Emergency control of cyber-physical systems in the technological environment

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Abstract. The task how to increase the industrial object crucial infrastructure reliability and safety is being studied formed with cyber-physical systems. To solve this task they represent a cyber-physical production as a complicated dynamic systems with tide and continuous conveyor cycles, which behavior is under control in the state parameters space. The cyber-physical systems actions of the inner technological environment factors and cyber-physical production external factors must be analyzed to study single and systematic actions of chaos creating character in equipment, which add some components to the control error. The emergency control is a directed cyber-physical action to maintain the cyber-physical production dynamic system in a non-variant state to the equipment failures and interferences. The control method and parameters are determined as a result of the assessment of the state of cyber-physical production performed in its phase space according to the predicted trajectories, probably indicating the dynamics of the technological environment and the risks of uncontrolled situations. The actual information of the cyber-physical production states includes the cyber-physical systems functionality modes data, which is proposed to be accumulated in a virtual environment to which the technological automatics of different hierarchy levels is connected to. The parametric states space dynamic system behavior trajectory forming principle is defined to make concrete separate cyber-physical systems and the cyber-physical production in general.

1. Introduction
The cyber-physical production (CPP) technological environment consists of a combination of interacting cyber-physical system (CPS) elements of physical and information functioning nature and forming a complicated dynamic system. The dynamic system control task is to regulate separate CPSs and their groups by means of component signal actions (electric, electromechanical, hydraulic, pneumatic and other) from the physical world and the digital twins information actions (net, computing and other) from the virtual world. The CPP control chain is for maintaining the technological environment dynamic system in its non-variant state to failures or any CPS damage and also resistant to interferences provoking emergency situations.

To solve the CPP control task is done by means of the technological environment monitoring controlling CPS structure and parameters and by means of dynamic system analysis based on industrial object representation with models in the space of states changing their characteristics in time. The state
space let analyze all CPSs behavior features online and describe CPP parametric dynamics by means adapted for automatic (robotized) control. The CPS states parameters changes being monitored in different points of CPP control helps to control with a function of technological objects and processes distributed synchronization covered with reverse connections.

Multilevel control systems, configured from the physical and virtual circuits of the CPS, define CPP as a multidimensional industrial object, the processes in which have a delay. Technological limitations and uncertainties of the CPP environment are associated with a delay in the control channel due to the transmission of information in the form of an Internet of Things (IoT) radiofrequency signal, and with a delay in the operational flow of the conveyor line, based on the final time of moving parts between neighboring CPS. Delays in the control and operational channels create risks of chaotic dynamics of CPP and generate a time shift in the processes of synchronization of the CPS in the space of state parameters.

A control channel delay consequence is the detection time period instability for CPS states parameters in the CPP general infrastructure accompanied with being monitored technological data fragmentation and errors collecting. The CPP behavior dynamic chaos could also create the CPS technological environment inner factors actions related to disturbances providing CPS control-ability failure and CPS failures, which are dependently given in the conveyor line chain. The CPP control strategy directed to its failures and interferences tolerance behavior and some measures against non-controllable situations is an agreed change of CPS states variables, which gives an industrial object in combination all the required technological environment functioning characteristics.

The CPP behavior prognostication to prevent an emergency or to decrease the probability of its appearance in the technological environment based on dynamic models where the adaptation and context control laws are defined to define the rules of quasi-autonomous CPS objects transition from one state to another. CPSs combined work without failures to support risks balance of the technological environment object random failure done with CPP complex states evaluation mechanisms using the CPS first parameters monitoring data and processes synchronization control, which of potential chaotic character.

2. CPS system dynamics
The CPP crucial elements against failure and for correspondence for operation requirements, which action the result-ness and the industrial object technological safety are CPSs. The CPS functioning stability violation is a main risk that a non-controllable situation appears and develops into a safety accident, which directly action the CPP automatics behavior prognostication. To identify emergencies (equipment damaged state, de-synchronizing of the CPS intersystem functionality and other) because of the CPP structure integrity being compromised (the technological data truth state violation) and to interpret probable consequences after a CPS breakage they view this as a virtual environment calculator function providing the smart factory technological safety control.

Each CPS parameters space point corresponds to a particular CPS state depending on being done right now operation by CPS. CPS dynamic change modes given with a general work tide is accompanied with a parameter change increments of which could be endlessly small or significant. Stable functioning modes when are dwelled by a CPS may provide the necessary quality of the item being manufactured define the permissible class of CPS states (phase space) in a plurality of equal weight states. Each class of permissible states defines the CPS possible behavior reached after a control with an error where the value does not exceed the CPS integrated automatics characteristics discriminate width.

The CPS control desired strategy being computed with a calculator in the CPP discrete virtual environment requires CPS movement in a parameter space with a trajectory from one equal weight state to another. The CPS states space division into classes formed in values of vector parameters necessary to identify processes and events happening in a CPS during the plan action change (being controlled) to action the control objects in some fluctuations. The random interferences CPS action and CPS inner processes features creates a probable mathematical calculations nature to define being prognosticated CPS dynamics trajectory in time and states space. To increase the prognostications accuracy and
reliability they make better metric properties of being controlled parameters and measurement results of the being monitored CPSs, which dynamic is known to a virtual calculator for current and previous CPS states.

The CPS system dynamics model functioning in a closed technological environment is a way to describe being controlled object behavior, which is characterized with quality and quantity changes of their parameters and properties, which lead to the CPS interclass transition in a state space. The CPS characteristics change is explained by action of under control (information and signal control actions, interferences being measured and other) and also not being registered (not being measured noises and disturbances) factors specific for the CPP technological environment. To overcome CPS actions of external and internal environment they require to identify the belonging characteristics of each CPS being monitored states to a particular class of parametric space.

The CPS properties correction reacting the CPP dynamics and technological environment states leads to appearance of working modes sequence, which bears a risk that the equipment initiates the state parameters with unpredictable consequences in CPS behavior. Incoming scenarios from each occupied CPS equilibrium point of directed CPS characteristics change as control objects creates an outburst of the CPS behavior bifurcations, which could potentially be a dynamic chaos. Potentially stable objects without any external interferences and well functioning CPS equipment under the state of failures and critical technological loads (extreme) become non-controllable, which processes have no equilibrium any longer. The CPS functionality modes change from a balance state to an uncontrollable one through the dynamics, which is accompanied by the CPS behavior non-definition state, which distributes chaos like an avalanche into the technological environment and requires:

- to eliminate intersystem CPS conflict or a separate CPS functionality failure provoked with a single or random actions of unregistered factors;
- to form controlling action over the protection machine providing all CPSs sequence switch-off from the energy saving system in which functionality some failures detected or the being controlled parameters significant deviations from the reference values.

![Figure 1. The dynamic system behavior trajectory forming principle in the state parameters space: a) for CPSs, b) for a CPP.](image-url)

The CPS properties change quality evaluation leading to the equipment functioning dynamic equilibrium loss is done through the main diagnostic feature, which is the control error increment with a CPS norm of maximum permissible value functioning in accordance with the established technological rules.

In figure 1 the dynamic system behavior trajectory forming principle in the state parameters space is
given. They use the following designation: \( \mathbf{U}_i = (u_{i1}, u_{i2}, \ldots, u_{i,m}) \) - the control vector of CPS; \( \mathbf{Y}_i = (y_{i1}, y_{i2}, \ldots, y_{i,n}) \) - the parameters being measured vector of CPS; \( \mathbf{x}_i = (x_{i1}, x_{i2}, \ldots, x_{i,n}) \) - the state parameters vector of CPS; \( \mathbf{U} = (\mathbf{U}_1, \mathbf{U}_2, \ldots, \mathbf{U}_N) \) - CPP control vector; \( \mathbf{Y} = (\mathbf{Y}_1, \mathbf{Y}_2, \ldots, \mathbf{Y}_L) \) - CPP being measured parameters vector; \( \mathbf{X} = (\mathbf{X}_1, \mathbf{X}_2, \ldots, \mathbf{X}_L) \) - the CPP states parameters vector, which consists of \( N \) CPSs; \( \mathbf{x}(t) \) - the behavior dynamic trajectory of CPS in the state parameters space; \( \mathbf{X}(t) \) - the CPP dynamic behavior trajectory in a state parameter space; \( t(n-1), t(n), t(n+1) \) - fixed moments of time when the being controlled dynamic system is defined. The functional connections among incoming and out-coming dynamic system parameters are defined with a connection way (in a sequence, in parallel, parallel by chance) of automatics components.

3. The CPP system dynamics

The CPP dynamic system control, which consists of local interacting CPSs belongs to the little formalized technological tasks category with a high degree of CPS specialty differentiation within the conveyor line. The adequate properties technological environment and CPP dynamics accurate evaluation are provided with a mathematical apparatus of automatic control theory based on industrial object parameters representation methods in a state space. The CPP state parameters are defined in CPS states parameters and their dynamics abstained from control variable of physical trajectory accuracy for tool movement and executive mechanisms inside the CPS work chambers. The abstraction means are used to describe and control the CPP dynamics and let in states parameters space detect the discrete collection risks trends of technological safety related to theoretical and fact indications deviations in the industrial object functionality.

To provide the dynamic system necessary behavior they need to calculate metrics to characterize relations of the current CPP state to the basic one, which parameters depend on the initial states and are defined with virtual tools of intellectual control. The CPP behavior prognostication and its separate elements in time is done in a states parameters space by models of dynamic trajectories, each of which corresponds to a particular alternative option of technological environment development. Relationship of expected failures (deviations in operation) CPS and changes in the state of CPP, controlled parametrically, has a projection into the phase space of an industrial object in the form of a group of trajectories, the characteristics of which indicate the loss of stability and controllability properties of the dynamic system.

The CPP dynamics laws dependencies are calculated for different scenarios of CPS behavior to make real narrow specialty technologies, which are being controlled with a monitoring system to provide tool means of the equipment states parameters monitoring and evaluation. The CPP states identification relates to the technological environment and information space edge definitions and factors influencing (external and internal) the structure and parametric CPS dynamics. The CPP distributed control synchronization process is based on virtual calculator data of CPS states and is done to decrease the industrial object functioning parameters sensitivity to single and group actions to affect the quality of the item being manufactured.

The CPS potential failures forming a discrete tide of events is a being prognosticated capable feature of the CPP automatic behavior and justify the task to synthesize a control system, which objects are adapted to the technological environment dynamics. The CPS action of non-systematic factors of random nature, which could be compensated with combined control methods when each separate factor action over the CPP dynamics being watched could not be practically evaluated in quality. Parameter registering of this action is done with indirect features appeared after a violation of mechanical or information CPS interconnections and with the technological environment.

Because of CPP structural complexity and multi-measure of its interdependent characteristics and reproduction of entire scale of being prognosticated technological environment dynamics trajectories in the states parameters space sometimes cannot be reached even with a calculation. The technological safety technical aspects say that prognostication depth is a probable measure, which could be calculated
for a CPP with some truth defines its dynamic system in accuracy and reliability parameters as a system with almost guaranteed quality of the item being manufactured.

4. Conclusion

To construct a robotized CPS division is an application task how to synthesize an Industry 4.0 smart factory to develop a failure-proof technological environment architecture acting without a direct human intervention or in automatic mode, which complete CPP operations over toxic, flammable, explosive, acidic or other types of hazardous materials. Due to possible changes of the technological environment properties after a CPS control loss a CPP is viewed as an industrial infrastructure object with the highest risks of non-favorable action on the environment.

The mathematical diversity of ways how to describe the Industry 4.0 technological equipment structures and properties let view the CPS behavior in a parameter space belonging to the CPP stabilization area corresponding to standard control mode (state of things). The aggregate approach how to control processes and CPSs includes the CPP technological task complex solution providing the constant presence of local CPSs into the simple attractor parametric area. The stable balance resulting trajectory definition of complicated architecture component how to connect and cyber-production CPS nomenclature is done through a plurality of formalisms (algebra and differential equations systems including non-equations, which are normal or for private derivatives) to control interclass transition dynamics for each CPS in a state space.

The parametric states identification and CPS interconnection is based on the operation and mode control errors matrix monitoring, which is available for a virtual calculator through measurements of continuous in regulation and discrete in item manufacturing stages CPS characteristics changing in time. The CPP control stabilization effect with CPS structure multilayer hierarchy is reached after an adaptive synchronization by the calculator of quasi-autonomous technological cycles operating with resource models and time-table. The CPS physical and virtual loops processes self-similarity violation and also CPS device structure and their digital twin are information criteria to manifest the negative dynamics or CPP functionality stability loss.

Model how to detect the CPP states change bearing risks for any CPS be more than just a simple attractor is based on subject oriented regulation software configuration with a high degree of CPS control characteristics similarity to the optimal ones. The physical environment components display into a space of models in their equal relations to the technological objects and processes, which are used for the centralized evaluation of the CPP states done according to the rules pre-defined with main statements convergence for the general control theory, computing and communications combined with structural and parametric CPS dynamics analysis.

The computing architecture integration based on a net covered with multilevel signal and information reverse connections leads to creation of the CPP technological environment being regulated, which is capable to restore their own stability and dynamic balance with the CPS hierarchy structure reconfiguration methods using technologies of adaptive and combined control. To reduce the risks of CPS control error reaching beyond the stable regulation area for discrimination characteristics relates to special scheme and algorithmic solutions supporting the necessary level of CPS functioning autonomous-ness and their abilities to self-set and self-organize.

The control tides intellectual analysis and CPS state parameters decreasing the risks of CPP being out of control is a special resource of the Industry 4.0 smart factory, which is used to define the individual rules of the technological environment CPS behavior. All CPSs states parameter detecting is done to form a virtual calculator reliable representation of CPP processes defining the best in combination being controlled features of the control strategy for adequately developing CPS interaction dynamics. The most smart factory designers interest relates to the methods how to detect emergencies of the CPP stability and control-ability loss with some indirect features, which do not affect the CPSs immediately and fully but with some significance for complex analysis of the industrial object dynamics. Such methods are based on the mathematical apparatus of fuzzy logic, a point scale of assessments and abstract models used in the artificial intelligence of CPP.
References
[1] Das T K, Adepu S, Zhou J 2020 Computers & Security 96 101935
[2] Drakaki M, Karnavas Y L, Tzionas P and Chasiotis I D 2021 Procedia computer science 180 943-949
[3] Koucham O, Mocanu S, Hiet G, Thiriet J-M and Majorczyk F 2018 IFAC-PapersOnLine 51(24) 1043-1050
[4] Villalonga A, Beruvides G, Castano F, Haber R E and Novo M 2018 IFAC-PapersOnLine 51(11) 200-204
[5] Rychener L, Montet F, Hennebert J 2020 Procedia computer science 170 648-655
[6] Chen W 2020 Computer communications 151 31-41
[7] Tantawy A, Abdelwahed S, Erradi A and Shaban K 2020 Computers & Security 96 101864
[8] Khalid A, Kirisci P, Khan Z H, Ghrairi Z, Thoben K-D and Pannek J 2018 Computers in Industry 97 132-145
[9] Ji Z, Yang S-H, Cao Y, Wang Y, Zhou C, Yue L and Zhang Y 2021 Process safety and environmental protection 148 1279-91
[10] Dibaji S M, Pirani M, Flamholz D B, Annaswamy A M, Johansson K H and Chakrabortty A 2019 Annual reviews in control 47 394-411
[11] Toro R, Correa J E, Ferreira P M 2018 Procedia manufacturing 26 1330-9
[12] Barrere M, Hankin C, Nicolau N, Eliades D G, Parisini T 2020 Journal of information security and applications 52 102471
[13] Christou I T, Kefalakis N, Zalonis A, Soldatos J and Brochler R 2020 IFAC-PapersOnLine 53(3) 173-8
[14] Ayodeji A, Liu Y-k, Chao N and Yang L-q 2020 Nuclear engineering and technology 52(12) 2687-98
[15] Lin T Y, Shi G, Yang C, Zhang Y, Wang J, Jia Z, Guo L, Xiao Y, Wei Z and Lan S 2021 Journal of cleaner production 281 124443
[16] Zhou C, Luo H, Fang W, Wei R and Ding L 2019 Automation in construction 97 138-50
[17] Forcina A, Falcone D 2021 Procedia computer science 180 436-45
[18] Decker N, Huang Q 2020 Manufacturing letters 26 48-52
[19] Jiang Z, Chang Y, Liu X 2020 Journal of industrial information integration 18 100130
[20] Magnanini M C, Colledani M, Caputo D 2020 Procedia CIRP 93 646-51
[21] Liu Y, Wang L, Xu X, Zhang L and Wang X V 2021 Robotics and computer-integrated manufacturing 70 102135