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Mechatronics 2019: Recent Advances Towards Industry 4.0

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Foreword

During the last few years, global scientific and technological community observe dramatic changes in the industry. This revolution, called transformation towards Industry 4.0, determines new paradigms resulting in process optimisation tendencies and leading to increase the production volume with simultaneous reduction of involved resources. To achieve this goal, cyber-physical systems with artificial intelligence capabilities are commonly introduced to production lines, resulting in dramatic increase of processed and stored data, as well as subsequent development of completely new IT infrastructure, such as 5G mobile phone network standards.

Such radical transformation of industry is not a choice, but a necessity. Radical increase of number of people on the Earth together with natural expectations of increasing the quality of life around the world leads to unsustainable development and environmental burden. As a result, the forthcoming generations will be forced to consume less than us facing natural resources' depletion. The only way to avoid such scenario is wide implementation of optimised, adaptive cyber-physical production systems.

As a result, we observe intensive development of IT systems and artificial intelligence algorithms. On the other hand, efficient production line requires highly developed mechatronics systems, which truly determine its productivity. However, mechatronics seems to be neglected in changes of Industry 4.0, whereas it will play a decisive role in further success or defeat of our technical civilisation.

We hope that this book will be the first step to restoring mechatronics to the right rank. This book presents the results of intense discussions during the Mechatronics 2019 Conference held in Warsaw, 16–18 September 2019, gathering scientists from Poland, Czech Republic, Korea, Ukraine and France. Topics cover both modelling and experimental verification of performance of advanced mechatronics systems, system integration and its reliability, maintenance and development of robotics, automation and measurement systems as well as MEMS and biomedical applications focused on rapidly ageing population.

We strongly believe that solutions and guidelines presented in this book will be useful for both researchers of technical sciences and engineers solving problems in the world of mechatronics.

June 2019

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Jiří Krejsa
Michał Nowicki
Anna Ostaszewska-Liżewska

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About the Editors

Asoc. Prof. Roman Szewczyk received his both PhD and DSc in the field of mechatronics. He is specialising in the modelling of properties of magnetic materials as well as in sensors and sensor interfacing, in particular magnetic sensors for security applications. He is leading the development of a sensing unit for a mobile robot developed for the Polish Police Central Forensic Laboratory and of methods of non-destructive testing based on the magnetoelastic effect. He was involved in over ten European Union-funded research projects within the FP6 and FP7 as well as projects financed by the European defence organisation. Moreover, he was leading two regional- and national-scale technological foresight projects and was active in the organisation and implementation of technological transfer between companies and research institutes. He is Secretary for Scientific Affairs in the Industrial Research Institute for Automation and Measurements PIAP. He is also Associate Professor at the Faculty of Mechatronics, Warsaw University of Technology and Vice-chairman of the Academy of Young Researchers of the Polish Academy of Sciences.

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Use of Methods of Tensor Analysis in the Evaporator Plant Operating System

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Abstract. The issues of the relevance of conduction of research in the areas of analysis and synthesis of evaporator plant operating systems were disclosed; the need of taking into account the peculiarity and interconnection of mass and energy flows of the entire sugar refinery was put forward. This explains the need for new methods of integrating the operating system so that, on the one hand, the evaporator plant operating system is an integral part of the whole system of the sugar refinery management. But at the same time, it shall be flexible and shall not require significant changes in the correction of processes or updating of automation equipment. The article presents a method for using the mathematical apparatus of tensor analysis for determining the nature of the change of the signal of the discrepancy and the formation of the control signal.

Keywords: Evaporator plant · Tensor model · Radius vector · Local coordinates

1 Introduction

As a rule, mathematical models [1] are used for correct operation of modern automation systems. They allow one to optimally adjust the regulators, construct robust system and work with forecasting. Thesis [2, 3] shows the results of research that are aimed at solving an important task of automatic optimization of distribution of heat resources between process sections of a sugar refinery; the algorithm of operational estimation of the state of the evaporator was developed. It was shown that the algorithm includes Kohonen self-organizing maps, the method of estimating the quality of clusterization and the method of indistinct classification on the basis of neural networks. Time series of technological variables of sugar production are used as input data.

But issues that are related to the need for continuous retraining of the system remained unresolved. The reason for this may be objective factors that are associated with a change in the conduction of the production method [4] and changes in the characteristics of the operation of the technological equipment [5, 6]. Fundamentally such an approach (training of the system in time series) cannot be used, for example,

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during transitions, at the moments of starting or stopping equipment, changing the conditions of operation of adjacent areas [7, 8]. This, in turn, leads to prolonged transitional processes, which causes an increase in the cost of energy and material resources. Therefore, this research needs to be updated.

Solving these problems requires the creation of universal mathematical models of the entire technological complex. Their coefficients shall be enumerated according to the current state and mathematical model, the coefficients of which shall be calculated according to the given (ideal) values of technological parameters. In this case, the management effect shall be calculated iteratively, according to the model of the current state and the model with the given technological indicators that shall improve the efficiency of operation of the entire technological complex.

The use of tensor analysis methods is the solution to these problems. For example, the following approach is suggested: use of methods of tensor factorization during the training of neural networks, which is indicated in study [9]. Recently methods of tensor analysis have been widely used in solving various problems. The use of tensors in operating systems is a perspective direction; tensors in recent years have been used in many areas, namely: use of tensors for image processing and computer vision [10]. Tensors are also used for data analysis, neural analysis and for the development of neural networks [9, 11, 12]. At present, tensor methods are already used in electrodynamics, in mechanics, in gravics, in elementary particle physics, in the study of the properties of crystals and in differential geometry. In [13] methods of tensor analysis were used in the development of robust regulator, which was involved in aircraft for reducing the shock vibration caused by the interaction of tires and flight strip. In study [14] the research and modeling of the KUKA KR6 robot that uses the inertia tensor used for constructing the manipulator Jacobian, which is essential for kinematic control, is presented. Methods of tensor analysis are used in medical examinations. For example, in [15] magnetic resonance imaging and image tensors are used for early diagnosis of insult. In study [16] methods of tensor analysis are used for modeling and tensor imaging, for controlling the physiological response of children.

Tensor methods are now also being used for food industry operating systems. For example, in [17] it was shown that by means of the calculation of tensors of mechanical stresses, factors influencing the shape of the cutting edge and the angle of inclination of the blade on the cutting of hard and crunch materials in the food industry were studied. This allowed one to find the optimal design of the cutting element. This further allowed developing appropriate algorithms for controlling the blade pressing effort in the automation system.

In study [18, 19] the use of methods of tensor analysis for synthesis of the operating system is indicated. An operation of the tensor product of the input data was used. Then the orthonormalization operation was executed for the found matrix; and then the components of the tensor were used as elements of the matrix in the model in the state space. That is, the coordinate approach to the synthesis of the operating system in the state space was used.

Such a widespread use of tensor methods in solving modern problems during the processes of analysis and synthesis of systems lies in the universality and flexibility. This is due to the fact that the tensors are not changing in the process of transition from one coordinate system to another. This allows aggregation of tasks, as well as perform decomposition of tasks, by moving from space to the subspace of reduction or increase in dimension and vice versa. Special program packages [20, 21] were developed for working with tensors that are a customization to MATLAB and are used for analyzing data arrays.

But one shall take into account that modern operating systems, and the evaporator plant automation system, including those constructed according to international (ISA-95) and European standards (IEC 62264) [7, 22]. Operating systems have a hierarchical structure, where the lower level is the automated operating system of the technological process, and at the highest level - a workflow process management system. The specified standards determine the distribution of the functioning of the whole system as a separate work of subsystems, at the level of each of which their goals are achieved (DCS, APC, MES) [23, 24].

The problem was not considered based on the analysis in this formulation. That is, it is necessary to develop a method of calculation and the principles of using tensor models in the operating system of the technological process with the possibility of integrating the developed methodology at each level of the hierarchical structure of modern operating systems.

2 The Results of Research

For the use of tensor methods in the work it was assumed that at a certain moment of time the technological evaporation process took the form of a transition process, which is characterized by a trajectory passing the system from the initial (steady) mode to the new given one. Upon that, the dimension of the technological space will depend on the number of variables on the input and output of a particular process unit. The coordinate axes shall be chosen as the absolute coordinate system, which corresponds to the dimension of the space of the evaporation process. That is, the number of axes will correspond to the number of parameters. Upon that, all the basic axes shall be mutually perpendicular (orthogonal) and have the same dimensions and levels of unit measure (that is, orthonormalized).

This nonlinear transition process was divided into shorter (linear) areas. This allowed its presentation as a path in which each subsequent step was calculated relative to the previous one Fig. 1.

That is, it was generally assumed that when managing the parameters of the evaporation process (change in temperature regime, consumption, pressure change, change in dilution for 5-th body), each controlled process at any moment turns from one current state to another. On Fig. 1, this transition is represented by a vector that connects transition points that are marked as M_i where i position of point ($i = 0 \ldots L$). This means that initial and final states are always present, for example, after the technological process, the system's indicators (environment) changed. Also, there is an initial and final state in the work of operating system, which forms the control action for transition from one fixed mode to another, for change of the state of the parameter (mode of the equipment - on/off) or to hold the system in the specified mode. This may be a periodic operation of the device, the introduction into operation or removal of the processing line from operation, the failure of the equipment or the change in the mode

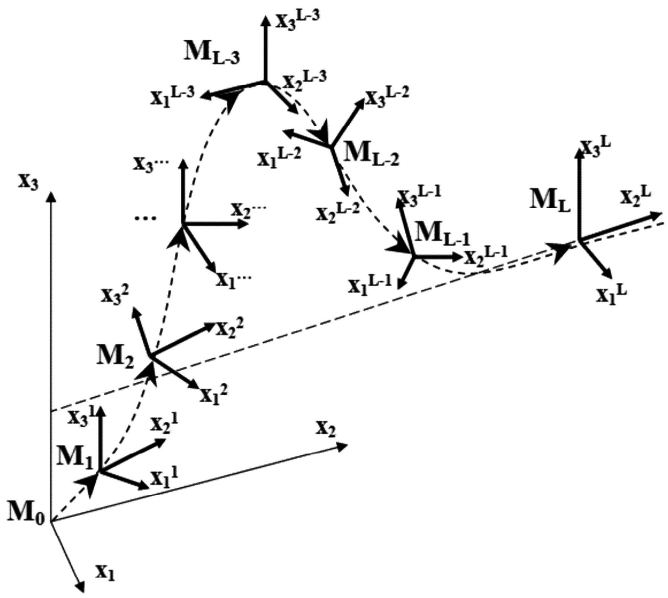

Fig. 1. Identification of the path and coordinates in the transition process of the operating system

of the evaporator plant. Assuming that every point M_i – is the central point of coordinates in the local basis, and a path that connects two points (for example M_0 and M_1) is a radius vector x.

Then the coordinates of the vector x can be presented as:

$$x = x_1 e_1 + x_2 e_2 + x_3 e_3 = \sum_{i=1}^{3} x_i e_i, \tag{1}$$

where e_1, e_2, e_3 are single vectors in the local basis e, which corresponds to point M_0. During the transition to point M_1 the basis shall be changed to a new one $\tilde{e}$. The following formula shall be used to change the basis:

$$\tilde{e}_i = S_i^1 e_1 + S_i^2 e_2 + S_i^3 e_3 = \sum_{i=1 j=1}^{3} S_i^j e_j, \tag{2}$$

where S is a matrix of direct transition from the old basis to the new one. For a reverse transition, the inverse matrix shall be used S^{-1}. The transition from the old basis to the new one and vice versa will look like:

$$(e_1, e_2, e_3) \underset{S^{-1}}{\overset{S}{\rightleftarrows}} (\tilde{e}_1, \tilde{e}_2, \tilde{e}_3). \tag{3}$$

Old and new bases and radius vectors will coincide in case of fixed technological process for local basis of reference point. Disturbing effects appear in case of change of the controlling act for transition to the new values of the system's output. Disturbing effects are caused by internal connections of the inertia of the system and the specifics of operation of the technological equipment. When the disturbing effects appear, the radius vector of the initial values of the system changes its geometric position Fig. 2.

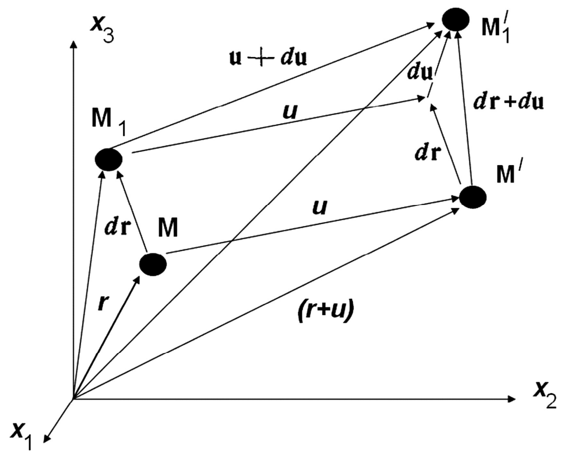

Fig. 2. Changing the state of a controlled system when causing a disturbing effect

Point $M(r)$ turns into point $M_1(r+dr)$. The union of disturbing effect and regulating action leads to different output and fixed values. Taking into account disturbing effect and regulating action, the system's state was already characterized by a radius vector, which is geometrically directed to a point $M_1'(r+dr,\ u+du)$.

For the synthesis of the operating system by the evaporator plant, the radius vector of the output values y = {Sк, bк, ρк} was assumed; radius vector of the state of the operating procedure of juice evaporation x = {Cп, ρп, iп, Cк, h, Dк, tк, W, D′, Gм, F, V, G, u, p, Gп, Gк}; regulating radius vector u = {Sп, bп, Dп, tп}. The value of the radius vector of management depends on the difference between the given and the actual output of the system. The output of the system depends on the values of the radius vector of the state and the radius vector of regulation. It is convenient to present this system by a description in the state space:

$$\dot{x} = Ax + Bu; \quad y = Cx. \tag{4}$$

where x is a radius vector of the state of the system; u is a radius vector of regulation, y is a radius vector of output values; A, B, C – system matrices. In the operator form the description of the system (4) looks like:

$$y(p) = Q(p)u(p), \tag{5}$$

where the transfer function

$$Q(p) = C(pE - A)^{-1}B. \tag{6}$$

Matrices *A, B, C* are behind quadratic and bilinear forms for the corresponding radius vectors. For a radius vector of the state of the system matrix A is behind the following formula:

$$f(X) = \sum_{i \leq K, j \leq N} a_{ij}x_ix_j = X^TAX, \tag{7}$$

where $X = \vec{x}$, $a_{i,j}$ – elements of a matrix of quadratic form $a_{i,j} \in A$, *i, j* – indices. The first index numbers the row, and the second one numbers the column, *i* = *1, …, K;* *j* = *1, …, N. K* and *N* – is the degree of a quadratic matrix. *A* is a symmetric matrix, which represents a tensor of the second rank, elements of which are calculated according to the formula:

$$a_{ij} = \begin{cases} a_{ij}^2 & i = j \\ \frac{1}{2}\left(a_{ij} + a_{ji}\right) & i \neq j \end{cases}. \tag{8}$$

Tensors of the second-rank (of the matrix of quadratic forms) for the radius vector of regulation and the radius vector of the output values are at the same level. The connection between the tensors will look like:

$$f(Y) = Y^TCY = (AX)^TC(AX) = X^TA^TCAX = \tilde{f}(X). \tag{9}$$

Type of tensors *A*, *B*, *C* depends on the choice of the basis in the state space. The transition to a new basis is replaced by variables (2). Tensors *A*, *B*, *C* in the new basis become the form

$$\tilde{A} = S^TAS, \quad \tilde{B} = S^TB, \quad \tilde{C} = CS. \tag{10}$$

For the tensor *S* orthonormal eigenvectors of a new basis are calculated [6, 21]. The tensor of the system shall be simplified to the diagonal:

$$\tilde{A} = S^TAS = diag(\lambda_1 \ldots \lambda_n). \tag{11}$$

The description of the output system in the new basis will look like:

$$\dot{x} = \tilde{A}\tilde{x} + \tilde{B}u; \quad y = \tilde{C}\tilde{x}. \tag{12}$$

This approach allows us to obtain equation of state, which is decomposed to n independent equations of state and output equations:

$$x_i(t) = \lambda_i \tilde{x}_i(t) + \tilde{B}_i u(t); \quad y(t) = \tilde{c}_1 \tilde{x}_1(t) + \ldots + \tilde{c}_n \tilde{x}_n(t). \tag{13}$$

The purpose of the synthesis of the evaporator plant operating system is finding a control law that ensures the fulfillment of the following condition:

$$\lim_{t \to \infty} |y_z(t) - y_v(t)| < \delta, \tag{14}$$

where y_z – fixed output values of the system, y_v – measured output values of the system, δ – acceptable deviation $\delta \geq 0$.

During the transition to a new basis in the local coordinates the operator (2, 3) transits radius vectors x, u, into the plane of the subspace M_L on which they are at the reference point. That is, they are orthogonal to each other. For the case $\delta >> 0$ in condition (14) the bases of measured and set values of the system are different. A graphical representation of the position of the vectors of the measured and fixed values in the local coordinates of the subspace M_L is presented in Fig. 3.

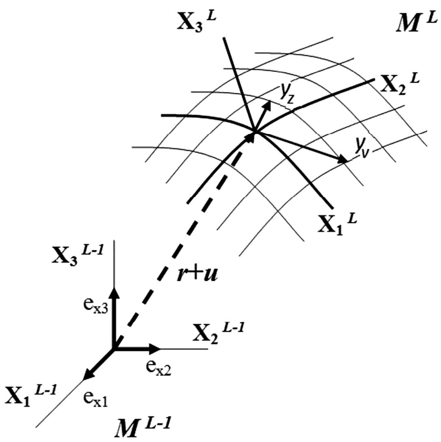

Fig. 3. Radius vectors of fixed y_z and measured y_v states of system

Figure 3 shows the transition from basis, which corresponds to point M_{L-1} to basis of point M_L. In local basis M_L axis X_1^L is parallel to the vector of the state of process of juice evaporation; axis X_2^L is parallel to the control vector, axis X_3^L is parallel to vector of output values of the system.

Vector that characterizes the deviation e with taking into account (5), (14) will look like:

$$e = y_z - Q_v u, e = \delta \leq 0. \tag{15}$$

That is, one shall locate a vector u $\in$ U_L (in this arrangement $U_L = X_2^L$), which will provide a solution to the expression (15). Optimal solution for the sub-space M_L. The problem in this arrangement is the problem of projection of a solution u on axis X_2^L, that an orthogonal subspace M_L, which is formed from the axes X_1^L and X_3^L. Tensor-projectors [25] are used for solving projective problems. The tensor of the second rank S is a projector in case if the following equalities are fulfilled for it:

$$S^T = S, \quad S \cdot S = S. \tag{16}$$

Condition (16) is fulfilled in case if the tensor S was obtained by orthogonal unit vectors, symmetric matrices calculated according to (7), (8). For example, for sub-spaces that were obtained separately for each radius vector x, y, u. For a non-symmetric subspace, for example, a subspace M_L. (Subspace $M_L \in C^{18\times4}$ is obtained according to radius vectors: x, which has a degree 18 and u, which has a degree 4). For a non-symmetric subspace M_L two orthogonal projection tensors are introduced:

$$\begin{aligned} P(A) &= A^+A, \quad A \in C^{18\times18}, \\ P(A^*) &= AA^+, \quad A \in C^{4\times4}, \end{aligned} \tag{17}$$

where A = M_L, A^+ is pseudo-inverse matrix to matrix A. SVD algorithms of decomposition were used for finding pseudo-inverse matrices.

The following projections are obtained according to found tensor-projectors (17):

$$\Pi p_{M_L} x = (E_{17\times17} - P(A)) \cdot x_v, \tag{18}$$

where $E_{18\times18}$ is a unity matrix.

3 Analysis of Simulation Data

The simulation of the work of operating system was performed using the MATLAB software package as a model of the control object. Dependencies according to [1–4, 8] were used. The model of the control object was used for obtaining the measured values for which the radius-vector of the measured values was located. The function of tensor multiplication “kron” of the MATLAB package was used for obtaining a tensor, which described the behavior of a system for a measured point. Elements from the DSP System Toolbox library of the MATLAB package were used for receiving the work with matrices.

According to [1–4], vector of output values of technological parameters y = {30.0, 65.0, 0.65}, vector of the state of production method of steam production x = {3.36, 0.14, 2.729, 0.8, 5.3, 126.0, 7.8, 0.1, 29.0, 12.4, 17.0, 0.27, 134.0, 2.1, 3.0, 120.0, 15.0}, control vector u = {33.3, 14.0, 8.1, 134.0}. For the given vectors, using the expressions (1) and (2), the tensors of the second in the form of matrices of the space-state system were found.

Figure 4 indicates Simulink model of evaporator plant with the calculation of control signals using tensors.

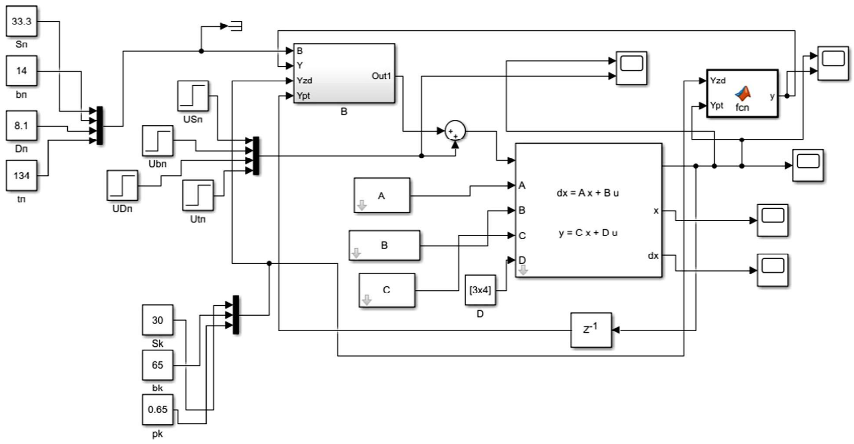

Fig. 4. Simulink model of the evaporator plant operating system with the use of elements of tensor analysis during identification of the object and synthesizing the control action

Figure 5, on the lower graph indicates the change of the disagreement signals that are used during the formation of the control signal, taking into account the curvature of the plane deviation for the measured radius vector from the plane for a given radius vector. These signals are generated with advance for 2 s. This is due to the fact that in the calculations there are regulated values of technological parameters that are used as disturbance and have a stepwise nature. At the beginning of applying disturbance of response diagrams (upper), from the control object, react with a delay. And the signals of the control actions are jump-like with the advance. It is explained by the fact that at the beginning of disturbance, the angles between the radius vectors have the maximum value and decrease with each iteration.

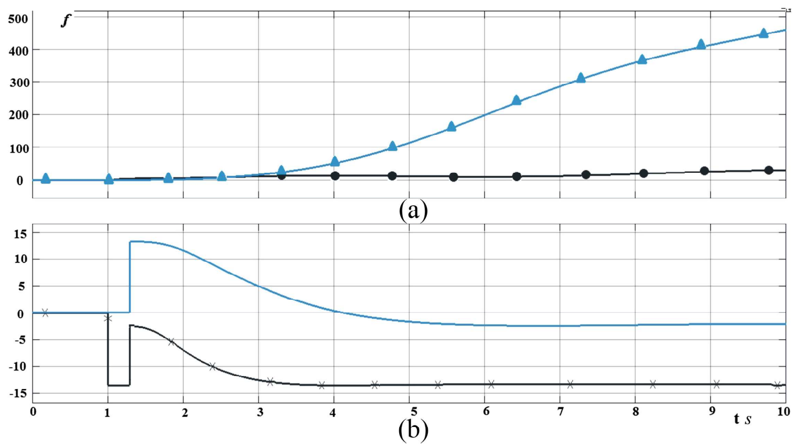

Fig. 5. Results of supply to the system of a step waveform through steam channels for temperature and pressure: a – change of the coefficients of the model (-▲- for temperature, -●- for steam pressure); b – signal of disagreement (× - for temperature, ▬ - for steam pressure)

4 Conclusions

That is why approaches to using tensor analysis techniques for an operator system are considered in this research. The universality of the method, the possibility for processing and storing a large amount of information, aggregating information by the way of allocating spaces and subspaces will be the benefits of this approach. This will allow the co-ordination of the interaction of all technological sites against each other. This approach to management will improve the efficiency of the operation of both the same apparatus (technological site) and the enterprise as a whole. Such a operating system can be implemented only with the use of a methodology that will coordinate the work of all elements of the complex. The use of such a technique will allow the creation of the necessary control actions, taking into account the work of the individual apparatus. It will also coordinate its work as a structural unit in the technological line (complex), in case of occurrence of deviations and transients.

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