Conceptual Approach to Managing Technological Processes of Industrial IoT Workshop

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***Abstract*—Usage of industrial networks of Internet with net-centric control is the driving trend of the future material manufacturing of goods and services. The bright future of this approach is out of doubt provided these complex net-centric systems will function with high reliability. Such systems are characterized by complex multi-parameter operability modes controlled by a large number of criteria. This paper describes a solution to the problem of smart and reliable net-centric control of technological processes.**

Keywords—net-centric control; technological process; industrial IoT system; reliability; multi-criteria optimization.

I. THE STATE-OF-THE-ART OF RESEARCH IN THE AREA

Today, Industry 4.0 [1] is the paradigm of manufacturing of the future. Its essence is in organizing material manufacturing of goods and services on the basis of Internet networks which integrate information exchange among sensors, data ports, control devices, and other terminal objects with means of smart operational and strategic control of technological processes – the so called Internet of Things (IoT) [2]. In IoT Data Processing Centers (DPC) are added to control processors distributed over the network nodes, which use pre-programmed rules and procedures of control. These computers analyze these rules, inference new ones and modify old ones based on the data on the network state which circulates in form of data flows, thus demonstrating the so called net-centric control of an industrial network.

For example, modern industrial lines (workshops) consisting of multi-functional Computer Numeric Control (CNC) machines, 3D printers, and robots are integrated into a network which includes a DPC for creating the pre-conditions for efficient planning and optimal realization of technological processes to be run in parallel and adapted for low-volume or single-piece manufacturing in the areas of machine-building, raw materials processing, assembling of multi-components devices, etc [3].

Although each CNC machine has its own controller for performing complex technological operations (for example, smart CNC machines of Yamazaki Mazak Corporation), it is not intended to coordinate logistics of the whole workshop. To provide this functionality IoT workshop is designed as three-level hierarchical network (Fig.1).

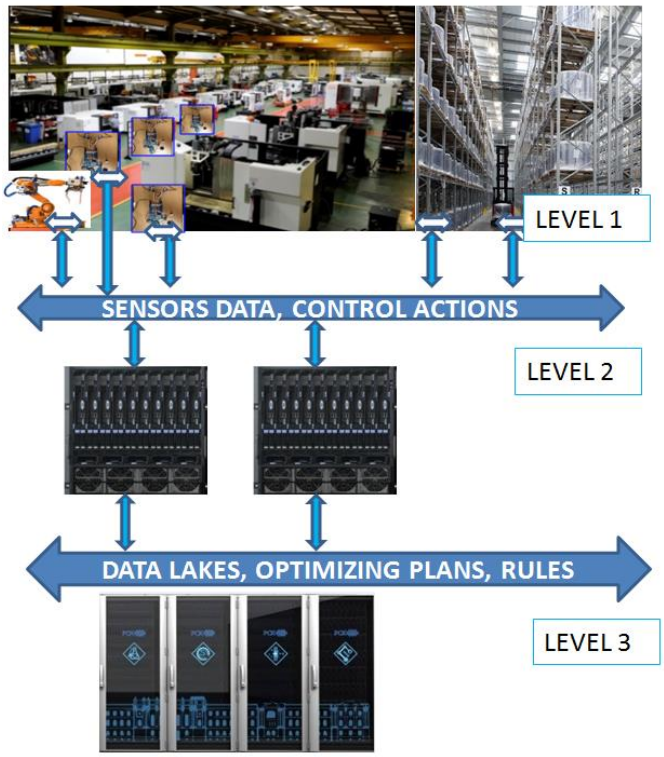

Fig. 1. Example of a workshop shown as a three-level hierarchical network

On the first level data from sensors of network objects is gathered. This data describes the state and conditions of each object (machines, robots, warehouses, controllers, etc.) which allows the controllers of the second level to control the process of each technological "macrooperation" (MO) by IoT network objects. Each MO initiates implementation of a concrete sequence of more trivial technological operations controlled by embedded controller of network object.

The second level provides managing planned sequences of technological MO performed by machines, robots and automated warehouse. Also it transfers data regarding network objects and their environment to the third level. These data streams create "data lakes" available for analytics on the third level.

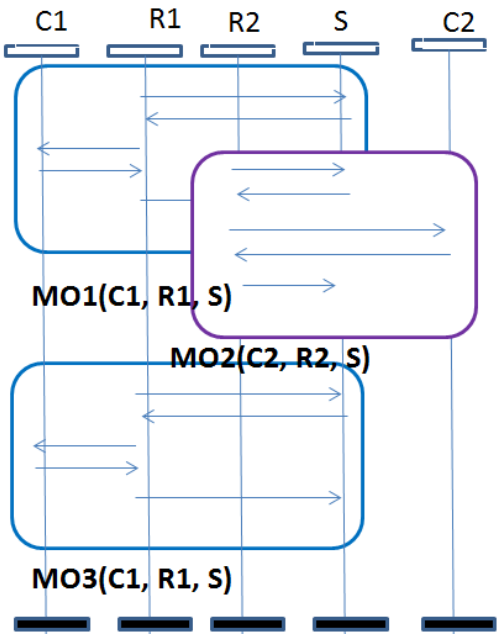

Fig. 2. Example of an MSC diagram with planned sequence of technological MO within a workshop

An MSC (Message Sequence Charts) diagram [4] shown in Fig.2 contains message sequences between CNC machines (C1, C2), robots (R1, R2) and automated warehouse with prototypes and complete products (S). Each MO is a sequence of messages which implement automated programs of embedded controllers.

The third level provides "data lakes" analytics which is used for dynamic planning of the whole workshop functioning. This planning includes optimization of implementing MO by network objects considering possibility of concurrent implementation, synchronization, regions of allowed values for object states parameters, conditions for reliable execution, etc. As success criteria are specified for each network object in all working modes, the third level shall dynamically solve the task of multi-criteria planning as well as specify new rules of measuring state parameters of network objects or modify existing ones.

This approach is prospective without any doubt provided complex net-centric systems ensure efficient planning and highly reliable functioning. Industrial IoT systems are characterized by complex multi-parameter operability modes controlled by a large number of criteria.

According to the analytic agency Juniper Research, there are 13.4 billion on-line devices which are permanently in the network. By 2020 their number will increase threefold – up to 38.5 billion devices. The major areas where IoT technologies develop are transport, medicine, industrial manufacturing, and the like.

The major direction is extending the scope of IoT and extending the functionality and smartness of decision making with IoT. However, using these varieties of the IoT technology is risky and requires reliable protection. In this paper an approach to creating the theory and technology of reliable and efficient functioning of IoT as a large industrial system is described.

II. Hierarchical Decomposition of Multi-Criteria Tasks of Selecting a Variant

Methods of solving multi-criteria tasks of selecting a variant in implementation of complex IoT systems which integrate a number of processes of various physical nature, along with methods of control of these processes on the basis of a hierarchy, aggregation, and algorithmic decomposition in the model of a system under analysis by the DPC are considered. A direct solution of the initial multi-dimensional task with a number of hard-to-compute criteria is assumed to be either impossible or counter-productive due to constraints imposed by the balance of real-time and consumed resources. The major problems relate to the high dimension of the vector of adjustable (selected) parameters of the IoT being optimized and with a big number of particular criteria of optimality.

The proposed approach is based on applying the known procedures of system analysis to a particular subject domain under consideration. In contrast to the published results [5-20], there's a number of new refining and interpreting results. The discourse is developed up to formal computational algorithms ready for implementation in many domains where IoT systems are applied.

In net-centric systems a number of activities flow within the network – they are operations on collecting information on the state of system objects and control actions on them. Sequences of operations coming to an each controllable object determine its program of actions or a technological operation (a series of technological operations) for industrial IoT systems. The success level of control of these sequences of technological operations is measured with a particular objective criterion. Due to a large number of controllable objects in a technological network, there's a large number of objective criteria. There's a need to develop a common objective criterion of an IoT systems which takes into account all technological processes; based on this criterion one should develop a general algorithm of control and functioning of the overall system, which is a distinguishing feature of net-centric control system.

The major task to be solved has the form:

$$\begin{gathered} f_0^1(x_0) \to \max, \ldots, f_0^{n_0}(x_0) \to \max, \\ x_0 \in X_0 \subset R^{N_0}, x_0 = x(0) = (x_1(0), \ldots, x_{N_0}(0)) \end{gathered} \tag{1}$$

where $f_0 = (f_0^1, f_0^2, \ldots, f_0^{n_0})$ is a set of objective criteria, which define requirements to the output parameters of the system being optimized, and X_0 is a set of variants of the considered system which are realizable physically and algorithmically.

A solution of the optimization task (selection of optimal variants) is understood as a set $\Pi_{f_0}(X_0) = \Pi_0(X_0) \subset X_0$ of efficient (Pareto-optimal [8]) solutions from X_0.

Applying the described constructive approach assumes solving the aggregation task, which requires to take into account the following specifics:

- General multi-level models of optimization processes allow to reduce the initial complex task to a series of efficiently decidable tasks using sequential aggregating (abstracting).
- The aggregation process starts at the zero, most detailed (low) level of system description where a direct solution of the task is inefficient because of its complexity and high dimension.
- The number of aggregation levels is selected in such a way, that the final dimension of the vector of adjustable parameters were acceptable for applying standard procedures of optimization [6,7].
- One can obtain more and more algorithmically simple objective functions (which are introduced informally at each level derived by experts from the consistency conditions) with aggregation.

III. Levels of the Process of Multi-Criteria Optimization

A model of levels of multi-criteria optimization is given in Fig.3.

In the considered model the initial low level corresponds to the most detailed description of the system with a big number of arguments and another big number of particular criteria, usually of high computational complexity. As mentioned above, it is hard to solve the problem of constructing the set $\Pi_{f_0}(X_0) = \Pi_0(X_0) \subset X_0$ directly.

According to the algorithm described below, a successive enlargement of the problem description is performed through transition to the next (higher) level which contains less variables and particular criteria. As a result, an observable set of particular criteria depending on a relatively small number of arguments is obtained at the highest (strategic) level. Constructing a Pareto set at this level becomes algorithmically feasible. Thus, moving upward is accompanied at each level by introduction of aggregated variables and new sets of particular criteria, consistent with the criteria of the adjacent lower level in the sense specified below. This process of successive aggregation and decomposition is described below.

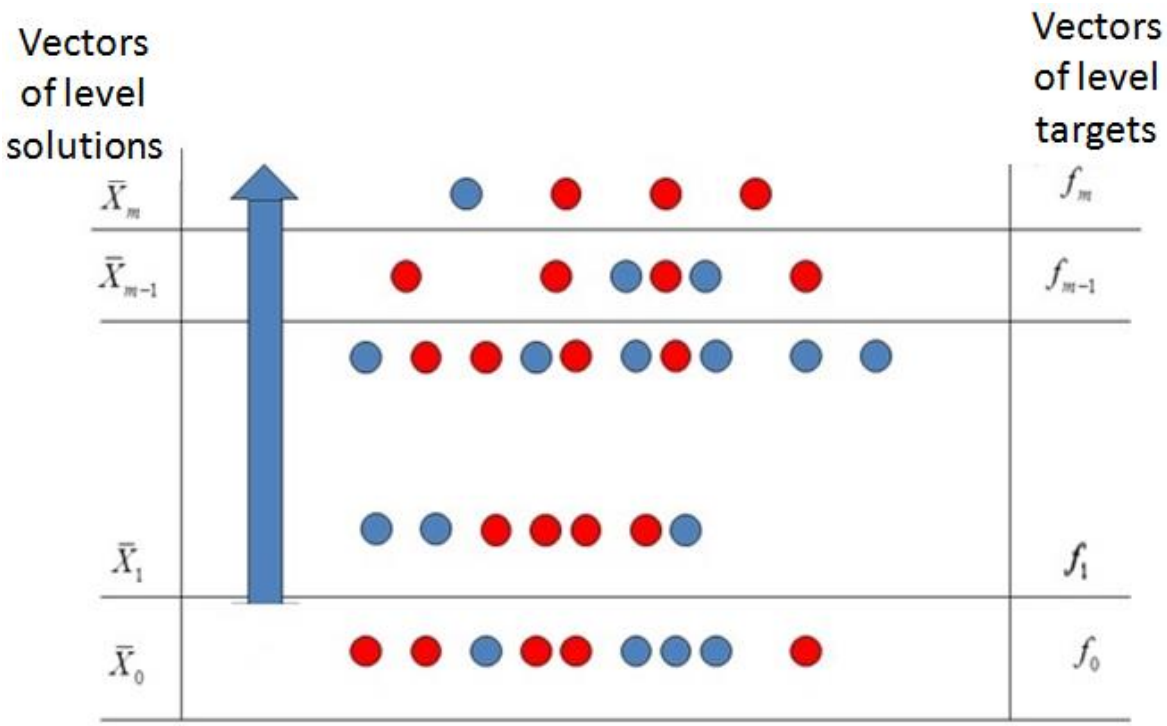

Fig. 3. Levels of the process of multi-criteria optimization

IV. AGGREGATION LEVELS

Let's introduce aggregated parameters of the next 1st level:

$$x(1) \in X_1, X_1 \subset R^{N_1}, N_1 < N_0, \quad x(1) = \varphi_1(x(0)), X_1 = \varphi_1(X_0) \tag{2}$$

where φ_1 are aggregation functions which define the structures of parameters of level 1 through parameters of level 0.

Then experts should specify criteria of level 1:

$$f_1(x(1)) = (f_1^1(x(1)),..., f_1^{n_1}(x(1))) \tag{3}$$

As $N_1 < N_0$ the set $x(1)$ provides more integrated and enlarged description of the planning process than the set $x(0)$.

Functions φ_1 and f_1 should be consistent with $f_0, x(0), X_0$ in such a way that plan 1, which is Pareto-better than plan 2 w.r.t. criteria of level 1, was better than plan 2 w.r.t. criteria of level 0 as well.

As a result of continuing the aggregation process, the following chain is obtained:

$$\begin{aligned}
&x(0) \in X_0 \subset R^{N_0},\ f_0(x(0)) \in R^{n_0};\\
&x(1) = \varphi_1(x(0)) \in X_1 \subset R^{N_1}, N_1 < N_0,\\
&f_1(x(1)) \in R^{n_1};\\
&----------\\
&x(k+1) = \varphi_{k+1}(x(k)) \in X_{k+1} \subset R^{N_{k+1}}, N_{k+1} < N_k,\\
&f_{k+1}(x(k+1)) \in R^{n_{k+1}};\\
&----------\\
&x(m) = \varphi_m(x(m-1)) \in X_m \subset R^{N_m}, N_m < N_{m-1},\\
&f_m(x(m)) \in R^{n_m}.
\end{aligned} \tag{4}$$

where

$$X_{k+1} = \varphi_{k+1}(X_k) = \{x(k+1) = f_{k+1}(x_k) / x(k) \in X_k\}, \quad 0 \le k \le m-1. \tag{5}$$

Selecting the number m of aggregation steps (in real practice not greater that 4) is determined by the fact that the dimension of N_m should not exceed 50 and criteria $f_m(x(m))$ should be algorithmically simple.

After specifying all aggregation steps from bottom to top, the top-to-bottom very process of parameterized optimization starts (Fig.4). At the upmost (strategic) level m a respective Pareto set is constructed in accordance with the introduced criteria of the upmost level. Then one goes down in the planning graph in accordance with the above equations until level 0 is reached and the resulting Pareto set (some subset of it, to be exact) is constructed. The described process of optimization is a process of successive narrowing the set of considered (controlled) vectors on the basis of additional information in form of intermediate vector criteria of optimality introduced at each hierarchical level. The introduced "level-ranked" criteria of optimality reflect the level of task details. As a result (and this is the main point), variants rejected "from general considerations" at the previous hierarchical level are not analyzed at subsequent levels with more numerous and complete sets of particular criteria.

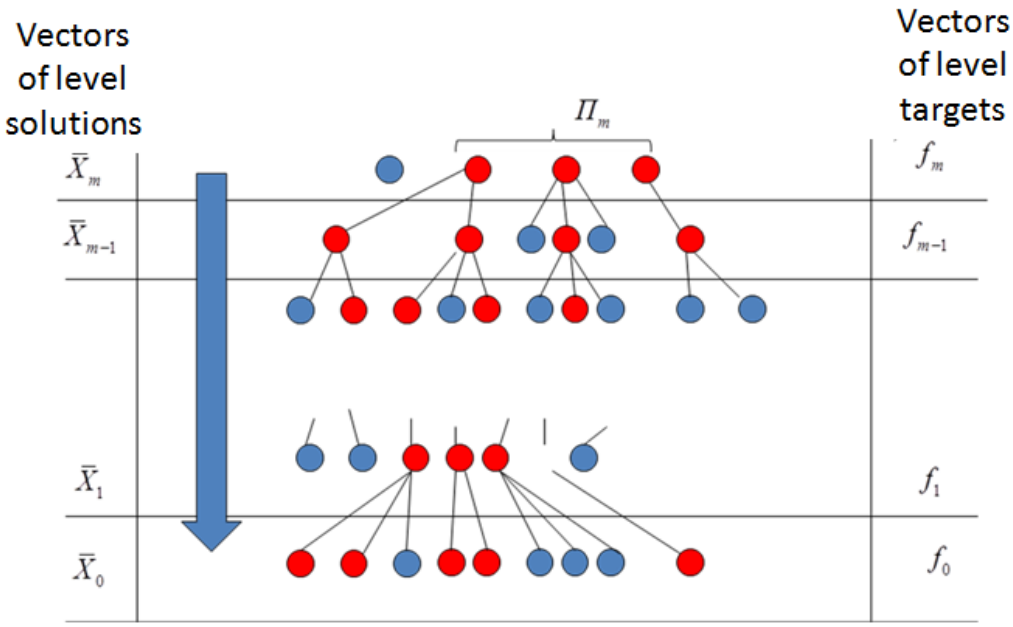

Fig. 4. Example of the process structure of objective optimization with net-centric control

V. THE MASTER EQUATION (ALGORITHM) OF THE OPTIMIZATION PROCESS

Upon execution of all aggregation steps, i.e., upon introducing $x(k), X_k, f_k, 0 \le k \le m,$ the multi-criteria component of the optimization task may be solved as follows.

Let's find

$$\Pi(X_m) = \Pi_{f_m}(X_m) = \Pi_m(X_m) = \Pi_m \qquad (6)$$

and all solutions of the equation

$$\varphi_m(x(m-1)) = x(m), \forall x(m) \in \Pi_m \subset X_m \qquad (7)$$

These solutions define the set $\overline{X}_{m-1} = \varphi_m^{-1}(\Pi_m).$

Then let's find the sets

$$\Pi_{m-1}(\overline{X}_{m-1}) = \Pi_{m-1}, \overline{X}_{m-2} = \varphi_{m-1}^{-1}(\Pi_{m-1}). \qquad (8)$$

The result of this process is $\Pi_0(\overline{X}_0).$

All this may be formalized in form of the master equation of multi-objective optimization:

$$\Pi_k = \Pi_{f_k}(\overline{X}_k) = \Pi_k(\varphi_{k+1}^{-1}(\Pi_{k+1})),$$
$$k = m-1,...,0. \Pi_m = \Pi_{f_m}(\overline{X}_m) \qquad (9)$$

Approbation of the described approach has demonstrated its applicability for deploying and managing technological processes within an industrial workshop with 8 adjustable criteria for its effective functioning.

VI. CONCLUSION

Approach to solution to the problem of net-centric control of technological processes for IoT systems is proposed. Methodic of control automation of multi-parameter network with required balance between tens of criteria for effectiveness of technological processes stages is considered. Both approach and methodic were successfully applied in industrial IoT application.

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