right.,\qquad (2)$$

where L_x – the set of random level, $B=\left\{b_1,b_2,\ldots,b_z\right\}$ – the characteristic vector of the set L_x,

$i = \left(1 : \left|L_x\right|\right)$, x – random level index; y – random index of the set element L_{x-1}.

CPS built according to the function and software is based due to the service-oriented paradigm (SOA) as the distributed system with the user-server architecture [3]. In general SOA is the style of the software development, based on the application of the distributed changeable modules, which provide the standard interfaces and are built using the object-oriented programming (e.g. using CORBA). It can be said, that as to its ideology the SOA is the object-oriented program model (OOP) with much higher abstraction level. Taking into consideration the mentioned above, let us analise the CPS structure from the point of view of standards of the IEC 61499 type [7, 8]. These standards specify the architecture and requirements to the programming of the distributed systems of measuring and control of the industrial process, that is, they are designed for the automation systems of the real time, which can include the levels of elements, nodes and subsystems of dispatching (SCADA, DCS) of the hardware infrastructure. As to the subsystems of the enterprise management (MES, ERP), they, as a rule, work in the package regime of processing, but, as it will be shown below, the general principles of building the functional infrastructure, modality and distribution of calculations IEC 61499 can be included to them.

In accordance with the standard IEC 61499-1 the functional infrastructure of the automation systems, to which the industrial CPS are included, possesses the following hierarchy:

- system – the set of devices including the network, which provides their interaction;
- device – the hardware unit possessing certain set of functions;
- software attachment – the software unit performing the given function or solving a task;
- functional block (FB) – the smallest software unit, from which the attachments are formed;
- resource – special functional block, which encapsulates the independent function or the task (e.g. provides necessary services for the other FB and attachments).

The presented four-level hierarchy mostly corresponds to the functional implementation of the element and node levels. The devices of higher levels work under the control of one or some operation systems and can include the virtual machines, systems of data base control, etc. Basing on it the set determination of he system in the functional infrastructure will correspond to the expression (1). The set determination of the functional structure of the unified device:

$$
\begin{aligned}
&\left\{Dev_{\gamma}\right\} = \left\{LevF_{\gamma f}\left\{\ldots\left\{LevF_{\gamma 1}\right\}\right\}\right\} = \\
&= \left\{\bigcup_{\zeta^{f}=1}^{k^{f}} ConF_{\gamma f \zeta^{f}}\left\{\bigcup_{\zeta^{(f-1)}=1}^{k^{(f-1)}} ConF_{\gamma f \zeta^{f}(f-1)\zeta^{(f-1)}}\left\{\ldots\left\{\bigcup_{\zeta^{1}=1}^{k1} ConF_{\gamma f \zeta^{f}\ldots 1\zeta^{1}}\right\}\right\}\right\}\right\} = \\
&= \left\{\bigcup_{\zeta^{f}=1}^{k^{f}}\left\{\begin{array}{l}
\left\{\bigcup_{\psi^{1}=1}^{e^{1}} App_{\gamma f \zeta^{f}\psi^{f}}\left\{\bigcup_{\omega^{(f-1)}=1}^{t} FB_{\gamma f \zeta^{f}\psi^{f}\omega^{f}}\right\}\right\}, \\
\left\{\bigcup_{\zeta^{(f-1)}=1}^{k^{(f-1)}}\left\{\begin{array}{l}
\left\{\bigcup_{\psi^{(f-1)}=1}^{e^{(f-1)}} App_{\gamma f \zeta^{f}(f-1)\zeta^{(f-1)}\psi^{(f-1)}}\left\{\bigcup_{\omega^{(f-1)}=1}^{t^{(f-1)}} FB_{\gamma f \zeta^{f}(f-1)\zeta^{(f-1)}\psi^{(f-1)}\omega^{(f-1)}}\right\}\right\}, \\
\left\{\ldots\left\{\bigcup_{\zeta^{1}=1}^{k1}\left\{\bigcup_{\psi^{1}=1}^{e^{1}} App_{\gamma f \zeta^{f}\ldots 1\zeta^{1}\psi^{1}}\left\{\bigcup_{\omega^{(f-1)}=1}^{t} FB_{\gamma f \zeta^{f}\ldots 1\zeta^{1}\psi^{1}\omega^{1}}\right\}\right\}\right\}\right\}
\end{array}\right\}\right\}
\end{array}\right\}\right\}, \quad (3)
\end{aligned}
$$

where $LevF_{\gamma x}$ – the set of software levels, $\left(Lev_{\gamma(x-1)} \subset Lev_{\gamma x} \subset Dev_{\gamma}\right)$, $Con_{\zeta^{x}}$ – the set of components of the corresponding level $\left(\forall Con_{\zeta^x} \subset Lev_x\right)$, App_ψ – the software attachment $\left(\forall App_{\psi^x} \subset Con_\zeta\right)$, FB_ω – functional block (module) $\left(\forall FB_{\omega^\psi} \subset App_\psi\right)$, $\left\{1:k^x\right\}$ – the index set of the software levels components, $\psi = \left(1:e^x\right)$ – the index of the software attachment of the component χ, $\omega = \left(1:t^x\right)$ – the index of the functional block of the attachment x, x – random index.

Horizontal connections between the components of any level with the (3), in accordance with the principles of the user-server architecture and building of software attachments, are not available. $Com_i \bigcap Com_j = \phi \ \left(i \neq j\right)$, where Com_x –random component of level, $\left(i, j\right)$ – random components indexes.

The sets (3) contained by the levels, being the sets of the upper level, are specified by the characteristic vector, which corresponds to the system-forming connections:

$$LF_{x-1} \subset L_x \left| \exists LF_{(x-1),y} \in LF_{x-1}, b_i = 1 \right., \qquad (4)$$

where LF_x – the set of the random level with the (3), $B = \left\{b_1, b_2, ..., b_z\right\}$ – characteristic vector of the set LF_x, $z = \left|LF_x\right|$, $i = \left(1:z\right)$, x – random level index, y – random index of the level component L_{x-1}.

The efficient method of determination the current state of the cyber-physical system for the further investigation is its treatment as the single information space composed of the real and virtual components [9]. Such approach is based on the philosophic concept, according to which the state of the natural or artificial object or process can be estimated as the information being obtained through the retrieving and processing channels.

In the biological systems the channels are created in the CPS, the notion of the *sensory infrastructure of the system* can be stated as the configuration of the information channels created by the sensors, which determine the current information state of the system.

The sensors applied in the CPS as to their purpose can be divided into those determining the state of the hardware component of the system, those, which determine the functional state and those determining the software of the system. The first and the second, being specified by the corresponding FB, provide the measuring of the physical parameters of devices (e.g. temperature, current voltage, interface signals levels, mechanical parameters) in the real time, and the measurements needed for the performance of its functions by the system. The third ones, being the integral component of the corresponding FB, control the operation of the software attachments comprising both the system and the users softwares. The control deals with those of time parameters, the loading of the central processor and operation memory, measurement of the results correctness, calculation and data transition. The measurements needed for the control, processing of their results are performed in the real time using the virtual sensors contained by the software modules (system or users). To develop such software modules (Component-based software engineering, CBSE) the Event-driven architecture (EDA) are used in the SOA, which, in its nature, corresponds to the concept of the IEC 61499 standards of the functional blocks and systems of the real time.

Let us introduce some notions:

– the sensory-hardware infrastructure – the configuration of the system information channels determining the state of its hardware structure and is formed by the FB and physical sensors of the structural separated hardware system objects (the elements nodes and subsystem level devices);
– the sensory-functional infrastructure – the configuration of the system information channels determining its functional state and is formed by the FB and physical

sensors of the element level devices;

– the sensory-software infrastructure – the configuration of the information channels determining the state of its software and is formed by the FB virtual sensors.

The information channels of every structural unit consist of the channels of the lower level structural units, which belong to it in accordance with the (2), (4) and its own sensors forming the unified information space of the system state.

According to the presented above statements the set presentation of the sensory structure of the unified functional block looks as follows:

$$\left\{FB_{\omega}\right\}=\left\{\left\{\bigcup_{\lambda=1}^{v} SenA_{\omega\lambda}\right\},\left\{\bigcup_{\varsigma=1}^{r} SenF_{\omega\varsigma}\right\},\left\{\bigcup_{\iota=1}^{p} SenP_{\omega\iota}\right\}\right\}, \qquad (5)$$

where $SenA_{\omega\lambda}$ – the set of the FB sensors contained by the sensory-hardware CPS infrastructure, $SenF_{\omega\varsigma}$ – the set of the FB sensors contained by the functional CPS infrastructure, $SenP_{\chi\iota}$ – the set of the FB sensors contained by the sensory-hardware CPS infrastructure.

If the FB does not contain sensors forming one or more mentioned above infrastructures, the corresponding set will be empty $\left\{SenX\right\}=\phi$, where X – the infrastructure sign from the (5).

The structure sets from the (1, 3, 5) being changed into the information on their state, the expression for the set determination of the information state of the cyber-physical system will be obtained basing on its sensory infrastructure:

$$\begin{aligned}
\left\{In_{SenSys}\right\} &= \left\{In_{Lev_{\alpha}}\left\{In_{Lev_{(\alpha-1)}}\left\{\ldots\left\{In_{Lev_{1}}\right\}\right\}\right\}\right\} = \\
&= \left\{\bigcup_{\beta^{\alpha}=1}^{m^{\alpha}} In_{Con_{\alpha\beta^{\alpha}}}\left\{\bigcup_{\beta^{(\alpha-1)}=1}^{m^{(\alpha-1)}} In_{Con_{\alpha\beta^{\alpha}(\alpha-1)\beta^{(\alpha-1)}}}\left\{\ldots\left\{\bigcup_{\beta^{1}=1}^{m^{1}} In_{Con_{\alpha\beta^{\alpha}\ldots1\beta^{1}}}\right\}\right\}\right\}\right\} = \\
&= \left\{\bigcup_{\beta^{\alpha}=1}^{m^{\alpha}}\bigcup_{\gamma^{\alpha}=1}^{n^{\alpha}} In_{Dev_{\alpha\beta^{\alpha}\gamma^{\alpha}}}\left\{\bigcup_{\beta^{(\alpha-1)}=1}^{m^{(\alpha-1)}}\bigcup_{\gamma^{(\alpha-1)}=1}^{n^{(\alpha-1)}} In_{Dev_{\alpha\beta^{\alpha}\gamma^{\alpha}(\alpha-1)\beta^{(\alpha-1)}\gamma^{(\alpha-1)}}}\left\{\ldots\left\{\bigcup_{\beta^{1}=1}^{m^{1}}\bigcup_{\gamma^{1}=1}^{n^{1}} In_{Dev_{\alpha\beta^{\alpha}\gamma^{\alpha}\ldots1\beta^{1}\gamma^{1}}}\right\}\right\}\right\}\right\}
\end{aligned}, \qquad (6)$$

$$\begin{aligned}
\left\{In_{Dev_{\gamma}}\right\} &= \left\{In_{LevF_{\gamma f}}\left\{\ldots\left\{In_{LevF_{\gamma 1}}\right\}\right\}\right\} = \\
&= \left\{\bigcup_{\zeta^{f}=1}^{k^{f}} In_{ConF_{\gamma f\zeta^{f}}}\left\{\bigcup_{\zeta^{(f-1)}=1}^{k^{(f-1)}} In_{ConF_{\gamma f\zeta^{f}(f-1)\zeta^{(f-1)}}}\left\{\ldots\left\{\bigcup_{\zeta^{1}=1}^{k1} In_{ConF_{\gamma f\zeta^{f}\ldots1\zeta^{1}}}\right\}\right\}\right\}\right\} = \\
&= \left\{\bigcup_{\zeta^{f}=1}^{k^{f}}\left\{\begin{array}{l}
\left\{\left\{\bigcup_{\psi^{1}=1}^{e^{1}} In_{App_{\gamma f\zeta^{f}\psi^{f}}}\left\{\bigcup_{\omega^{(f-1)}=1}^{t} In_{FB_{\gamma f\zeta^{f}\psi^{f}\omega^{f}}}\right\}\right\}\right\}, \\
\left\{\bigcup_{\zeta^{(f-1)}=1}^{k^{(f-1)}}\left\{\begin{array}{l}
\left\{\bigcup_{\psi^{(f-1)}=1}^{e^{(f-1)}} In_{App_{\gamma f\zeta^{f}(f-1)\zeta^{(f-1)}\psi^{(f-1)}}}\left\{\bigcup_{\omega^{(f-1)}=1}^{t^{(f-1)}} In_{FB_{\gamma f\zeta^{f}(f-1)\zeta^{(f-1)}\psi^{(f-1)}\omega^{(f-1)}}}\right\}\right\}, \\
\left\{\ldots\left\{\bigcup_{\zeta^{1}=1}^{k1}\left\{\bigcup_{\psi^{1}=1}^{e^{1}} In_{App_{\gamma f\zeta^{f}\ldots1\zeta^{1}\psi^{1}}}\left\{\bigcup_{\omega^{(f-1)}=1}^{t} In_{FB_{\gamma f\zeta^{f}\ldots1\zeta^{1}\psi^{1}\omega^{1}}}\right\}\right\}\right\}\right\}
\end{array}\right\}\right\}
\end{array}\right\}\right\}
\end{aligned}, \qquad (7)$$

$$\left\{In_{FB_{\omega}}\right\}=\left\{\left\{\bigcup_{\lambda=1}^{v} In_{SenA_{\omega\lambda}}\right\},\left\{\bigcup_{\varsigma=1}^{r} In_{SenF_{\omega\varsigma}}\right\},\left\{\bigcup_{\iota=1}^{p} In_{SenP_{\omega\iota}}\right\}\right\}, \quad (8)$$

where In_{SenSys} – information state of the system sensory infrastructure, In_{x} –information state of the corresponding components.

The forming of the CPS sensory-hardware, sensory-functional or sensory-software infrastructures is carried out by the exclusion of sets from the (8), which the needed infrastructure does not contain.

Conclusion. The investigation carried out made possible to state the notion of sensory, sensory-hardware, sensory-functional and sensory-software infrastructures. The principles of the unified approach to the identification of the current state of the cyber-physical system were stated being based on the sensory infrastructure. The set-theoretic model of the information state of the cyber-physical system was proposed on the basis of its sensory infrastructure, decomposition of which makes possible to determine the current state of its hardware, functional and software components.

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ТЕОРЕТИКО-МНОЖИННА МОДЕЛЬ ІНФОРМАЦІЙНОГО СТАНУ ПРОМИСЛОВОЇ КІБЕРФІЗИЧНОЇ СИСТЕМИ

Сергій Волков

Одеська державна академія технічного регулювання та якості, Одеса, Україна

Резюме. *Наведено результати дослідження, яке дало змогу визначити поняття сенсорної, сенсорно-апаратної, сенсорно-функціональної і сенсорно-програмної інфраструктури кіберфізичної системи та сформулювати принципи єдиного підходу до ідентифікації поточного стану кіберфізичної системи, заснованого на її сенсорній інфраструктурі. Запропоновано теоретико-множинну модель формування інформаційного стану кіберфізичної системи на базі моделі сенсорної інфраструктури, декомпозиція якої дає змогу визначити поточний стан її апаратної, функціональної та програмної складових.*

Ключові слова: *інформаційний стан промислової кіберфізичної системи, сенсорна, сенсорно-апаратна, сенсорно-функціональна і сенсорно-програмна інфраструктура кіберфізичної системи.*

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