Formation principles of digital twins of Cyber-
Physical Systems in the smart factories of Industry
4.0

A V Gurjanov¹, D A Zakoldaev², A V Shukalov², I O Zharinov²

¹ Director, Stock Company «Experimental Design Bureau «Electroavtomatika» named after P A Yefimov, 40, Marshala Govorova St., St. Petersburg, 198095, Russia
² Faculty of Information Security and Computer Technologies, St. Petersburg National Research University of Information Technologies, Mechanics and Optics, 49, Kronverksky Av., Saint Petersburg, 197101, Russia

E-mail: mpbva@mail.ru

Abstract. The task of organizing the production of instrument-making enterprises of Industry 4.0 using digital twins of Cyber-Physical Systems (CPS) based on cloud services is considered. Cloud services are a component of SPS, acting in production as active Internet agents for the manufacture of instrumentation products. The combination of CPS, united by a single computerized control system, forms the production infrastructure of a smart factory. Smart Factory is a manufacturing plant of Industry 4.0, operating in automatic mode. A scheme of interaction between the components of the smart factory Industry 4.0 and cloud services for the production activity of the instrument-making enterprise is proposed.

1. Introduction

Modern instrument-making production is focused on the introduction of new digital technologies that provide information support for technological processes of manufacturing instrument-making products. Such digital technologies are [1-3] additive technologies, sensor technologies, BigData technologies for processing large arrays of production data, cloud technologies, etc. Manufacturing enterprises introducing promising digital technologies in the technological processes of manufacturing instrument-making products are the smart factories of Industry 4.0 [4, 5]. Smart factories implement a closed technological cycle of manufacturing products in automatic mode due to the deep automation of production processes. The main production unit of a smart factory is a cyber-physical system [6, 7], which has two components: a component at the level of a physical device and a component at cyber level (a cloud service containing a digital twin of a physical device). The interaction of components is provided by means and protocols of the Industrial Internet of Things (IIoT) [8, 9]. The primary task of building the automatic production of Industry 4.0 is to determine the composition of the components of CPS and the order (scheme) of interaction of these components.

2. Models of CPS at the physical and cyber levels

The models of CPS at the physical and cyber levels are shown in Figure 1.

The physical component is formed [6, 7]:

- digital controller, which is the core of the automatic control system of CPS, and implements the algorithm for performing the technological operation of manufacturing a part (product);
- actor system, which is a set of tools fixed on a single base (rotational-translational motion of the base is carried out by an electric motor under the influence of control signals from the controller);
- working chamber of the technological process, inside which the processing of the material, which is a blank for the manufacture of parts, being a part of the product is performed;
- sensor (set of sensors), which provides measurement of the parameters of the technological
process of manufacturing parts in the working chamber. The sensor measurement results are transmitted via the main feedback line to the controller. In the controller, the sensor measurement results are compared with the expected values (an error value is generated) defined by the reference tool path. The reference trajectory is fed to the controller input from the technological process algorithm library. By comparing the two input values, a control action is generated in the controller, which corrects the actors position in the direction of decreasing the control error value.

![Diagram of CPS models](image)

**Figure 1.** Models of the CPS at the physical and cyber levels.

The cyber world component of the cyber-physical system is located in the cloud service and implements the information model (digital twin) of the physical device. The information model of a cyber-physical device consists of:
- controller model;
- actor model;
- work chamber model of the technological process;
- sensor model (s).

The components models of the physical devices of the cyber-physical system are discrete-time mathematical equations solved by the computing resources of cloud services.

The main purpose of the digital twin of the physical device of CPS is to support the pre-production phase. At the preparatory stage of production, the operator by means of modeling evaluates the possibility of manufacturing a part using a digital product model on a certain type of equipment, the properties of which are described mathematically. Such assessment is based on the results of technological operation at the level of mathematical models in the cloud service. Thus, at the stage of preparation of digital production, the routing sheet for the manufacture of instrument-making products within the production complex of an instrument-making enterprise is issued. The simulation results are also used by the computerized control system of a smart factory to ensure the self-organization property of cyber-physical equipment in digital production. Information exchange between the components of the cyber-physical system at the physical and cyber levels is carried out over a wireless communication channel using the protocols of the Industrial Internet of Things. Data exchange on the results of technological operations at the physical and mathematical models levels can also be used to improve the accuracy of the cyber-physical system in the production using the digital Kalman filter.
The scheme of components interaction of the smart factory of Industry 4.0

The scheme of interaction between the components of the smart factory of Industry 4.0 and cloud services for the production activity of the instrument-making enterprise is shown in Figure 2. The physical level of the smart factory of Industry 4.0 is represented by a set of cyber-physical systems that are combined into technological lines to perform the route sheet for the manufacture of an instrument-making product. Information exchange between cyber-physical systems is implemented by the Systems-to-Systems (S2S) technology. Physical interaction of cyber-physical systems is implemented by means of a robotic transport system that moves the workpieces and parts between the equipment and the finished goods warehouse. Control (monitoring) of the state of technological operations in production is carried out by an operator using Human-to-Machine technology (H2M) and technical means of an automated workplace [10, 11].

![Diagram of interaction between components of the smart factory of Industry 4.0 and cloud services for production activities.](image)

The cyber-physical level of the smart factory of Industry 4.0 is implemented by means of cloud services containing in the form of ready-made libraries [12]:
- technological processes algorithms for the manufacture of instrument-making products, implemented by the technological equipment available at the production;
- digital models (digital twins) of cyber-physical systems installed in production;
- digital models of instrument-making products, technical documentation for which entered the smart factories for the digital factory of Industry 4.0 products manufacture;
- regulatory and technical documentation regulating the procedure for performing technological operations in production and their compliance with the requirements of state and industry standards;
- BigData algorithms for processing large arrays of production data resulting from measurements from sensors of cyber-physical systems [13].

The interaction of the components of cyber-physical systems with cloud services is carried out over a wireless communication channel using the IIoT protocols. Each cyber-physical system acts as part of a smart factory being an active Internet agent operating in the “self-service on demand” access mode. To organize such a scheme of components interaction, each cyber-physical system is allocated an individual port of information exchange in a single wireless communication channel for a production...
line (workshop, plant). Technological line components of the smart factory of Industry 4.0 at the physical level and their equivalent components of the digital counterparts of cyber-physical equipment with temporary characteristics of the production operations are shown in Figure 3.

![Figure 3. Process line diagram of the smart factory of Industry 4.0.](image)

- \( \tau_i \) - execution time of the production operation on cyber-physical equipment (physical device) in the process chamber;
- \( \tau'_i \) - execution time of the production operation, obtained by computer simulation tools in the cloud service (time \( \tau'_i \) is a random value, since it includes the temporal characteristics of IIoT traffic in the protocol with guaranteed packet delivery). The finished product warehouse and production site for storing materials and blanks in the smart factory are shown in Figure 3 with equivalent databases, the models of which implement cloud storages. Time \( \tau_i \) with even indices characterizes the execution of production processes performed in the working chambers of cyber-physical systems [14]. Time \( \tau_i \) with odd indices characterizes the execution of production processes by a robotic transport system. Analysis of the information flows implemented between the components of the smart factory of Industry 4.0 at the physical devices and cyber levels shows that the cyber-physical production control scheme is a closed-loop digital automatic control system. A feature of this automatic control system is the delay in the control channel, due to the temporal characteristics of the IIoT protocol with guaranteed packet delivery. The packet delivery time for the IIoT protocol with a wireless communication channel is a random value, therefore, the control system of the production automation of the smart factory of Industry 4.0 has a random delay.

4. Conclusion

The transition of the existing enterprises of Industry 3.0 to digital manufacturing techniques is linked to a significant modernization of the software and hardware of organizations. It is obvious that such replacement of enterprise infrastructure components will lead to reduction in production time and to an increase in product quality. However, step-by-step modernization of the enterprises of Industry 3.0 will not lead to the emergence of the smart factory of Industry 4.0. To create the smart factory of Industry 4.0, it is advisable to use new production areas, advanced cyber-physical equipment integrated into production lines, and qualified personnel who have been pre-trained in digital production technologies. Priority industries for the introduction of digital production technologies are:
automotive instrumentation, railway instrumentation, aviation instrumentation, rocket and space instrumentation.

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