Cyber and Physical Systems Topology for the Industry 4.0 Smart Factory

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Abstract. To project digital companies of the Industry 4.0 is a production task which requires to implement in the industrial infrastructure the elements of multi-agent environment. Multi-agent environment is components (cyber and physical systems) of two elements: the automatic one in physical level and program one (model) in the virtual level. Physical element is a digital system of automatic control. The program one is a code fragment to describe the functionality of cyber and physical system with a mathematical model. There is a scheme of physical and virtual cyber and physical system components interaction for digital automatic production of the Industry 4.0. The properties of the Industry 4.0 production company (a smart factory) depends on the interaction scheme of the digital company infrastructure. Cyber and physical systems interaction scheme is generated in a smart factory cloud. There are some options of cyber and physical systems topology which are good for the Industry 4.0 production infrastructure.

1. Introduction

The development of information technologies and progressive technological cyber and physical equipment [1-3] gives sufficient conditions to project the flexible productions of the Industry 4.0. Such automatic flexible productions are a new type of company [4, 5] which creates items without humans. The main advantage is deep automatizing of item manufacturing technological operations and also transporting (transportation) of items between cyber and physical systems (CPS). The control of cyber and physical equipment is done [6, 7] with computerized system the core of which is an artificial intelligence which is a program in a calculation cloud.

The behavior of agents which are cyber and physical systems can be described mathematically in discrete equations of automatic control with random delay. To unite agents in multi-agent [8-10] production environments helps to create multi-measure system of higher rank the functionality of which can be described with variables of condition and control which are vector and matrix. Agents interaction is for object and orientation approach using the principle of central and non-central control. Non-central control of cyber and physical production helps to avoid break-down of the smart factory production infrastructure. The main idea how to control a CPS is to grant a non-conflict access for the CPS to the informative resources of the company virtual environment [11, 12].

The ways how agents interact in a multi-agent environment are based on the technologies [13-15] of Internet of Things (IoT), cloud technologies, technologies of Systems-to-Systems (S2S), Machine-to-Machine (M2M), Humane-to-Machine (H2M), additive technologies and other technologies of the Industry 4.0 cyber and physical systems.
2. **Cyber and physical system as a multi-agent environment component**

Cyber and physical technological equipment is a new type of production machines to function in a hybrid line with humanless and paperless technologies. Cyber and physical equipment is a narrow thing which may complete only a set of particular technological operations. Such technological operations in automatic mode are:

- placement of radio and electronic components to the SMD (Surface Mount Device) to a PCB (Printed Circuit Board) in the item designing;
- 3D-printing of parts (additive technology of production) created from metallic or organic raw materials;
- optical, X-ray or functional quality control of the items being produced.

Cyber and physical system as an agent of a multi-agent digital production environment (encapsulated calculation system) has the following properties:

- target orientation of CPS actions to complete a particular production task (a fixed set of technological operations) as a part of the Industry 4.0 smart factory;
- communication or when an intellectual agent may interact with other agents of multi-agent environment with some defined channels of connection and interfaces to complete the production task;
- reaction or when an intellectual agent may perceive the changes of multi-agent production environment to make it safer the completion of technological operations including the ecological and industrial safety;
- proactivity or when an intellectual agent may be an active (leading) component in a multi-agent environment using the artificial intelligence to complete production tasks of cyber and physical technological equipment self-organization (adaptation and automatizing of production infrastructure).

Cyber and physical system is unlike the machines of the Industry 3.0 it has an additional component (a sub-system) which is performed in a virtual cloud. The production machine of the Industry 3.0 (computer numeric control (CNC)) have an interface terminal, mechanisms, calculator and software which together work in a single item (the machine) which is the physical level only. In the Industry 3.0 agents interact in a multi-agent environment where operator controls a CPS (technological equipment) through a terminal and the machine itself is an instrument which has or does not have localized intellectual capabilities.

The Industry 4.0 approach to organize production process in a smart factory requires the application of CPS intellectual capabilities including the components of virtual resources to organize intellectual multi-agent environment. So a cyber and physical system of the Industry 4.0 has two components (see figure 1):

- physical equipment with a work chamber to complete technological operations, gears, condition detectors of technological processes, technological equipment functionality detectors and a digital controller;
- virtual agent in a CPS cyber-level cloud with mathematical models to describe the technological operations, CPS mathematical models as a digital system of automatic control and ontology model to describe a CPS as a digital twin.

Physical level CPS are simple reflection agents to complete a particular set of technological operations. Virtual level CPS are studying agents to form effective behavior strategies for technological equipment in a multi-agent production environment of the Industry 4.0 smart factory.

Ontology is a formalized description of definitions (processes, operations and other) and their interaction for the subject field of a digital production. Ontologies are needed to create specifications of all types of CPS production which are part of the Industry 4.0 smart factory.
Figure 1. Cyber and physical system components for automatic digital production of the Industry 4.0.

CPS work chamber complete technological operations to transform blank (material) into an item. The technological process quality control is done periodically (the period of discrete digital system of automatic control) which proves dynamic properties of CPS. Detectors (accelerometers, pressure detectors, humidity detectors, temperature detectors and other) of technological operation completion to find out the current values of the cyber and physical production variables. The variable values to describe the technological operations completion are calculated in a cyber-level CPS cloud using mathematical models of CPS and the models of technological processes. Work parameters calculations give the needed values of the digital automatic systems as a digital twin in the cloud. Digital twin calculation is done with imitation modelling.

CPS physical level controller has a program agent (code fragment) which control the quality of technological operation inside the CPS work chamber. Controller compares the current value of technological operation completion variables and its desired values. The comparison results are the motions to the CPS work chamber gear from the controller. The executive gears are like a crank with a reducer, step engine and other automatic elements. So the detectors, controller and executive gears is a closed loop of CPS physical level in a digital system of automatic control.

Physical and virtual components CPS interaction is done with standards of the industrial Internet of Things which transfer the data wirelessly. Ontology model to describe CPS is done after the transformation of CPS description mathematical models into terms of semantic digital production united into ontology dictionaries of the Industry 4.0. So CPS ontology model is a way to describe an agent in the multi-agent system and a kind of interface to support the technology of Systems-to-Systems for the cyber and physical systems to interact.

Like the Industry 3.0, CPS and operator interaction is based on the technology of Humane-to-Machine. The H2M for interaction between operator and a CNC machine is based on controller programming (to place the control program in the machine memory which describes the order how to do technological operations of the item manufacturing which is the 3D-model) in the manual mode. The Industry 4.0 CPS is controlled by operator with the technology of H2M remotely with the industrial Internet of Things. Control program, control commands and variables is transferred by the user in the controller of the physical CPS with the protocols of IoT with guaranteed packages delivery. In this case CPS is described as digital system automatic control terms with random delay. There is a delay in the CPS channel because:

- random delays when the information is being transferred in a wireless channel from the user (or other people in digital production) to the cyber and physical system;
- technical restrictions (limited pass through of the channel) of temporal specifications in communication nets of industrial data.

A CPS has receiver and controller of the IoT channel which helps to transfer informatively the production data with other CPSs which are part the united technological line of a digital production. Cyber and physical production components united in a workshop is the production infrastructure of the Industry 4.0 smart factory. The multi-agent production environment conditions are changed because there are some results of CPS activity in each moment of time keeping in mind the dynamic properties of IoT.

3. CPS topology as the Industry 4.0 smart factory

Virtual generations of CPS dynamic configuration can be done in a smart factory based on the net architecture SDN (Software Defined Networks). This CPS self-organization has some approaches simultaneously based on: theory and methods of automatic control; mathematical theory of graphs.

Multi-agent virtual dynamic configurations of CPS have several topologies of net to complete production tasks available for the smart factory technological equipment. An almost optimal plan of item manufacturing which is good for some multi-criteria tasks. The most popular types of (see figure 2) of CPS topology of ring, bus, point to point, star, matrix and other.

![CPS topologies](image)

**Figure 2.** CPS topologies of virtual environment to organize production activity in the Industry 4.0 smart factory: a) bus topology, b) point to point topology, c) star topology, d) ring topology, e) matrix topology.

Agent interactions in the digital production virtual environment is based on the technology of Systems-to-Systems and is done automatically using semantic forms to describe production processes, components and technologies in languages of digital production ontologies. For different types of CPSs to interact (equipment of different purpose, for example, a robot manipulator which transfer a PCB to the receive area to place radio and electronic components in SMD) they use semantics from digital production ontologies placed as a resource agent of virtual environment.

Virtual environment agents interaction with physical agents of the Industry 4.0 digital production is based on digital technology of IoT where physical machines are objects of control which receives
remotely the control values from cloud calculator (Industry 4.0 smart factory cloud) or from the operator. Processes of CPS in physical level and in virtual components level defines the micro-level of the smart factory multi-agent environment. In practice the principles of net control (net centering) include the agents behavior in multi-agent environment and also defines the multi-agent environment behavior in micro-level.

To project a multi-agent environment and organize CPSs interaction they use branch standards. The most popular standards and programs of industry development which are good enough to create a digital company of the Industry 4.0:
- FIPA (Foundations for Intelligent Physical Agents);
- MASIF (Mobile Agent System Interoperability Facility);
- DARPA (Defense Advanced Research Project Agency).

4. Conclusion
To implement multi-agent environments into production infrastructure of the Industry 4.0 smart factory they revised the business processes of the industrial company. The expected advantages of such agent implementation in multi-agent environments are reduced time of item manufacturing, reduced cost of production in a smart factory when at the same time the item quality gets higher.

The main developments of multi-agent environments which have cyber and physical systems in the Industry 4.0 production are the following:
- cyber and physical systems self-organization based on artificial intelligence technology may synchronize the completion of production processes for groups of cyber and physical systems in a smart factory;
- the organization of distributed calculations with the technology of BigData to collect and process the vast amounts of industrial data;
- good functionality of cyber and physical production based on the control algorithms using central and non-central principles;
- cyber and physical systems learning and multi-agent environment based on neural nets and real or model learning patterns (set of dynamic conditions) after the put into the field activity and after the real exploitation of the technological equipment.

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