Control, computing and communication in industrial cyber-physical systems with feedback

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Abstract. The cyber-physical production base technologies are control, computing and connection being applied altogether in the industrial object technological processes automatic regulation systems. They use control technologies in multi-loops and multi-channel regulation systems forming a hierarchy structure. Automatics functional elements unite in the intermediary regulation scheme stabilizing hierarchy control objects, which states are detected with sensors. Computing technologies are used in the cyber-physical production imitation virtual environment and provide processes simulation based on control models and cyber-physical systems digital twins structured in hierarchy levels. The regulation accuracy increase is provided with physical and model processes results comparison detecting non-definition factors acting production processes accuracy. The communication technology is used for the cyber-physical systems net information exchange given with the Internet of Things parameters. The cyber-physical systems continuous work in the non-ideal communication net regulation interval is provided with preventive control signals compensating operation and information delay of automatic conveyor lines. There is a scheme given of multi-loop and multi-channel automatic cyber-physical production using control objects hierarchy based on cyber-physical systems hierarchy and item manufacturing technological tasks.

1. Introduction

To synthesize industrial automatics systems to regulate the cyber-physical production (CPP) technological processes is united in a single technical specifications cyber-physical systems (CPSs) and control system optimization design task, which completes the functionality within given industrial object efficient functioning parameters [1, 2]. The CPP optimization criterion, which actions the CPS control way is the cost of end product (being manufactured) to be minimized. As the optimization procedure disciplining states when the control system is being projected studies mathematical equations and non-equations restricting technical and economic indications of the CPP activity [3]. Such CPP technological systems efficiency includes information, measuring and controlling automatic loops and is significantly defined with the item manufacturing automatizing process level and the data processing calculation means productivity in the modelling environment [4, 5].

The industrial automatics elements design ideology base is a multi-loops and multi-channel control system to coordinate the CPP functioning, information and time components functionality. In the
Industry 4.0 paradigm the CPP is viewed as a constantly developing (evolution-ing) technological system with dynamic processes, which must be physically and virtually controlled [6, 7]. The physical loop provides control of the vector of controlled variables of the CPS and CPP, the virtual control loop adjusts the processes [8]. The CPP control loops structure large diversity with cyclical changes in process corrections are designed on the typical automatics elements, which functions are in concord with the industrial object technological task in the level of private computing, measuring, controlling operations and net data exchange operations [9, 10].

To keep the CPP control requirements in technical and economic being manufactured items indications is done with analytical model means realized in a virtual environment. The CPP analytical models are a way to describe the typical automatic elements materialized in the physical environment with closed control systems loops sections [11, 12]. The operational communication of the CPS with the control system of the virtual environment and the operational transmission of estimates of the current state of the objects of the machine environment to the CPP physical environment are implemented by wireless data transmission technologies based on the industrial Internet of Things (IoT) [13, 14].

The CPS technological parameters evaluations must be controlled, which characterize the high frequency data properties changes and general CPP parameters with a low frequency property data updating [15]. The cross connections among the automatics loops are justified with the CPP phase variables dependencies, which is processed in the virtual environment providing the industrial object robustness and control-ability with discrete regulations through net mechanisms [16, 17]. The virtual environment control algorithms use different schemes of the CPP parameters optimal stochastic evaluation within its permissible values range. The virtual environment CPP computing task controls the control system processing units processing technological data net tides. The CPP automatics design task is a multi-factor one and could be solved with control principles, parallel computing and wireless connection methods [18].

2. The CPP automatics elements

The CPP automatic control system is designed with feedback principles and consists of base elements unification united in a closed loop [19, 20]:

- the control object, which depends on the digital company hierarchy structure level and could be a CPS, a production section or the technological division in general;
- measuring (sensitive) automatics elements includes the CPS integrated combination of industrial information detectors and detectors distributed within the company technological environment;
- the values being registered analogue and digital filtering elements, their mathematical pre-processing and parameters values statistic evaluation, which are relevant for the industrial object technological task;
- comparison elements generating dissonance signals among the desired and fact (being monitored) control object states vector values in the CPP structure hierarchy corresponding level;
- regulator (controller device) completes mathematical (software and algorithm) dissonance signals vector transformation into a desired control signals vector with the CPS processing core resources;
- the CPS executive mechanisms elements, which make the direct action on the control object with control organs tools.

Comparison elements, automatic sensitive elements and pre-processing and technological environment evaluation parameters elements form information and measurement channel in the CPP automatic control system. Executive mechanisms elements connected to the regulator and completing its control commands, which together forms information and controlling CPP automatics channel.
3. The CPP automatics multi-loop and multi-channel model

The CPP automatic control system constructed in hierarchy structure is a dependent automatics system where the technological environment parameters values in different hierarchy have a reciprocal action. Information and control automatics channel forms a set of rules necessary to solve the CPP given technological task expressed with control signals acting the CPS elements. The information and measuring automatics channel defines the technological environment parameter evaluations, which corresponds the control object current state. The CPP control closed automatic system multi-loop and multi-channel scheme is given in figure 1.

![Figure 1. The CPP control closed automatic system multi-loop and multi-channel scheme.](image)

The scheme base how to construct a closed automatic system is the loops hierarchy principle, which is adequate to the topology tasks hierarchy being solved by CPS elements (groups) being regulated with information models and logical control laws. The number of hierarchy levels in the CPP structure is defined with control objects hierarchy with common horizontal and vertical connections. The CPS horizontal connections system is an automatic loop being controlled in the production section level. The CPS vertical connections system is an automatic loop, which control object is the technological division in general resettable according to the evaluation vector values of the horizontal hierarchy level CPS current state.
The parameter regulation in vertical and horizontal CPP structure hierarchy levels use the common laws and typical elements based on the control with feedback of the automatics closed loops. The multi-channel and multi-loops CPP automatic model unites physical elements of technological CPSs and digital CPS twins logical elements, which in parallel calculate control signals. The automatic loops enclosure informatively dependent on communication channels provides the increased control accuracy and stability reserve for objects placed in a higher hierarchy level.

The CPP control system hierarchy depth depends on the CPS functional capabilities and the accepted ways of computing centralizing (de-centralizing) and ways to decompose technological tasks. The hierarchy structure includes simultaneously separate CPS elements and their groups as the computing net terminal units formed in a production section. The CPS groups hierarchy order in the CPP structure is reflected with private control laws interconnection being realized with technological CPSs and general laws, which are true for the industrial object physical environment. The hierarchy structure schemes interconnection is a consequence of directed action property, which are normal for automatics dynamics sections.

4. The CPP automatic control
The CPP automatic system, which functions in all hierarchy level in modes, which are quite approximated to the real time dynamic properties depend on the CPS control quality indications and industrial object organization structural features. The technological division necessary functioning equipped with a CPS connected to the information and computing net of the IoT can be reached through:

- CPS groups horizontal integration into separated hierarchy control levels within each of which among separate CPSs (technological processes executors) direct and indirect (detour) feedback channels are implemented and for the item being manufactured they implemented conveyor delivery routes (assembly units, materials, components and other);
- CPS groups vertical integration into regulation loops being enclosed in each other and forming a CPP automatic control system, which integrity is supported with an information exchange providing the equipment for crossing and higher levels of technological data hierarchy.

Interpenetration of different automatics hierarchy loops and in combination with the automatics control function decomposition and calculations in technological subtasks given to a CPS and net infrastructure components, which let significantly improve the product quality control, which manufacturing is done within a hierarchy level or as a result inter-level CPS interaction. An additional reserve to increase technological result-ness of industrial object connected to some CPS units production potency improvement equipped with intellectual automatics control, computing and communication systems.

Approximation of the technological data processing calculation means to their sources (control objects) and consumers (control subjects) creates the states to control the CPP processes based on optimal criteria acting within the restrictions of physical and mathematical systems. Optimal control criteria to be maximized (minimized) in the scales of entire CPP are: CPS productivity in the forced working mode; parameters reproduction accuracy during a serial item being manufactured; components and materials consumption being used in technological processes; the self-cost of the product automatic manufacturing and other.

5. The CPP control closed loop computing
The CPP computing division is a congregation of server equipment completing mathematical calculations in fog or cloud environment and CPS peripheral devices equipped with processing elements and software components. Functions solved by the CPP computing division are defined with the item manufacturing technological tasks and communication net processing units components and CPSs interconnection type. In the industrial object the computing division processes measuring data and forms control signals necessary for the product automatic manufacturing with CPS resources corresponding to
the electronic documentation in the quality and technical and economic indications (digital twins). Also the computing division has the control tasks of CPS correct state and CPP transition provision to the reserve technological schemes and assembly units movement routes if some equipment fails.

The computing division functionality features specific for CPP technological tasks and considering the CPS algorithm structures (program codes) are:

- parallel functioning of distributed calculators presented in the class of office equipment (server) and of industrial design in the modes, which maximum-ly approximated to the real time;
- controlling programs with optimization algorithms completion containing cycles of double calculations (triple) of the most critical technological tasks (the being regulated calculation parameters accuracy);
- non-structured technological data processing containing information redundancy justified with partial measurement duplication being provided with the CPS devices in different levels of the calculator net hierarchy;
- the CPS physical devices synchronous control with items being manufactured material tides and technological data information tides realized through a net with operation systems being configured for CPS components options and CPP tasks;
- the calculation process decentralized control uniting in a single combination several different types of scheme solutions in tiers and parallel forms for the net commutation of the cloud environment processes (fog) and autonomous CPS processes (edge);
- multi-processor calculations in the CPP hierarchy structure supports multi-time program codes completion in the closed and rapid (in fog or cloud environment) and super rapid (in an integrated CPS system) cycles technological tasks;
- the calculation net resulting topology and conveyor material tides movement trajectory forming depending on the calculation tasks completion time, the equipment chains reliability indications, CPS operation productivity and other.

To integrate computing divisions into CPP reciprocal dynamic chains control loops is justified special requirements how to organize amendments calculation procedure correcting technological processes. The most perspective approach how to achieve the maximum realizing productivity is to create controlling programs with cyclic calculation processes being completed with private CPS processing elements and which has different discretion periods. For such computing divisions it is actual a frequent method to divide periodical calculation processes, which are done in parallel and asynchronous-ly in the CPP information system (virtual).

6. The CPP control system communication

The CPP communication system includes the coding rules of controlling messages and traffic discipline exchange providing connection to the net of different types CPS physical devices participating in the item manufacturing. The IoT channel is a direct control data transmission channel regulating processes and synchronizing the equipment. Computing and control technologies united with communication means in the CPP hierarchy structure is viewed as machine and non-machine CPS component, which exploitation properties may create the general industrial automatics closed loops.

The CPP control theory position is of dynamic systems category (industrial objects), which has some delay in control channel and in operation channel. The controlling parameters delay is defined with the IoT communication net properties. Operation delay, which is true for the material tides justified with end (non-zero) conveyor parts transportation time (assembly units) among technological CPSs interconnected with a transport CPS.

The process presence of several types CPS interaction in simultaneous delay requires to calculate preventive control signals considering different types CPSs connection scheme into a technological chain, which realize a regulation way of CPP operations and each CPS initialization states. The preventive control accompanies all CPS functionality in the modes from its initialization to stop when
technological process completion is over and is calculated from the CPS position in the functional conveyor elements chain.

The preventive control signals participate in the conveyor line regulation settings and each product transporter individual settings and a technological CPS. The control is done with given in the software algorithm and provides the primary start and CPS braking and movement synchronizing with given product speed being transported with a manipulator among stationary placed CPSs. The path automatics control system in starting and stop operations interval is done with a prevention of necessary CPSs switch-off sequence, which is the reverse order of the parts movement in the workshop. The acceleration of tide and transport CPP system is closed with the CPS closed conveyor the parts movement process stop in delivery routes is initiated from the head CPS. Intervals among parts taking-out operations (taking-in) within a CPS conveyor line participates in the CPP operation delay time. New tasks are accepted with a CPS when the technological equipment part releasing is done, which were manufactured before.

The control channel delay action given with the IoT parameters justified with non-prognosticated effects making data «aging» and net traffic transmission conflict until some information packages are lost. The communication environment properties non-ideality consideration (in volume in channel passing through ability, in data transmission time and other) is done in the CPS software codes individual settings considering in the control parameters regulation algorithm as the containing functions of several net information packages.

7. Conclusion
The multi-loop and multi-channel CPP control system is a combination of CPS dynamic sections united in automatics functional elements considering constructive, physical and information industrial object features. The CPP environment control process is based on CPS states measurements (evaluations) manufacturing the product under the states of technically originated nature random disturbances and target directed regulating actions being defined in the computing division. To organize the CPS interaction based on the hierarchy control system unlike other approaches to coordinate the technological equipment actions may simultaneously regulate the states of all CPP objects in general (single) principles based on industrial automatics laws.

The CPP automatic system functions built with a closed-loop scheme and uniting transformers and detectors (measuring devices), regulators and executive mechanisms control organs acting the technological processes are the following:

- measuring providing a loop to control the numeric indications vector, which together characterize the objects being regulated technical states and technological processes accompanying quality being done in a CPS;
- information providing technological data systematic processing within CPP processes being analyzed sufficient to calculate the CPS regulators parameters corresponding the control object current characteristics;
- controlling providing automatic support the CPS given functionality modes with a target changing of values being regulated or by technological processes indications stabilization, which together action the item being manufactured quality.

Information processes from the CPP control systems are sewn with the CPS technological functions algorithms and CPS parameters regulation algorithms, which in parallel is completed in the computing division of multi-measure (multi-communication) industrial object. The automatics elements machine components acting the production processes indications and item quality is defined with general law dependencies, which are typical for the technological CPSs functionality (engineer) and control systems. The CPP quality control is done with the comparing of physical and model (calculation) CPS functionality results, which may identify the factors of non-definition acting the technological processes and not being considered in the regulation algorithms.
The controlling variables holding within the given values and their change with a given law in the CPP hierarchy structure is provided with automatics interacting elements, which serve as intermediary regulators. The control hierarchy object functionality modes stabilizing united in a multi-terminal communication net based on an adaptation mechanism engaging continuous detecting of CPP technological environment with sensors.

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