Complex Scheduling of Measurement and Calculation Systems Functioning

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Abstract

The article suggests a polymodel description of cyber-physical systems (CFS) functioning, that represent multifunctional hardware and software complexes aimed at reception (transmission), storage, processing and forming of controlling actions both for the service objects (SO), conducting a given set of target tasks that are not included into CFS, as well as at ensuring their own reliable operation. Within the subject field, related to scientific device engineering, these models and relevant algorithms applying them, have a big scientific and practical value, as due to optimization of the measuring and computing operations (MCO), they allow to generally increase efficiency of using precise instrumental complexes in the specified environmental conditions. The developed polymodel description is based on the original dynamic interpretation of relevant processes.

Keywords

Cyber-physical systems, measuring and computing operations scheduling, dynamic models, optimal software control, software tools.

1. Introduction

[1] Currently various classes of cyber-physical systems (CPS) are becoming the major component of digital production and digital economics in general; these systems involve measuring, telecommuncational and control subsystems. [1,2]. Hereafter CPS is referred to a centralized and/or distributed hardware and software system, implementing physical and infocommunicational procedures of processing, accumulation, storage, search, protection, dissemination and usage of data and information, as well as interacting with objects of the real world through physical processes.

Based on the CPS projects of “Smart Manufacturing”, “Smart Houses”, “Smart Energy”, “Smart Transport”, “Smart Life Safety System”, “Smart Healthcare System”, “Smart and Safe Cities”, “smart” defense-relevant objects etc., such systems can ensure implementation of technologies for controlled self-organization within traffic management on the city streets by means of analyzing data on status and driving direction, received from vehicles; coordinated functioning of production equipment for effective manufacturing of small sets of various items, as well as electricity generation by providing workload optimization of thermal electric power stations, nuclear power plants, hydroelectric power stations, etc.

In this case the CPS measurement and calculation subsystems can be considered as variants of intellectual self-managed measurement and calculation systems with a number of specific features. In the first instance these features include the following [3]: the number of measurement channels within one CPS can involve from tens to hundreds of units even in the upcoming years; measurement channels can include sensors of various values, both scalar and tensor, whereby in the territorial aspect the sensors can be placed remotely from each other; measurement information is transmitted over long distances through wire and wireless communication channels.

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Measurement information processing can be implemented by means of various computational technologies, including cloud technologies, at the same time the processing must be implemented close to the real time scale [4]. CPS control subsystems are characterized by similar features.

Creation of economically effective CPS is possible only in case the data, information and supporting knowledge, is characterized by high confidence, received swiftly and the operational costs are sufficiently small. Due to limited scope of the article let us consider only the issue of developing the MCO scheduling plan, as the most important and time-consuming stage of the complex scheduling on CPS functioning [5, 6].

2. Scheduling problem description

Let us assume that there is a set of service objects (SO): $\tilde{\mathrm{A}} = \{\tilde{\mathrm{A}}_{\mathrm{i}}, \mathrm{i} \in \tilde{\mathrm{N}}\}$, forming part of some SO group and aimed at solving the joint set target task (i.e., monitoring of eco-economic objects condition). To ensure SO proper functioning it is required to permanently conduct evaluation and correction of navigational data on board of each SO. This task is implemented by CPS [2, 9]: that include hardware and software complexes, which solve tasks on reception (transmission), storage, processing and forming of controlling actions both for the service objects, that are not included into CPS, and at ensuring their own reliable operation.

Let us introduce a set of CPS: $\tilde{B} = \{\tilde{B}_j, i \in \tilde{M}\}, \tilde{M} = \{1,\dots,\tilde{m}\}$. Herewith, due to availability of unitized hardware and software tools in order to provide informational interaction on SO and CPS, in case relevant information is available, each of the listed elements of SO and CPS is capable to a certain extent conduct functions of any other element, based on the emerging situation.

To ensure convenience of further representation we introduce the generalized set of interacting objects (IO) $B = \left\{B_l, l, i, j \in M = \tilde{N} \cup \tilde{M} = \{1,\dots,m\}\right\}$. Let us also review a set of operations for interaction (OI) $D^{(i)} = \left\{D_\gamma^{(\mathrm{i})}, \gamma \in \Phi\right\}, \Phi = \{1,\dots,s_i\}$.

All considered, at the informative level the task on scheduling of CPS functioning for implementing MCO (which are a subset of OI) can be formulated as follows: it is required to find such an admissible control programme for information-computational operations and CPS (their functioning scheduling), so that within its implementation all the operations, that are a part of relevant technological cycles of SO control, would be conducted timely and in the full scale, and the quality of informational support to the SO would meet all the specified requirements. At the same time, if there are several admissible programmes for CPS control received, it is required to select the best possible (appropriate) programme (comprehensive plan) based on the accepted optimality criterion [10, 11].

3. Dynamic models for CPS fucntioning scheduling

Formalization of the scheduling task, as it was described in the introduction, will be implemented, applying the dynamic interpretation of the process on technical operations realization, suggested by the authors. Based on the problem description of CPS scheduling, let us introduce the following models for programme control.

The dynamic model for programme control of interaction operations (including the computing operations) in CPS (model M_o).

$$\begin{aligned} M_o = \Bigg\{ \mathbf{u}^{(o)}(t) \mid \dot{x}_{i\gamma}^{(o)} = \sum_{j=1}^{m} \varepsilon_{ij}(t) \cdot u_{i\gamma\mathrm{j}}^{(o)};\ x_{i\gamma}^{(o)}(t_0) = 0; \\ x_{i\gamma}^{(o)}(t_f) = a_{i\gamma}^{(o)}; \sum_{i=1}^{m} \sum_{\gamma=1}^{s_i} u_{i\gamma\mathrm{j}}^{(o)} \le c_j^{(o,1)}; \\ \sum_{j=1}^{m} \sum_{\gamma=1}^{s_j} u_{i\gamma\mathrm{j}}^{(o)} \le c_i^{(o,2)}; u_{i\gamma\mathrm{j}}^{(o)}(t) \in \{0,1\}; \\ u_{i\gamma\mathrm{j}}^{(o)} \left[\sum_{\tilde{\alpha} \in \Gamma_{i\gamma 1}} (a_{i\tilde{\alpha}}^{(o)} - x_{i\tilde{\alpha}}^{(o)}) + \prod_{\tilde{\beta} \in \Gamma_{i\gamma 2}} (a_{i\tilde{\beta}}^{(o)} - x_{i\tilde{\beta}}^{(o)}) \right] = 0; \\ i, j = 1,\dots,m; i \ne j; \gamma = 1,\dots,s_i \Bigg\}, \end{aligned} \tag{1}$$

with $x_{i\gamma}^{(o)}$ — the variable, characterizing the state of IO implementation ($D_\gamma^{(i)}, D_{\tilde{\alpha}}^{(i)}, D_{\tilde{\beta}}^{(i)}$); $a_\gamma^{(o)}, a_{i\tilde{\alpha}}^{(o)}, a_{i\tilde{\beta}}^{(o)}$ — the specified volumes of operations implementation; $u_{i\gamma j}^{(o)}(t)$ — control action; $u_{i\gamma j}^{(o)}(t) = 1$, if operation $D_\gamma^{(i)}$ is implemented, and in the opposite case $u_{i\gamma j}^{(o)}(t) = 0$; $\Gamma_{i\gamma 1}, \Gamma_{i\gamma 2}$ — a set of numbers of interaction operations, conducted with object B_i, immediately preceding and technologically related to operation $D_{\gamma}^{(i)}$ applying logic operations «AND», «OR» respectively; $c_j^{(o,1)}, c_i^{(o,2)}$ — are defined constants, characterizing the hardware restrictions, related to CPS functioning in general; $\varepsilon_{ij}(t)$ — the known matrix time function, whereby the spatitemporal restrictions are set, related to interaction of objects B_i (or $\bar{B}_k$) with B_j, this function receives the value 1, if B_i gets into the defined zone of interaction B_j; 0 — in the opposite case.

The dynamic model for controlling interaction operations (including computation operations) in CPS (model M_e).

$$\begin{gathered} M_e = \Big\{ \mathbf{u}^{(e)}(t) \mid \dot{\mathbf{x}}_i^{(g)} = F_i(t)\mathbf{x}_i^{(g)}; \\ y_j^{(i)}(t) = \mathbf{d}_j^{\mathrm{T}}(t)\mathbf{x}_i^{(g)} + \xi_j^{(e)}; \\ \dot{Z}_i = -Z_i F_i - F_i^{\mathrm{T}} Z_i - \sum_{j=1}^{m} \sum_{\tilde{\gamma}\in\Gamma_i} u_{i\tilde{\gamma} j}^{(e)} \frac{\mathbf{d}_j \mathbf{d}_j^{\mathrm{T}}}{\sigma_j^2}; \\ i \neq j; i, j \in \tilde{M}; 0 \leq u_{i\tilde{\gamma} j}^{(e)} \leq c_{j\tilde{\gamma}}^{(e)} u_{i\gamma j}^{(o)} \Big\}, \end{gathered} \tag{2}$$

with $\mathbf{x}_i^{(g)}$ — state vector of OS B_i; $F_i(t)$ — is the specified matrix, characterizing the dynamic of variable change (computed parameters), describing OS state (i.e., their spatial position or aircraft systems state§); $\xi_j^{(e)}$ — uncorrelated errors of SO parameters measurements, that are conducted by CPS technical means B_j; it is supposed that measurement errors comply with the normal distributive law with zero mathematical expectation and dispersion equal to σ_j^2; $D_{\tilde{\gamma}}^{(i)} \in D^{(i)}$; $u_{i\tilde{\gamma} j}^{(e)}(t)$ — control action, defining intensity of SO measuring parameters $y_j^{(i)}(t)$ (i.e. distance to SO, temperature and humidity aboard SO), that are conducted in the remote mode with technical means of CPS B_j; $c_{i\tilde{\gamma}}^{(e)}$ — specified values, characterizing technological capabilities of means B_j while implementing operation $D_{\tilde{\gamma}}^{(i)}$; Z_i — matrix, reciprocal to correlation matrix $K_i(t)$ of errors in evaluating state vector OS B_i; Γ_i — a set of interaction operations, conducted by CPS with OS B_i; $\mathbf{d}_j(t)$ — given vector, that defines specifications of measuring tool equation technical implementation of CPS B_j; K_{i0} — value K_i at the start time $t = t_0$; $\sigma_{\gamma i}^2$ — specified determination accuracy χ-й of the state vector component $\mathbf{x}_i^{(g)}(t)$ OS. The major difference of the model (2) from the ones previously proposed is that the operations on CPS state parameters measurement, through restrictions over control actions $u_{i\tilde{\gamma} j}^{(e)}$, are directly connected to MCO, implemented by CPS, specified in the model M_o. This allows to research the task on scheduling MCO procedures of data collecting, transmitting and processing, and the tasks on scheduling measurements of the controlled objects parameters from unified system positions.

Quality evaluation of CPS MCO programme control processes (or, in other words, quality of MCO operational scheduling) can be conducted using various objective functions. Let us introduce some of them:

$$J_1^{(o)} = \frac{1}{2} \sum_{i=1}^{m} \sum_{\gamma=1}^{s_i} \{[a_{i\gamma}^{(o)} - x_{i\gamma}^{(o)}(t_f)]^2 + \sum_{j=1}^{m} \int_{t_0}^{t_f} \eta_{i\gamma}(\tau) u_{i\gamma j}^{(o)}(\tau) d\tau\}, i \neq j; \tag{3}$$

$$J_2^{(e)} = \vec{b}_{\gamma}^{T} K_i(t_f) \vec{b}_{\gamma}; \tag{4}$$

$$J_3^{(e)} = \sum_{i=1}^{m} \sum_{j=1}^{m} \sum_{\tilde{\gamma}\in D^{(i)}} \int_{t_0}^{t_f} u_{i\tilde{\gamma} j}^{(e)}(\tau) d\tau, j \neq i, \tag{5}$$

with $\eta_{i\gamma}(\tau)$ — known monotone functions of time, that are selected taking into consideration the given scheduled time frames of the start (finish) of implementing OS of MCO with CPS B_i. The indicator (3) is introduced in case it is necessary to evaluate depth of boundary conditions fulfillment, as well as the value of total fine for not implementing the operations specified scheduled time frames. For OS, where we consider instrumental complexes, aimed at solving tasks on monitoring specified environmental objects (SEO) state, the operations, related to evaluation of their position, that therefore allow to define SEO position, have the special significance. Thereby the value of quality indicator (4) characterizes the determination accuracy of χ –й component of vector $x_i^{(g)}$ ($\vec{b}_{\chi} = \|0 0 ... 1 ... 0 0\|^T$ — specified intermediate vector, which defines the required element with number χ in the correlation matrix $K_i(t)$). Objective function of type (5) allows to provide quantitative evaluation for CPS resources consumption while implementing operations $D_{\tilde{\gamma}}^{(i)}$, related to OS state changes.

Further, let us provide formal problem statement on scheduling MCO, implemented by CPS. It is required to find such admissible control, that answers the required limitations and transfers the dynamic system from the specified initial state into the specified final state. In case there are several such control actions (complex plans), it is required to select the best possible (optimal) among them, ensuring that components of the generalized vector take extreme values.

Previously the works [12,13] demonstrated, how it is possible to narrow down the task on scheduling operations and distributing resources in complex technical objects to two-point boundary value problem, applying Boltyansky's method of local sections. In this case the task on MCO scheduling is formulated as task on searching for optimal programme control, that ensures required determination accuracy of CPS and OS position within minimum time frames (or with minimum power consumption from MCO implementation) [14]. Traditionally, the tasks of this class (tasks of scheduling theory) are solved applying the method of mathematical programming [5,11,15]. The suggested usage of methods for theory of optimal control in order to solve tasks of the scheduling theory allows to improve the quality of scheduling results (including increase of efficiency on plans development, reduction in energy consumption within its implementation, etc.) [5, 16].

4. Results analysis on solving scheduling of measuring and computing operations in CPS

The search for a MCO complex plan is implemented in two stages. At the first stage in order to initialize the generalized procedure for measuring and computing operations optimization there was an admissible heuristic plan synthesized. In order to implement it the well-known FIFO algorithm ("first in, first out") was used. At the second stage the multi-step procedure for solving the two-point boundary value problem was conducted, to which the initial nonclassical task on calculus of variations was narrowed. The results of two stages implementation are shown in Fig. 1.

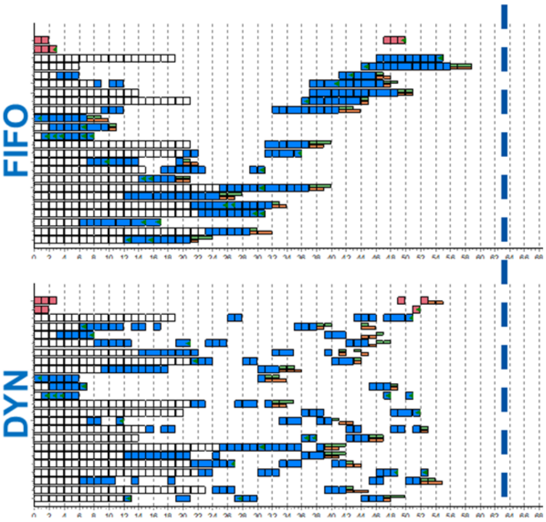

Figure 1: The results on heuristic and optimal scheduling of MCO, implemented by CPS

Application of this approach allows to reduce the amount of unprocessed informational flows by 20%; eliminate unbalanced resources consumption; reduce interruptions of scheduled time in operation implementation by 17%; increase the generalized quality indicator by 19%.

Moreover, additional researches of processes on implementing measuring operations, related to evaluation of various factors influence on the mentioned factors, were held. The graphs (Fig. 2, Fig. 3) show, that for each OS with a new interaction session with CPS the accuracy of measurement of its position parameters increases.

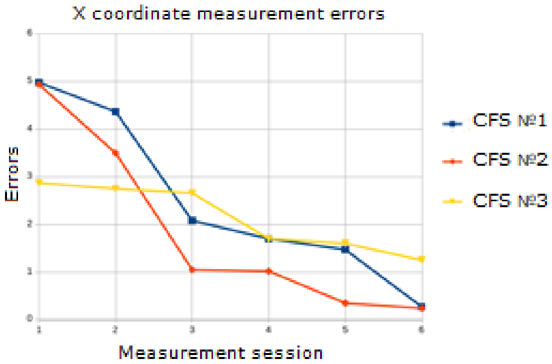

Figure 2: The graph of coordinate measurement errors change, depending on the service session for various OS

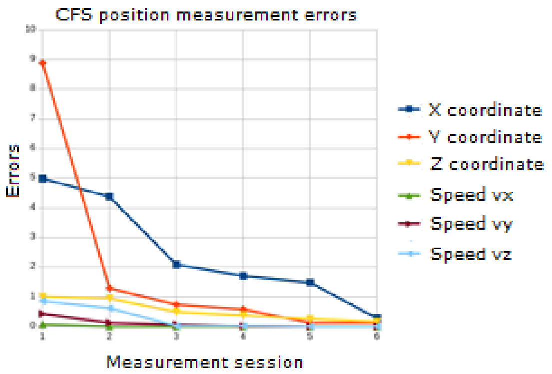

Figure 3: The graphs for coordinate measuring errors change, depending on the interaction session for a selected OS

In order to evaluate the influence of changing various parameters on measurement accuracy 2 groups of experiments were conducted, within which the coefficients, that are referred to errors cross-correlation matrix and measuring instrument dispersion were changed.

In the first group experiments were sequentially held with changing coefficients, included into correlation errors matrix. In each of the experiments the coefficients of errors correlations were sequentially reduced over all parameters. The experiments results are shown in Fig. 4.

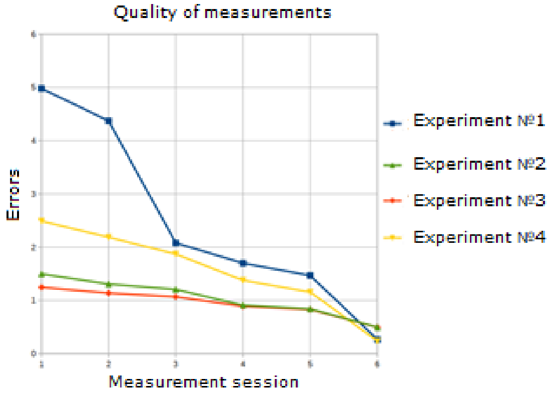

Figure 4: Graphs of coordinate measurement errors change, depending on the interaction session for a selected OS

The graph (Fig. 4.) shows, that reduction of coefficients in the errors correlation matrix leads to improvements in the measurement quality.

The results show, that after optimization process the gained amount of measuring information is received within shorter period of time. It should be also mentioned that, provided there are the largest values in the correlation matrix of measuring tool errors, the largest improvement in measuring quality is observed as a result of optimization.

Within the second group of experiments the parameters of measuring tool disperison were sequentially reduced by half (Fig. 4). The graph shows that the influence of measuring tool dispersion parameters in a lesser extent affects the results of measurements optimization.

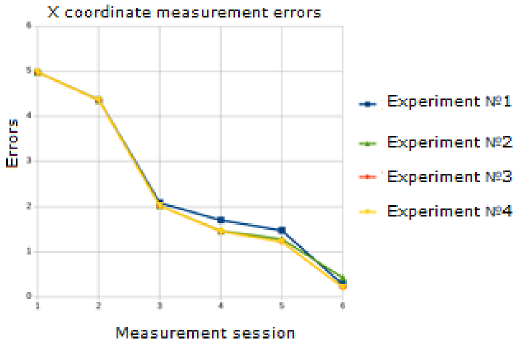

Figure 5: Graph of the conducted experiments results with change in CPS measuring tool dispersion parameters

In all the conducted experiments identical consistency of measurement quality improvement with each new session of OS interaction with CPS is observed.

5. Conclusion

The article provides a polymodel description and results of solving task on planning MCO of CPS. The main features and differences between the suggested models are that within dynamic interpretation of MCO, included into CPS technological cycle, processes implementation, the dimension of the solved scheduling tasks and strength of association in scheduling algorithm are notably reduced. This dimension is defined within solving scheduling task at each time point by a number of independent tracks in the general network graph, implemented by CPS, by current spatiotemporal, technical, technological restrictions.

The studies on the developed models features and characteristics showed, that by means of CPS operation rational (optimal) scheduling, firstly, the general capacity of CPS increases and, secondly, CPS resource consumption for MCO implementation reduces, and as well time lags in CPS control paths reduce, thirdly, there is a reduction of peak informational loads within sudden changes of CPS structure. Moreover, based on dynamic description of CPS functioning processes, it is possible to explicitly connect its elements and subsystems control technology with results of target application of instrument complexes, implementing data on SEO reception, processing and analysis, as well as with characteristics of CPS hardware and software complexes. MCO complex scheduling offers interesting prospects on forming justified requirements to CPS characteristics. In [17] information is provided about multiple ways to apply the suggested approach in practice in order to solve tasks of scheduling theory, emerging in various subject fields (space technology, shipbuilding, state administration, etc.).

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