Conceptual Approach to Building a Digital Twin of the Production System

S. I. Suyatinov

Abstract The digital twin is an important component of the cyber-physical system. This new structure of the production system was the result of the development of information technology. The article shows that, despite the long history and success in the development of production information systems, the concept of building digital twins of production systems is at an early stage. One of the problems in creating digital twins is the need for integration and joint processing of a large amount of heterogeneous information. It is shown that the problem of reflecting the current state of the production system is in many ways similar to the problem of the internal representation of the surrounding world in living systems. It is proposed to choose the theory of the levels of the physiologist N. A. Bernstein as the basis of the conceptual approach to the development of digital twins. The mechanisms of forming models of the external world at every level are outlined. A description of the hierarchical system for processing different types of information and obtaining an invariant representation of the external world are presented. The principles of constructing a virtual image in the organization of motor activity are formulated. The implementation of these principles when building a digital twin of the production process will improve the efficiency of integration methods and joint processing of information.

Keywords Cyber-physical system · Production element · Central nervous system · Virtual image · Big data · Digital twin

1 Introduction

The continuous process of computerization of production, begun in the middle of the last century, has now acquired new opportunities in the field of scientific research. This is the so-called NBIC technology. The technological paradigm of the NBIC is based on the fundamental laws inherent in living systems, and is a synthesis of nano-, bio-, informational, and cognitive technologies [1, 2]. Microminiaturization

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of sensors and calculators, as well as information and communication technologies allow recording, transmitting and processing large amounts of information about the smallest details of the production process, accumulating and storing information about products throughout the entire life cycle. Increased computing power, as well as intelligent methods for processing large volumes of information, allowed for real-time control of all hierarchical levels of the production system.

These technological advances formed the basis of the fourth industrial revolution (Industry 4.0). In accordance with the concept of Industry 4.0, enterprises are built on the principle of cyber-physical systems, and the cornerstone of the new industrial concept is the inclusion in the production system of its virtual image in the form of mathematical models [3–6]. The principal feature of the virtual image of the industrial system is its dynamics, i.e. change its state in the rhythm of the production process. That is why the system of numerical simulation of the production process using input measurement information has been called the "digital twin". The digital twin allows not only to monitor the current state of production, but also to predict its future state.

2 Digital Twin in the Structure of Cyber-Physical System

Currently, there is a methodology for constructing a digital twin of a product. The concept of designing digital twins of production systems is at an initial stage. Therefore, the development of approaches to the synthesis of the structure and algorithmic filling of the digital twin is an important problem.

The idea of building a digital twin has a long history. The starting point can be considered the emergence of automated process control systems (APCS) [7]. The development of these systems proceeded along the path of improving the services presented, expanding the range of their application, selecting and standardizing the best solutions. So there were the methodologies realized in the form of the standardized business processes providing information support of administrative decisions at different hierarchical levels of the organization of production [8–11].

In general, production information systems can be divided into three categories. The first is computer-aided design (CAD) systems that allow you to create digital models of designed objects. A feature of these systems is the ability to explore the properties of the designed product, using various options (visual, mathematical, schematic) of its virtual image. This also includes (often used in conjunction with CAD-systems) engineering calculation automation systems (CAE systems) and automation systems for preparing programs for machine tools with numerical control (CAM systems).

Information systems of the second category are designed to control the equipment. These include CNC direct digital control systems, which allow rapid re-adjustment of machine equipment to increase production flexibility, and PHM systems designed to predict the status and control equipment operability. PHM-systems use information from sensors installed directly on the equipment, as well as models of the equipment under test.

The third category includes systems that allow to automate the management of information flows of organizational and technical services and strategic management. The main information systems for managing the production activities of an enterprise are MES (corporate production management systems), ERP (automation of enterprise resource planning) and CRM (customer relationship management system). The strategic management services the OLAP system—a set of technologies for the rapid processing of information, including the dynamic construction of reports in various sections, data analysis, monitoring and forecasting of key business indicators used to analyze and make management decisions.

Figure 1 shows the hierarchical structure of information support for production management. Information support is carried out at all stages of the production process, starting from the design stage. The special integration role of the PLM-system should be noted. It provides the interaction of various automated systems (CAD/CAE, CNC, PHM, ERP, CRM and others) in a single information space.

A distinctive feature of the considered information structure is its ability to generate a large flow of heterogeneous information, which, however, is used fragmentarily within a certain stage of the life cycle and within its hierarchical level. Figuratively speaking, the waste information remains in dead storage.

Production is most efficiently managed using digital twin technology. In essence, digital twin is a structured information that changes in pace and in accordance with

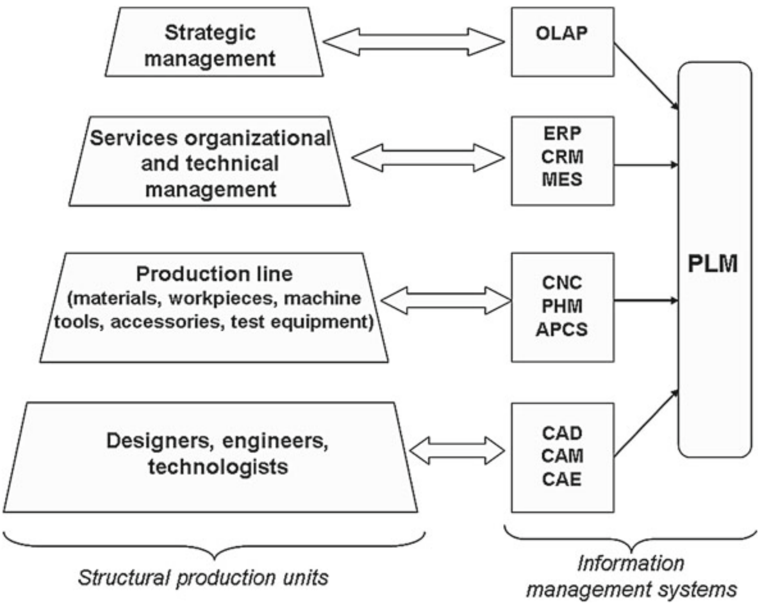

Fig. 1 Information support of production management

changes in the production system itself. The basis of the digital twin technology is a half-a-bit simulation using information (signals) about the current state of the system.

Figure 2 shows the structure of the "production—digital twin" system. The management personnel of top-level use information management systems in their activities. At the lower production level, with the help of sensors D_1, ..., D_n, measuring information is collected about the operation of equipment—production elements PE_1, ..., PE_n. The digital twin is represented by a set of models. The database (*DB*) of the digital twin stores information in the form of planned targets, technical specifications, technological maps, standards and other similar documentation.

In the analysis and forecasting block, the entire array of available data is processed with specific goals. We will single out the main ones: diagnostics of the state of the production process, identification of "narrow" places; assessment of the state of the

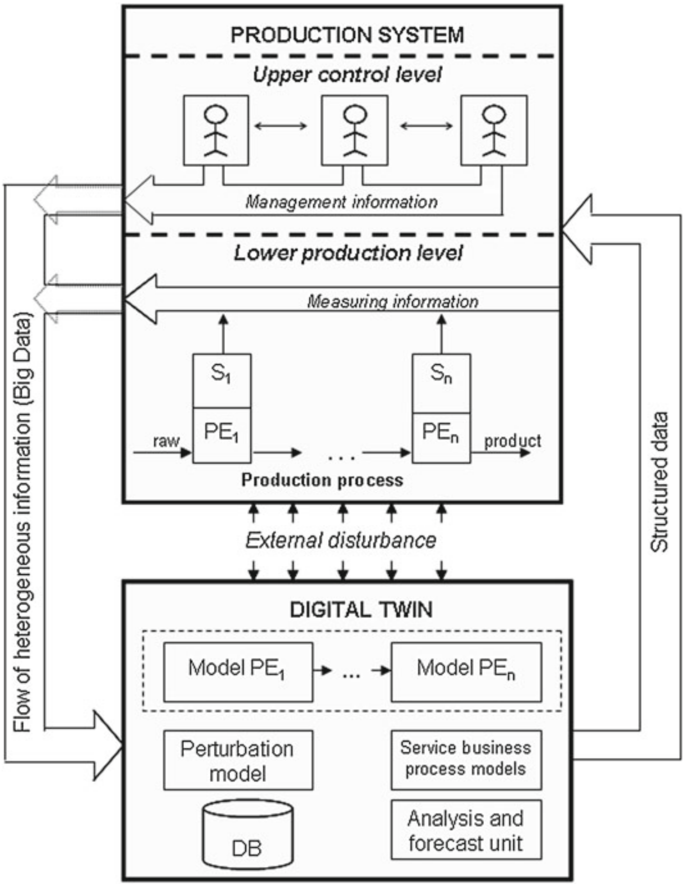

Fig. 2 Production system and its digital twin

equipment in order to organize repair according to the actual state; forecast of the state of the production process under the influence of disturbing factors and re-profiling.

It should be noted that, despite the transparency of the ideas of building a digital twin, their practical implementation is a complex scientific and technical problem. In the first place, this is due to the need to structure large volumes of heterogeneous information, identify the patterns hidden in them and make management decisions. In this regard, it is of interest to have a successful experience in solving similar problems in other areas.

3 Virtual Image in Biological Systems

It is rightly believed that biology is the source of fruitful systemic ideas. In this case, we take into account the fact that all life exists due to the mechanism of internal reflection of the real world. Based on this, we consider the mechanisms of creating the virtual images in biological systems. The existence of an internal model (image) of the outside world is a necessary condition for the survival of a living organism.

In a living organism, the nervous system is a tool for the formation, preservation and use of a model of the external world. In the process of evolution of living matter improved mechanisms for the formation and use of internal reflection of the external world. In the most perfect form, these mechanisms are implemented in the central nervous system (CNS) of a person. In a simplified form, the process of forming and using the model of the outside world can be represented as follows. The process is implemented using the main functional ability of the brain to memorize and predict [12–14]. Using all the available information, the central nervous system in the learning process builds and remembers many virtual models corresponding to different situations, different states of the organism itself and the outside world. Only the best models are remembered.

In the future, faced with the current effects of the environment, the CNS selects the model that best suits the specific case. This model determines human behavior. Thus, for a given purpose of behavior in the CNS formed a program of action and create a model of "how it should be". The model, in particular, predicts the reaction of the senses in the implementation of the program. Then the predicted values are compared with signals from receptors and corrective actions are formed. Thus, we see an analogy with the functions of the digital twin, for example, in the problems of monitoring the state of the equipment. Having studied the available details of the described generalized mechanism, it is possible to use the best solutions in the construction of digital twins of technical systems.

For a number of reasons, these mechanisms are revealed in the most accessible form when studying the process of controlling the movement of a person by the central nervous system. The mechanisms of formation and use of virtual images in the CNS of a person in the organization of movement were studied by Russian neurophysiologist N. A. Bernstein [15, 16]. According to Bernstein, for the implementation of any form of movement (from the simplest form to complex forms), an action program is created in the human CNS, which is a virtual image of a specific behavior (movement).

A virtual image or behavior model is formed in the CNS in the learning process, which is carried out in several stages. Initially, the external and internal motion pattern is formed from the signals of various sensors. At the same time, a person learns to re-encode, according to Bernstein, afferent signals into effector commands. The accumulation of a “re-encryption dictionary” is one of the most important events of this period. In essence, the “re-encryption dictionary” is the set of models from which a virtual image (action program) of the required movement is subsequently formed. A large number of repetitions of the elements of the movement allows you to find models (“re-encryption”) that provide the desired response in response to any deviations in any type of movement.

In the case of the digital twin, the “action program” is a production cycle developed on the basis of previously accumulated engineering knowledge. “Re-encryption dictionary” is a model of the stages of the production process, and “corrective actions” is a model of regulation in case of deviation of organizational and technological indicators.

In accordance with Bernstein’s theory of sensory corrections, the brain not only sends a specific command to the muscles to perform any movement, but also receives signals from the peripheral sense organs about the results achieved and, on their basis, gives new corrective commands. Thus, there is a process of building movements in which there is not only direct but also continuous feedback between the brain and the executive organs. The entire system forms a closed loop of interactions, known as the Bernstein Ring. The general scheme of the ring is shown in Fig. 3.

The Ring includes motor “exits” (effector), sensory “inputs” (receptor), object of subject action, block of re-encryption, generator of a target program, setting driver and device for comparison. The successive stages of complex movement are recorded in program. At any given moment, some of its particular stage, or element, is being worked out, and the corresponding private program descends into the setting device. From the setting device, the signal Sw is fed to the comparison device. A feedback signal Iw arrives at the same block from the receptor informing about the state of the object. In the comparison device, these signals are compared, and at the output of it, signal Δw is obtained, i.e. mismatch signals between the required Sw and the actual Iw. They get to the re-encryption unit, where correction signals come from, and through intermediate instances (regulator) they get to the effector.

The result of any complex movement depends not only on the actual control signals, but also on a number of additional factors. Disturbing effects make deviations in the planned course of movement, and do not give into preliminary accounting. Therefore, the mechanism of movement is a continuous process of comparing the position and state of the organism with its virtual image.

At the same time, motion control has a multi-level nature, organized on the principle of multi-loop feedback. The predicted values of the receptor signals for the implementation of specified behavior models and the actual outputs of the receptor

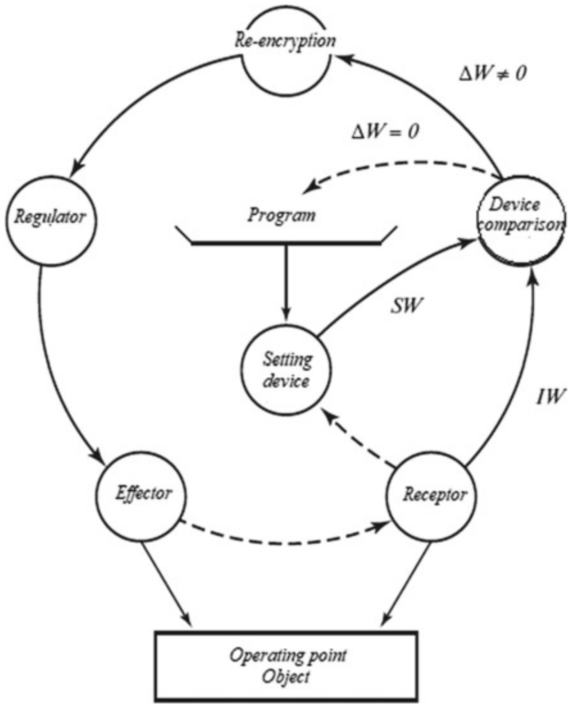

Fig. 3 Bernstein Ring

field at all levels are compared. Thus, multi-model, multi-scale control is implemented. Here it should be noted the special importance Bernstein's theory of movements construction levels for understanding the structure of the virtual image and the mechanisms of processing a large number of heterogeneous information [17–19].

The essence of the theory is that, depending on the source of feedback signals and the content of information (whether they report the degree of muscle tension or relative position of body parts), afferent signals come to different sensory centers of the brain and accordingly switch to motor paths at different levels.

Each level has specific, peculiar only to it, motor manifestations. Each level has its own class of movements. The scientist singled out five levels, denoting them with letters: *A*, *B*, *C*, *D*, and *E*. Levels differ in the degree of detail of the motion representation. Intra-level and inter-level interaction is based on the Bernstein Rings principle.

Level *A* receives signals from muscle proprioceptors, which report the degree of muscle tension, as well as from organs of equilibrium. At level *B*, signals that report the mutual position and movement of body parts are mainly processed. This is the level of analysis of the state "in the space of the body." Level *C* receives all information about the external space; it builds movements adapted to space-time properties (to form, position, length, weight, time, etc.). Level *D* is a cortical, higher level of abstraction. It does not set specific movements, but sets a specific result of movement. Level *E* sets the meaning or purpose of the movement.

Thus, the biological virtual image has a hierarchical structure.

The models of each level are associated with the corresponding sensory fields, differing in the degree of abstraction and detail of motion fragments. Such a structure allows us to assign a sequential set of models and corresponding corrections to them in accordance with a complex movement, represented as a sequential implementation of the simplest elements. In this case, the separation of models by levels allows you to combine models of different detail and abstraction in one image. The hierarchical mechanism of interaction of a virtual image of a human motor reaction is shown in Fig. 4.

Such a structure allows us to put in accordance with the complex movement, presented in the form of a consistent implementation of the simplest elements, the subsequent set of models and their corresponding corrections.

For objective reasons, Bernstein N. A. described the functions of levels D and E located in the cortex in the most general form. It should be noted that the analysis of the functioning of the brain are certain hypotheses. Their accuracy is based on the results of numerous studies. From the standpoint of modern data, the cerebral cortex (neocortex) has a structural-functional organization, similar to the considered multi-level model. Functionally, the organization of the neocortex is in the form of a "sectoral" hierarchy.

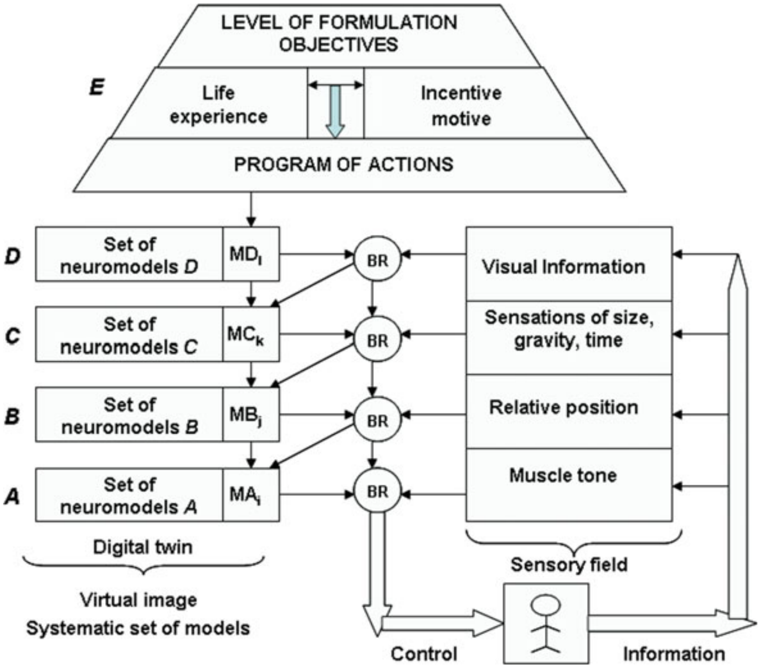

Fig. 4 The interaction of man and his virtual image in the process of organizing movement

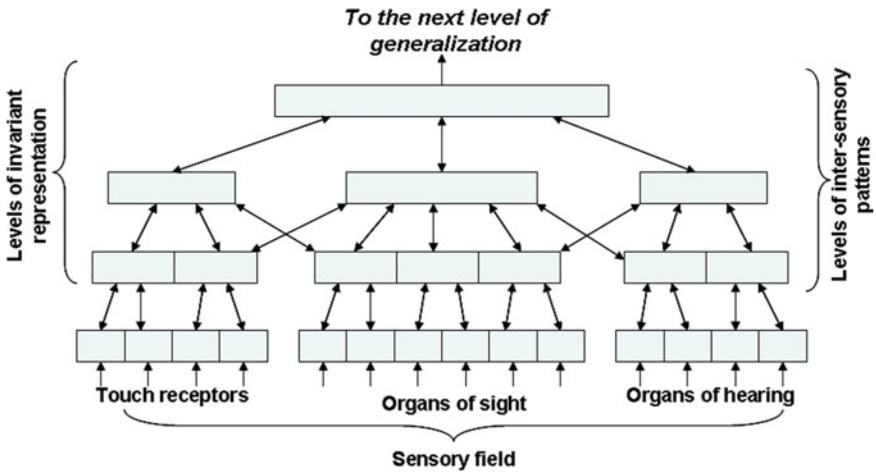

Fig. 5 Multilevel architecture of presentation and processing of information in the neocortex

There are zones of visual, auditory, motor and other perceptions and information processing. Each of these zones has a hierarchical structure. The neurons of the lower level fix individual, particular elements of the image. At the next level, a more generalized image is constructed from particular elements. In this case, a common characteristic of generalized images is their relative invariance to changes in the particular elements of the underlying images. This is how the parts roll up and the formation of a generalized image with the basic properties for this level. Figure 5 shows the simplified architecture of representation and inter-sensory information processing in the neocortex.

The figure shows the next important detail. Numerous studies have established that the levels of "sectoral" zones are interconnected by direct and feedback links. This allows you to form polysensory cybernetic models at different levels, integrating heterogeneous information. In addition, interzone communications allow producing intersensory forecasts.

Currently, the structure and principles of motion control in biological systems are reflected in technical systems with intellectual properties [20–23].

4 Principles of Building a Digital Twin

The analysis of the mechanisms for forming the internal reflection of the external world allows us to formulate the following basic principles of the conceptual approach to building a digital twin of the production system:

- Hierarchical structure of digital twin production system;

- The presence of a multichannel information system (sensory fields) for monitoring the external environment and the internal state of the system;
- Multiscale representation of the virtual model: the behavior program (functioning model) has a hierarchical structure containing consistent submodels of varying degrees of detail and abstract representation, which are implemented in the form of cybernetic models of the “input-output” type and are focused on the appropriate levels;
- Invariant representation of the external environment and motor activity;
- Permanent learning of the system in order to improve the adequacy of the model and improve their own behavior;
- Multimodel reflection of the outside world: as a result of training, each level has its own multi-sensor model;
- Subordination and level matching: the top-level model selects one of several lower-level models;
- Multi-circuit control: achieving a complete goal is equivalent to achieving a set of sub-goals at each hierarchical level;
- Availability of mechanisms for predicting changes in the external world, own behavior and also advanced control.

The stated principles can serve as a conceptual basis for the construction of applied systems using the elements of intellectual control inherent in living organisms.

5 Conclusion

In the process of evolution, nature created and perfected the mechanisms of reflection of the external world in the form of an internal image. The formation and preservation of the internal image is carried out using neural network structures. The hierarchical organization and inter-level relationships of these structures provide the formation of multisensor models and an invariant representation of the image at various levels. The analysis of the mechanisms of formation of the internal image in the organization of the movement made it possible to formulate nine principles of organization of the virtual image. The stated principles can serve as a basis for creating an effective structure of the digital twin.

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