Proactive Management of Information Processes in the Industrial Internet

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Abstract. The paper presents the scientific and practical foundations of the developed applied theory of proactive control of information processes in the industrial Internet based on cloud and fog computing. The main scientific contribution of the research results is that modern informatics, thanks to the developed theory, is enriched with the methodology and methodological support developed in classical cybernetics and neocybernetics. The paper shows the main elements of this theory, analyzes the possible ways of its development and practical use.

Introduction

The conducted analysis shows that the concept of the Industrial Internet (IIoT), developed at present, and client-oriented, small-scale, flexible virtual productions, that implement it on the basis of real geographically-distributed industrial capacities are able to cope with the current global crisis situations in the economies of different counties [1-5]. According to the existing concept of the Industrial Internet the operating equipment and produced items should be applied as active system components, managing production and logistic processes. They would include cyber-physical systems (CPS), ensuring connection between virtual space of the Internet with the real physical world. CPS can plan and customize their actions in accordance with surrounding conditions and their expected (forecasted) changes; learn new behavior models and scenarios, as well as be self-managed, including implementation of functions for proactive monitoring, management and metrological self-management. Their widespread integration would result in greater global changes than introduction of computers and the Internet. Global transition to CPS and related Industrial Internet and Internet-of-Things is considered as the 4th Industrial Revolution, that is called Industry 4.0 in Germany [5-7]. In order to implement it, it is required to properly organize the corresponding management-information and info-communication processes based on integration of cloud, border and fog computations within the framework of created and permanently developing Industrial Internet, where an important role is allocated to the existing and advanced cyber-physical systems (CPS), creating physical and informational basis for applying positive and negative feedbacks not only at the technological, but also – that is extremely important – at the organizational levels of industrial production management.

Unlike the Internet-of-Things, within the Industrial Internet the order of computation and parameters of computation operations are defined by the production process technology (regularity). In this case there are a lot of alternative ways to organize the computation process, that accompanies production and provides it with the necessary informational support. Each way and the corresponding computation plan can be assessed using such criterial functions as speed (intensity) of operations and...
works implementation, energy consumption, sustainability indicator of telecommunication channels workload, production resources, indicators of scheduling sustainability and robustness, etc [7].

The major problem of effective distribution of both informational-management and info-communicational resources, as well as physical (production) resources in the IIoT covers the following aspects. Definition of effective management programs for informational and production processes in the IIoT can be implemented only after we specify the list of technology structures, functions and algorithms for information processing and management, and define technologies, functions and algorithms for production processes management in the IIoT, that must be implemented in corresponding elements and subsystems. At the same time, distribution of functions and algorithms across elements and subsystems of the IIoT depends on the plan structures and parameters and control laws within these elements and subsystems. Analysis of the existing approaches to solving the considered classes of the tasks of multi-criteria structural-functional synthesis has shown that these tasks have not been sufficiently studied [7]. New scientific and practical results were received in the framework of the following research directions: synthesis of complex objects (CO) technical structure (including the IIoT) within the known laws of their major elements and subsystems functioning (1st direction) [8-9]; synthesis of CO functional structure or – in other words – synthesis of programs for control of CO major elements and subsystems for the known technical structure of CO (2nd direction) [10,11]; program synthesis for creating and developing new generations of CO, regardless of the stage of existing CO and integrated CO combined functioning [12-14]. A number of iteration procedures is known, that can be applied to obtain joint solving of tasks studied under the 1st and 2nd directions [10].

At the same time, generalized and complex research on the issues of informational and production processes management within CO (including IIoT), that take into account all the above-mentioned aspects of their structural dynamics, unfortunately, has not been performed yet. Under these circumstances it is reasonable to develop a relevant theoretical basis (concepts, models, methods, algorithms, and techniques) to solve various classes of tasks on structural-functional synthesis and proactive management of informational, production processes and flows in the Industrial Internet. Herewith by proactive management we mean management aimed not only at dynamic response to negative events that have already occurred (as within reaction control), but also exclusion of their further development, as well as pro-active prevention of accidents occurrence by developing (or targeted search) of system-functional reserves in the relevant system for proactive monitoring and management, that ensure dynamic development of fundamentally new capacities to oppose possible predictable and unpredictable abnormal emergency situations, applying the methodologies and technologies of system (complex) modelling as well as multiple-option situationally-adaptive forecasting [7,10].

1. Conceptual and set-theoretic problem definition of the synthesis of technologies and programs for the Industrial Internet management

In order to set formal description of the problem we introduce the following structures and functions:

\[ G = \{ G_X, X \in NS \} \] – a set of possible types of IIoT control systems (CS) structures; first of all, topological (Top), technological, (functional (Fun)), technical (Tech) structures, software and brainware structures (SB), structures for information provision (IP) are emphasized.

In order to connect the above-mentioned sets of structures we introduce a dynamic alternative multigraph (DAMG) of the following form:

\[ G_X^{<t,w>} = (X_X^{<t,w>}, F_X^{<t,w>}, Z_X^{<t,w>}), \]  

wherein \( \chi \) – index, characterizing the IIoT CS structure, \( t \) – index (number), corresponding to the current temporal value, that is able to take both discrete and continuous values (according to the set of researched applied tasks), \( w \) – current index (number), corresponding to tuple of current values of models parameters, describing IIoT CS and adjusted by its external and internal adapters. \( \chi \in NS = \{ \text{Top, Fun, Tech, SB, IP} \} \) – a set of indexes, corresponding to the typological, functional, technical structures, as well as SB, IP structures. \( t \in T \) – a set of time points;
\( X^{<t,w>}_{X} = \{ x^{<t,w>}_{<X,l>}, l \in L_{X} \} \) – a set of elements forming a part of the structure \( G^{<t,w>}_{X} \) (DAMG vertex set) at a time point \( t \);

\( F^{<t,w>}_{X} = \{ f^{<t,w>}_{<X,l,l'>}, l, l' \in L_{X} \} \) – DAMG arcs set of the type \( G^{<t,w>}_{X} \), reflecting relations among its elements at a time point \( t \);

\( Z^{<t,w>}_{X} = \{ z^{<t,w>}_{<X,l,l'>}, l, l' \in L_{X} \} \) – a set of parameter values, indicating quantity values of relations among DAMG corresponding elements.

Moreover, let us assume that a set of permitted representing operations (based on the problem description of each particular task of IIoT structural dynamics proactive management) of the above-mentioned arcs on each other is defined:

\[
E^{(t,w)}_{(x,X')} : E^{(t,w)}_{(x,X)} \rightarrow E^{(t,w)}_{X'}
\]  

(2)

Figure 1 shows an option to specify such representation in a graphical form for a defined time point \( t \). Topological, technical and functional structures of IIoT CS can be applied as possible structures, shown in the Figure.

Let us set the composition operation of the defined representations at a time point \( t \):

\[
E^{(t,w)}_{(x,X')} = E^{(t,w)}_{(x,X)} \circ E^{(t,w)}_{(x,Y)} \circ \ldots \circ E^{(t,w)}_{(x,X')}
\]  

(3)

A set of multi-structural conditions of IIoT CS will be recorded as follows:

\[
S_{\delta} \subseteq X^{t}_{\text{Top}} \times X^{t}_{\text{Phys}} \times X^{t}_{\text{Ext}} \times X^{t}_{\text{MEO}} \times X^{t}_{\text{EO}} \times X^{t}_{\text{Op}}, \delta = 1, \ldots, K_{A}.
\]  

(4)

Herewith it is assumed that each IIoT CS multi-structural macrostate at a time point is set as a result of relevant DAMG composition operation, that describes each type of the considered systems structure [11].

Besides, in [7] we introduce a set of permitted operations of IIoT CS multi-structural states representation on each other, as well as a set of the indicated representations compositions:

\[
\Pi^{<t,w>}_{\delta,\delta_{i}} : S^{<t,w>}_{\delta} \rightarrow S^{<t,w>}_{\delta_{i}}
\]  

(5)

\[
\Pi^{<t,w>}_{\delta_{i},\delta_{j}} = \Pi^{<t,w>}_{\delta_{i},\delta_{i}} \circ \Pi^{<t,w>}_{\delta_{i},\delta_{j}} \circ \ldots \circ \Pi^{<t,w>}_{\delta_{i},\delta_{j}}
\]  

(6)

Figure 1 in the graphical form shows an example of implementing the specified representations of multi-structural states on each other for a time point \( t_{1} \). Using a set of composition type (6) variants it is possible to intentionally implement generation of various scenarios on structural dynamics of both IIoT and control systems.

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Fig. 1. Options of IIoT CS multi-structural macrostates, as well as a fragment of multi-structural scenario dynamics development

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Graphical interpretation of the considered tasks on IIoT CS structural dynamics management in such case comes to searching for such a multi-structural state $S^*_g \in \{S_1, S_2, ..., S_k\}$ and such a sequence (composition) of implementing representation operations of type (6) $\Pi^<t,f,w>_g \circ \Pi^<t,f,w>^* g \circ \Pi^<t,f,w>_g$, that ensure selection of the best possible (from the point of generalized efficiency index) technology and program for IIoT CS structural dynamics management, ensuring their transition from the specified state into the required multi-structural state [7].

Along with the graphical interpretation of the researched problem [7,10] its set-theoretic description is suggested: it is required to develop principles, approaches, models, methods, algorithms, software allowing us to synthesize such technologies and programs for proactive management of informational and production processes of IIoT $\langle U^t,f,S^*_g^{t,f} \rangle$, whereby the following conditions are met:

$$J^t_g\left(X^t_\chi, \Gamma^t_\chi, Z^t_\chi, F^t_{<\chi,\chi'}^t, \Pi^\in\theta \right) \rightarrow \text{extr}_{U^t,g \in \Delta^t_g},$$

$$\Delta^t_g = \{<U^t,g,S^t,f>_t | R^\beta_{\Pi^t^1_{\delta_1,\delta_2} \circ \Pi^t^2_{\delta_2,\delta_3} \circ \Pi^t^3_{\delta_3,\delta_4} : \chi \in \mathcal{B}> \leq \rangle_g^t \},$$

where $\chi \equiv \{\text{Top, Fun, Tech, PMP, IP}\}$ – a set of indexes, corresponding to the topological, functional and technical structures, software and brain-ware, as well as informational provision structures (SB, IP), tET – a set of time points; $X^t_\chi = \{x^t_{\chi,l}, l \in L^t_\chi\}$ – a set of elements, forming a part of structure of dynamic alternative multigraph $G^t_\chi$; $\Gamma^t_\chi = \{y^t_{<\chi,l'}, l', l \in L^t_\chi\}$ – a set of multigraph arcs of the type $G^t_\chi$, reflecting relations of its elements at a time point t; $Z^t_\chi = \{z^t_{<\chi,l'}, l', l \in L^t_\chi\}$ – a set of parameters values, showing quantity values of relations among multigraph corresponding elements; $F^t_{<\chi,\chi'}$ – representation of an enterprise information system various structures on each other at a time point t; $\Pi^t_{<\delta,\delta'}$ – composition operation of multi-structural macrostates with numbers $\delta, \delta'$ at a time point t; Ut – control actions, allowing to synthesize both information system structures and its functioning processes; $J^t \theta$ – cost-effectiveness, time consumption and resource indicators, characterizing the quality of an information system functioning, $q \in Q = \{1, ..., q\}$ – a set of numbers indicators; $\Delta^t_g$ – a set of dynamic alternatives (a set of the Industrial Internet structures and parameters, a set of its functioning programmes); $\mathcal{B}$ – a set of numbers for spatiotemporal, technical and technological limitations, defining the computation processes implementation; $\mathcal{R}_g$ – specified values; $T = (t_0, t_f]$ – time interval, when technologies and informational processes implementation plans are synthesized.

2. Analysis of possible ways to solve the defined problem

In general, the defined problem is referred to the problems of multi-criteria structural-functional synthesis of a complex object (in this case IIoT) image and programs for its proactive management at different stages of its life cycle, and it is characterized by high dimensionality, nonlinearity of models, that describe the structure and functioning of IIoT elements and subsystems, necessity to provide constructive and comprehensive consideration within the corresponding models of both factors of uncertainty, caused by disturbance effects from the internal and external environment, as well as the factors related to multi-aspect quality assessment of the selected controlling actions.

Moreover, speaking about modelling-algorithmic level of the considered problem description, the problems of deep (integrative) alignment of the methods, models and algorithms, that are used within IIoT CS complex modelling, still remain the most important scientific and methodological problems, as the problem of parametric and structural adaptation of a multiple-model complex, that describes
IIoT functioning, the problem of multiple-model complex verification and validation, the problem of automatization of process on an IIoT functioning complex modelling.

The preliminary analysis showed that it would be possible to overcome all the indicated problems only if a complex approach is applied, based on fundamental and practical results, obtained by an interdisciplinary branch of systematic knowledge. In such case to prove that practical results, obtained within the implemented works on forming effective IIoT CS are complete, coherent and self-consistent, we can use the fact, that the same features of such objects have already been proved, but for other subject fields. To illustrate this statement we provide Table 1 which shows that fundamental results, obtained within the qualitative theory of complex dynamic objects, can be applied to solve various classes of tasks on analysis and synthesis of technologies and programs for managing information and production processes within the IIoT.

Preliminary researches show quite interesting perspectives concerning the plan to implement practical transition from technologies of reaction control to technologies of proactive control in the field of IIoT. This transition becomes possible within large-scale utilization of logical-dynamic models of the new class for managing both informational and production processes in the IIoT [7,10,14]. This class includes models for proactive management of motion, channels, resources, complexes and parameters of targeted, supporting and additional operations, flows and structures in the IIoT. We managed to present this multiple-model complex in the generalized form as a multilevel alternative dynamic system graph with reconfigurable architecture [10].

Table 1

| Elements of qualitative theory for proactive management of informational and production processes in the IIoT |
|---------------------------------------------------------------|
| Major results of management theory | The suggested practical interpretation of fundamental scientific results, obtained within the management theory |
| Analysis of existing solutions in solving the tasks of CO structural dynamics control (SDC) | Verification of description on the IIoT processes management using the developed multiple-model complex |
| Terms of manageability and achievability within the tasks of CO SDC | Feasibility test on the IIoT management technologies on the interval of management, identification of major factors, that influence the targeted and info-technological capabilities of CPS |
| Terms of singularity of the optimal management programs within the tasks on CO utilization planning | Assessment of possibilities to obtain the optimal plan for managing information processes within the IIoT |
| Required and sufficient conditions for optimality within CO SDC tasks | Preliminary analysis on structure for managing information processes within the IIoT |
| Conditions of sustainability and robustness in the tasks of CO SDC | Assessment of CO SDC sustainability and robustness against disturbance inputs, changes in contents and structure of initial data |

The first advantage of the suggested generalized description is that at the conceptual, model-algorithmic, informational and software levels it ensures correct adjustment (according to the criteria of relation homomorphism and dynamomorphism) of the developed mathematical (analytic-simulation) models for proactive management of the IIoT structural dynamics with their logical-algebraic and logico-linguistic analogues (models), constructed on the basis of intellectual information technologies. As opposed to the existing scenario behaviour patterns of the IIoT functioning, based on finite-state machine and simulated descriptions, the suggested logical-dynamic approach at the constructive level allows us to solve both tasks on synthesis of the IIoT functioning technologies, as well as tasks on complex planning of information and production processes to ensure effective functioning of the Industrial Internet-of-Things. Meanwhile the created polymodel complex explicitly
managed to take into account such basic logical functions and corresponding limitations as “AND”, “OR”, “alternative OR”, “NOT”. Introduction of these functions and limitations did not result in exclusion of the IIoT synthesized program management (or, in other words, plans of their functioning) from the class of piecewise continuous functions. This allows us to use fundamental and applied results, obtained both in practical and modern management theory, on the practical basis, within solving the tasks on technologies and programs synthesis for information processes in the Industrial Internet. One more advantage of the suggested polymodel complex is that it helps to – in a consistent way (using one and the same mathematical structures) – formally describe both tasks on complex modelling of the IIoT management processes, and the tasks of their actions planning, plans correction (replanning), as well as tasks on operational management and monitoring of their condition, thus providing correct cross-model coordination by means of applying unified language to describe the considered processes [10].

**Conclusions**

So far, the results of researches, implemented within this subject matter in practice, were integrated at the level of information processes proactive management in the IIoT. The developed specialized mathematical software allowed us to increase effectiveness of information processes management within the Industrial Internet-of-Things (in terms of indicators such as efficiency, resource intensity and cost-effectiveness) by means of rational usage of computational resources, justified distribution of computation operations within heterogeneous nodes of fog computations and coordination of the goals level and system tasks in whole with the level of planning operations and distributing computation resources in it. Moreover, the usage of the IIoT proactive management helped to increase robustness (and to wide extent – sustainability) of information processes by means of targeted selection of those technologies and complex plans for PRO management, that are the least sensitive to local and global failures in the operation of information-management and telecommunication subsystems of the Industrial Internet.

Thus, summarizing the results of numerous conducted experiments, related to application of the developed mathematical and software synthesis of technologies and programs for managing information processes in the Industrial Internet, applied in various subject fields, it can be acknowledged, that by means of the implemented optimization on average, the indicator of operational efficiency of synthesized information process implementation can be increased by 15%, and the indicators of resource intensity and cost-effectiveness (in terms of energy or money) – on average can be improved by 30% as compared to the corresponding indicator values within applying traditional heuristic approaches and algorithms for solving tasks on calendar planning and scheduling applied to the considered subject field.

In order to simplify and ensure clear representation of results, related to evaluation of the IIoT operation plans sustainability and robustness, as a sustainability indicator of corresponding plans on information processes management implementation, we selected a statistical assessment of probability to reach the set threshold values by the indicators of the IIoT functioning quality for specified (optimistic, pessimistic and medium) scenarios of failures occurrence within information-management and telecommunication subsystems of the Industrial Internet. For the intervally-set disturbances within assessing the robustness of plans for managing the information processes as an indicator we selected a size of the intersection area of the approximated reachability region describing possible variants of range of values for quality indicators of the specified plan, with an area, that sets acceptable threshold values of the specified indicators, defined experts. In this case application of the suggested methods and algorithms for increasing sustainability and robustness of the synthesized technologies and complex plans on the IIoT functioning while solving practical tasks, allows us to increase the specified indicators by an average of 30% compared to indicators, obtained within applying traditional heuristic methods of ensuring sustainability and robustness of plans for the IIoT functioning. At this point the obtained fundamental and applied results were realized in practice in such subject fields as cosmonautics, ecology, robotic science, government administration, industrial production and logistics [7]. Further directions of
research will be related to organization of cooperation among management processes, implemented at the IIoT information and production levels.

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