Cyber-physical systems matrix control model

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Abstract. The Industry 4.0 technologies oriented for the modern industry as an application to solve the cyber-physical production control general task are viewed. A task to control is positioned as a hierarchy, which require some special schemes cyber-physical systems interaction organization to be developed. The control task hierarchy is converted to the control means hierarchy, within which they preserve the cyber-physical systems groups coordination unity organized in the company functional divisions in structure principle with variable equipment consistency. Information and functional cyber-physical systems interconnection are proposed to be defined within the technical architecture providing cyber-physical production complex automatizing. In the control system they underline the information component realizing not only calculation functions measuring but also net communication. Controlling and being controlled cyber-physical systems are proposed to be united into structures actively interacting with functional company divisions into closed automatic loops working out information and signal actions. There is a cyber-physical production hierarchy structure example given based on control processes tides formalized in physical and virtual levels. There is a cyber-physical systems matrix control model given to coordinate calculations, communications and industrial automatics functionality.

1. Introduction

Cyber-physical systems (CPSs) control methodology is one of the most important cyber-physical production (CPP) technological component to define rules, which must be observed during the item manufacturing procedures. The CPP control function automatizing including industrial object functionality logics are based on balanced indications control system characterizing in different levels the CPS behavior dynamics hierarchy responsible for particular sets of technological operations [1, 2]. The stages sequence containing ways to solve the great technological task by its decomposition and solving in groups the private tasks of lower complexity (enclosed works) forms a formalized chain of elementary control processes as a combination of regulating mechanisms of all company CPSs interaction [3, 4].

Intercrossing of technological information and measuring and controlling CPS components providing functionality of industrial object closed infrastructure, which is for automatic completion and
control of CPP processes, which are repeated several times without human participation (cyclic) [5, 6]. Oriented for metrics is the central CPS property, which let define each processes limits in the CPP structure separating one material parts tide from another (item) to control them locally. The processes limitation within a CPS and processes unification within a production workshop reflects a multifunctional character of the hierarchy structures control methodology completing the item manufacturing with separate CPSs integrated systems resources, which regulate in parallel the CPS groups functionality placed in a higher hierarchy level [7, 8].

The CPS control processes maximum approximation to the item manufacturing real technological processes is done with information technologies connecting with an Internet of Things (IoT) separate CPSs and their groups into organized formed hierarchy structures (CPS section, a production workshop or a division), within which some subordination relations are established [9]. A set of CPS roles (control subject or control object) are defined individually for each technological equipment unit and is concrete with the control function type expressed mathematically. The control technologies using mathematical (digital) models of infrastructure objects and CPP processes in a CPS relations formalized system provide the automatic regulation of conveyor work tides being done with CPS different hierarchy level [10, 11].

The item manufacturing processes quality control in the CPP hierarchy structures combines CPS control in information and signal (physical) actions, which are done within [12, 13]:

- the physical control loop with measurement and evaluation results of parts technological parameters (the first process CPS output);
- the virtual control loop with model experiments results of CPS digital twin simulation (the second process CPS output).

To combine heterogeneous actions types to control loops is reflected in the matrix scheme model how to unite CPSs into controllable hierarchy structures. The CPP material item tide is controlled in a CPS with equipment belonging property to a structural subdivision. Information tides are controlled in a CPS with equipment digital twin placement property in the system of edge, fog or cloud computing [14, 15].

The CPS control technologies focal point is concentrated on procedures of process dynamic stabilizing being regulated to support the necessary quality of the item being manufactured. The CPS control technology development and their subsequent automatizing is a base of system projection for functionally finished and stable robotized divisions, which could be addressed to complete one or several technological tasks. The CPP concept realized in physical level with a CPS technological workshop and in logical level of being controlled information and material tides, which is the base of the Industry 4.0 ideology providing continuous quality increase through an automatic regulation of its manufacturing quality process [16, 17].

2. The CPS hierarchy structure matrix control
The multilayer functional hierarchy grouping CPSs in controllable structures with technological belongings properties is an element of CPP automatizing, which basically differs the Industry 4.0 from the company equipped with traditional automatic systems. The CPS different sub-processes control is done within the item manufacturing general technological process, which is acted with some determined and random factors. The autonomous CPSs control chains concord in the level of private sub-tasks and CPP control target in the level of general task is done in the hierarchy architecture «pyramid» providing non-conflict technological equipment interaction based on CPS prioritized access realization to the general and computing resources.

CPS priorities being set directly in the item manufacturing process are set according to the accepted hierarchy system control criteria and are used to solve the logical power-up task and CPS functionality and stopping being controlled with the company physical and virtual environments regulators. To work-out and realize the controlling actions they apply different forms of physical objects and processes.
mathematical description, which unanimously corresponds the CPP tools and technical rules. The data exchange among virtual models (data processing centers) and CPS devices (technological subjects and control objects) provide manufacturing dynamic processes synchronizing and create potential possibility to regulate CPP structures optimally in the hierarchy co-subordination.

CPS subdivisions control organization each activity of which is directed to complete technologically limited subtasks requires CPP infrastructure special elements implementation to coordinate connections and CPS relation systems without any quality damage of the item being manufactured. Technological processes and being regulated parameters values control accompanying, which depends on information and signal actions are done to the three types of control:

- separate CPS automatic components control and their functional groups united into CPP technological lines (conveyors) and supporting mechanized continuous tides item movement processes in the manufacturing route distributed in several parallel branches;
- computing control done in isolated CPS integrated systems controllers and in territory distributed fog and cloud servers analyzing technological and information states of CPP infrastructure objects congregation;
- communications control directly providing the necessary CPS data exchange for parallel completion of several technological tasks stages, which require to transmit information and material tides from one process executor to another.

CPP organizing, which technological sections structure is changed with direct and concord among each other actions applied to regulator, calculation and net CPS components, which is typical for the Industry 4.0 objects projection and the adaptive type control hierarchy system ideology is based on a matrix scheme of CPSs interconnection shown in figure 1. The CPS interconnection matrix scheme supports a dependent control systems congregation functionality, which are bound physically and informationally and considering inter-channel controllable correlations of CPP parameters being regulated and controlled within given edges of technological processes. The formation of individual controlling actions for each CPS and general one is done through a commutator system uniting CPSs in time basis into closed automatic loops with feedback specialized to solve concrete technological tasks.

![Figure 1. The CPS model interconnection matrix scheme based on the single control principle, computing and communication.](image)

3. The CPS matrix control practical realization
In figure 2 there is an example of a CPP hierarchy given based on control processes tides formalized in physical and virtual levels. Several CPSs and their groups participate the structure, within which CPS are delegated to have controlling (control subject) or subordinate (control object) functions (roles). The structure contains different from each other CPS groups interconnection forming together a closed loop of the CPP automatic control system.

CPS control parameters modification is based on complimentary information and signal actions
principle eliminating deviations appeared in physical and virtual automatics loops. The CPP structure control is done cyclically with CPS processes correction, which is done parametrically. The technological operations sequence and their completion states is set with CPS interaction logic following the general target task of item manufacturing.

Control points fixing data necessary to correct the processes are defined as output chains of physical and virtual loops. Feedback information chain provides transmission in the CPS physical loop the technological processes modelling results reflecting item quality approximated to the ideal one. The feedback signal chain provides the transmission in the CPS virtual loop of the physical measuring results characterizing current quality of the item being manufactured.

The CPS virtual loop contains CPS models (digital twins) and mathematical control functions transforming input processes data into output information tide resources of the modelling environment. The virtual loop defines a reference model (reference process model) simulating with edge computing means and acting the being done in a CPS technological works quality.

![Diagram of CPP hierarchy structure](image)

**Figure 2.** The CPP hierarchy structure based on control processes tides formalized in physical and virtual levels (VL – virtual loop, PL – physical loop, CS – control subject, CO – control object, EC – edge computing, FC – fog computing, CC – cloud computing).

The CPS physical loop contains structural sections of automatics elements completing a sequence of technological processes operations, which constantly repeat with a given scheme. Control signals transmission among process executors context-ly leads to compensate the deviations of being controlled parameters from predetermined values established in a virtual loop.

The CPP control system multiple structure integrating several technological sections systematizes
the current CPS different hierarchy levels hardly related to each other processes and translate the physical measurements results in the fog computing models (cloud). The ways to transmit information and signal actions are defined with the IoT net architecture of an industrial object and let interact directly for enclosed hierarchy automatics loops.

The CPS intersystem relations are based on the control functions congregation for which the virtual environment defines a mathematical connection in the level of input data and output variables characterizing physical and information processes. The control physical loop input parameters are defined with material tides initiating technological processes. The physical control loop output parameters represent the materialized results of CPS structure functionality. The CPS virtual loop input parameters are given with technological processes digital twins. The virtual CPS loop output parameters are results of the process being done model calculation.

4. Conclusion
CPP is a combination of distributed in space groups forming multilevel subject hierarchy and control objects engaged into technological operations during the completion of which they support active net data exchange among processes executors. This is used to analyze the technological equipment state and to synthesize actions being output in control objects. The data transmission laws into controlling actions depend on the being regulated CPSs class and incoming (out-coming) material and information tides specifics circulating among the CPP hierarchy levels.

Parameters characterizing technological procedures completion and the process in general is a quantity indication of CPS functional activity and using in the matrix control model for operation correction of information and signal actions providing joint work and a set of the CPP automatizing means regulation. The matrix control model net specifics and triple subjugation of CPS into equipment working groups, which justifies the CPP infrastructure implementation necessity for the combined connection devices, which perform coordination of information tides for the edge computing functions.

The CPS program control is done with short and long cycles providing technological processes initiation, complete or partial task completion, operation procedure control and other types of equipment functional activity considering the CPS specifics and limits of parameters being regulated. The CPS technological tasks hierarchy systemized in a matrix control model reflects the CPP hierarchy structure with horizontal or vertical resources scaling. Technological processes being united in a dynamic net create the necessary states for additional CPS hierarchy (temporal) inside a fixed functional division (workshop) supporting rare or narrow specialty manufacturing operations.

The CPP hierarchy structure intensive dynamics makes it actual how to synthesize controlling organ (central regulator), which is to control simultaneously all technological processes and equipment being viewed as a single distributed control object. The structure complexity possible conflict of such a control object and regulator abilities of central controlling organ is a subject of the automatic control theory research added to the Industry 4.0 technological tasks.

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