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CYBER-PHYSICAL SYSTEMS MULTILAYER PLATFORM AND RESEARCH FRAMEWORK

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Abstract: **The issues of cyber-physical systems creation and approaches to their solving are formed in the article. The base principles of the multilayer platform for Cyber-Physical Systems are formed in accordance with achievements and modern conceptions of computer, information and telecommunication technologies application. The structure of the multilayer platform for Cyber-Physical Systems are offered, its applications and functions are described. Future directions for research within the framework of each of six layers of the Cyber-Physical System and within the framework of its general organization are formed. The expected results from its implementation are defined.**

Key words: **cyber-physical systems, cybernetic tools, physical world, interaction with physical world, information acquisition, data processing, decision making, personal service**

I. INTRODUCTION

During last years there has been an increased activity in the field of cyber-physical systems (CPS) development. Cyber-Physical Systems are integrations of physical processes and cybernetic tools [1-3] which provide the organization of measuring and computing, secure storage and sharing of measuring and service information, organization and implementation of impacts on the physical processes. Integrating these components in one system enables to receive qualitatively new results which can be used to create a wide range of innovative scientific, technical and service tools.

Creating and using of CPS is comparable in scale and influence with the effect of the Internet creating (as network of the local computer networks with heterogeneous computing and networking devices). Some research teams believe that the purpose of CPS creation is to significantly increase the level of human interaction with the physical world just as the Internet has increased the level of interaction between people [4, 5].

On the basis of the CPS concept, leading research institutions and groups around the world aim at finding new areas of information and communication technologies (ICT) development by combining and integrating the subsystems which have different functions in a flexible decentralized system. Currently, this perspective has gained particular relevance due to the significant increase of the opportunities for practical implementation of measurement, computing and communication components of such systems based on modern technological advances in manufacturing of the integrated circuits and wireless communication tools. The scientific research in the field of CPS is viewed as a strategic area of the US National Science Foundation.

The predecessors of CPS were embedded computer systems, which have appeared in 80s and are widely used in modern electro-technical equipment. Among recent achievements there should be noted the conception of SmartDust (system of many tiny microelectromechanical systems such as sensors, robots, or other devices) [6], offered by the scientists of the University of California (Berkley) and supported by DARPA. As well as this there should be mention the conception of ubiquitous computing [7] and conception of ambient intelligence [8], directed to research the problems of joint activity of many embedded networked devices that are integrated into the environment. Further development of these works resulted in the emergence Internet of things conception [9] which provides presence of physical objects in the global computer network.

II. RESEARCH BACKGROUND

Despite the high relevance of research many problems of CPS creation remain unsolved. A key problem is the integration of heterogeneous components. The theoretical justification of CPS design principles is insufficient. The questions of functional completeness and synergistic effect of integrating the various components into the system, and many others still remain unanswered.

The approaches to CPS design are based on the analysis of the features of interaction between physical world and cybernetic tools (measuring, computing, communications, control and executive). These features, in particular, include the speed of the physical world processes (as compared with computing and communication capabilities of the cybernetic tools), the

type of physical world processes (linear, nonlinear, synergetic), the opportunities to determine the status of the physical world process (completeness of an information, accuracy), the opportunities to change the status of the physical world process and so on. Therein there is currently no theoretical basis that would allow to move from analysis of these features to synthesis of CPS [3].

The analysis of the scientific works in this area points to two rods of CPS components that have emerged due to outstanding achievements in the field of integrated physical, computer and ICT technologies:
Intelligent telecommunication tools that provide real-time data acquisition from the physical world and its delivery and information feedback from the cyberspace;
Cyberspace that provides intelligent data management, offers computational facilities and mathematical services to distinguish useful information, provides analytics and decision making.

Generalized cyber-physical system structure is shown in Fig. 1 [10].

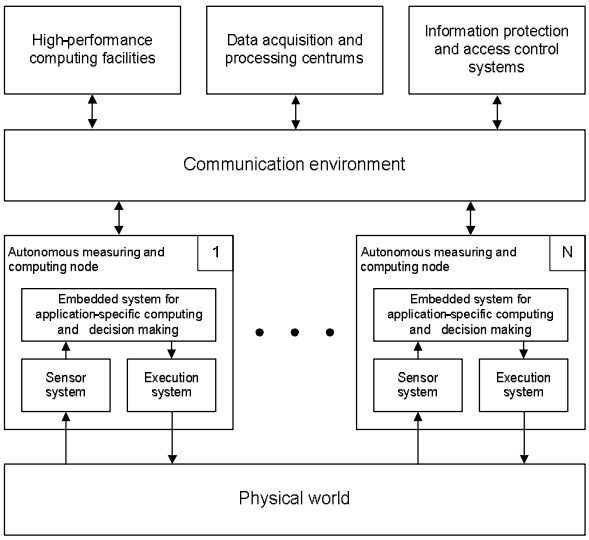

Fig. 1. Generalized cyber-physical system structure

CPS consists of a network of intelligent measuring and computing nodes combined by the communication environment and supported by high-performance computing facilities, information protection and access control systems and data acquisition and processing centrums.

This CPS structure is too general and does not disclose the possibility of effective consolidation of the efforts of a large number of groups that are working on CPS design and needs for detail and perfection, so that it will become a basis for integration of existing and future developments and for implementation of the available CPS.

III. PROBLEM STATEMENT

There is a necessity to examine the issues of CPS creating and approaches to address them using modern achievements and concepts of computer, information and communication technologies, and offer multilayer platform for CPS, which would ensure the integration of the methods and tools for measuring, processing, management, and information security.

IV. CPS RESEARCH CHALLENGES AND SOLUTIONS

Considering the results of previous work and gained experience [10] we can allocate the following main CPS research challenges:
To ensure the ability of integration in CPS a large number of different types of components;
To provide the user with needed information according to the interaction of the cybernetic tools with the physical world;
To provide high efficiency of CPS;
To effectively combine methods of centralized and decentralized CPS cybernetic tools management;
To provide such operation speed of cybernetic tools that allow achieving the desired quality of CPS operation;
To ensure the accumulation of acquired knowledge according to the interaction of the cybernetic tools with the physical world and their further use in the CPS;
To provide the identifiability of CPS components under conditions of dynamic change of its structure;
To ensure the secure functioning of the CPS.

Let us create the approaches to address those challenges.

The challenge of CPS components integration arises due to their heterogeneity and large number. Eventually, the task of integration into CPS the maximum number of physical world objects could be seen as strategic. The way to address this challenge is defined and the main decisions are worked out, especially in the global computer network – the Internet. This way is a comprehensive standardization of the CPS components information exchange technology.

To address the challenge of providing the user with needed information according to the interaction of the cybernetic tools with the physical world, the needed computing resources are entered to the cybernetic tools according to the CPS destination, and software packages that can distinguish useful information from the data streams received from the physical world. The signal and image processing technology and big data technology could be used here with their implementation on personal or cloud computer resources. Moreover, to distinguish and interpret useful information there may be required the technologies of computational intelligence, expert systems and self-learning.

To address the challenge of providing high efficiency of CPS is seen in intellectualizing of the information acquisition, transmission and processing. It presupposes efficient combination of centralized and decentralized control of CPS operation with main focus on decentralization and the artificial intelligence, which contains such elements of self-organization as self-configuring, self-tuning, self-prognosis, self-comparing, self-healing, self-protecting, self-learning.

To address the challenge of providing a required speed of CPS operation the analysis and selection of appropriate components of CPS has to be performed, both hardware and software, including selection of appropriate information exchange protocols.

To accumulate the gained knowledge and to use it in future CPS must include the facilities for large amounts of data archiving, supported by expert systems and self-learning technologies.

The challenges of CPS components recognition and their secure functioning are addressed through adaptation in CPS of appropriate computer network technologies.

V. CYBER-PHYSICAL SYSTEMS MULTILAYER PLATFORM

As the first major task of CPS creating, which will solve the above mentioned challenges, we see dividing it into independent hierarchical layers and development the principles of interaction between them. We believe that it will simplify the structural organization of CPS, its functioning and design.

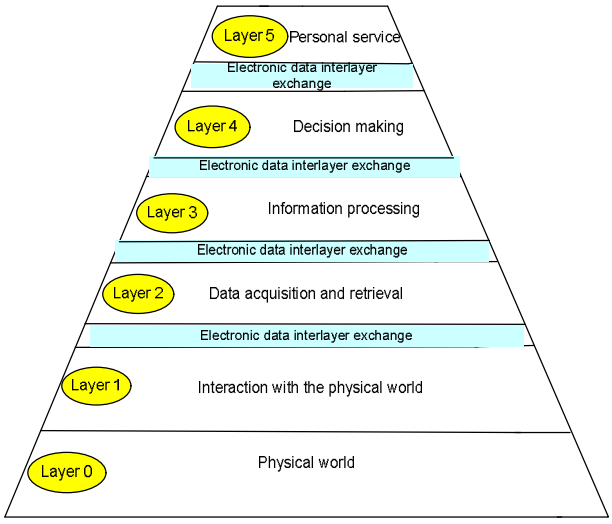

Fig. 2. CPS multilayer platform

In the basis of the proposed approach lies the development of the principles of CPS designing and operating as a multilayer, scalable, flexible and extensible platform, which provides protected interaction of measuring, computing, control, communication and executive components (Fig. 2). Ensuring the functional completeness of the different-purpose components of the platform and achieving synergies from their merger will bring the research and control of physical processes (environment, technological processes, research facilities, etc.) to a new level. Ensuring scalability, flexibility and extensibility will open the opportunities for application of the multilayer platform as the basis for a wide spectrum of CPS. We expect also development and implementation of the main components of multilayer platform in consideration of their further interaction within the frame of this approach.

The brief description of the CPS components according to its layers depicted in Fig. 2 is presented below, and the analysis of the research which is primarily to encountered from our point of view during the multilayer platform creation.

VI. CPS MULTILAYER PLATFORM RESEARCH FRAMEWORK

A. Physical world

The physical world is extremely diverse and multifaceted. It includes physical objects, biological objects, physical fields, Earth atmosphere, outer space, technological processes, social processes, technical systems, water and underwater objects, land and underground objects, the environment and so on.

The main types of interaction with the physical world include:

1. Measurement of certain characteristics of the physical world components including level of illumination, light intensity, temperature, depth, magnetic field intensity etc;
2. Monitoring the physical world components, including the behavior of animals, insects, plants, changes in the earth's magnetic field, in particular, in order to predict earthquakes, and more;
3. Formation of the physical world components, primarily by creating a variety of products, three-dimensional printing, growing crystals, growing plants, etc.;
4. Some impact on the physical world components, in particular, control of vehicles, production lines, electricity supply, heat supply, etc.;
5. Interaction between CPS and its users.
6. Tools of interaction with the physical world
7. According to the main types of interaction a list of tools of interaction with the physical world can be formed, which includes the following:
8. The physical world components characteristics measuring tools, which are used for measurements and have normalized metrological properties. They include measures of physical quantities; measuring instruments; transducers; measuring equipment; information-measuring systems; measuring-computing complexes, particular glucometers, thermometers, tonometers, magnetometers, etc.
9. The physical world components monitoring tools. These are different specially designed devices that act as a continuation and strengthening of the human senses, and also devices used as an instrument of influence on the physical world components (which transform observations on the part of experimental activities), where under the supervision one understands method of scientific research that is active, systematic, purposeful, and deliberate perception of the physical world component during which one gains knowledge about external aspects, properties and relationships of the studied component. They include video cameras, photo cameras, night vision devices, telescopes, latches of

vibrations, movement, levels, and other changes in the physical world.

10. The physical world components production facilities, in particular the production line, 3d printer, intensive agriculture, etc.

11. The physical world components controlling tools. These are specially designed various devices that act as a continuation and strengthening of the human body movement and used as a tools of influence on the physical world components in particular controllers, valves, brakes.

12. CPS-user interaction tools, including touch screens, keyboard, intelligent lighting systems, audio-video systems, vending systems, automated payment systems, etc.

In addition to research methods and means of improving the technical characteristics of the tools of interaction with the physical world the new research challenges which are to be solved arise during the multilayer basic CPS platform creation.

This particular classification study of modern sensors of the basic physical quantities and signals, research of the multi-sensor systems that provide measurement of several physical quantities, development of methods for combining sets of sensors in one sensor system, including selection of the optimal set of the physical processes parameters, and also sensor fusion. Among the priorities there is the creation of the methods and technologies for intellectualization of the tools for interaction with the physical world, including research and development of smart sensor systems, which provide application of the digital accuracy improvement methods, the use of auto-calibration, auto-tuning, reducing energy consumption and so on.

Apart stand questions of research and development of the CPS-user interaction intelligent systems, including intellectual touch screens, intelligent lighting systems, audio-video systems and other technical means for life intellectualization, automated payment systems, etc., as well as the creation of models of the executive systems.

An important component of the tools of interaction with the physical world is the interfaces of sensor and executive systems, creation of which is one of the priorities of the first CPS layer. In the first place it is necessary to conduct research and development of the universal interfaces of the sensor and executive systems, to explore the tools of interaction with the physical world from a position of their communication with other layers of CPS, including the information flow intensity. The result of these studies should be developing the basic protocols of information exchange between the layer 1 and higher CPS layers.

An important focus of CPS layer 1 is the development of requirements for information processing on 3th CPS layer and concerning the decision-making on the CPS layer 4 on the basis of the results of information processing obtained during the interaction with the physical world.

B. Data acquisition and retrieval tools

Data acquisition and retrieval tools are designed for real-time data acquisition from the physical world components characteristics measuring tools and its preprocessing, the same as from the physical world components monitoring tools and from the CPS-user interaction tools, as well as to deliver measurement and performance information to the physical world components controlling tools, to the physical world components production facilities and to the CPS-user interaction tools. They include the intelligent sensor systems, sensor networks, both wireless and mobile, distributed systems based on the autonomous exploration stations.

On the basis of the CPS multilayer platform concept at first it is necessary to revise the traditional approaches at this layer and to hold deep studies of the methods and real-time data acquisition tools from the physical world components characteristics measuring tools, from the physical world components monitoring tools, the methods and real-time information retrieval to the physical world components controlling tools, to the physical world components production facilities, especially from the perspective of their interaction with other CPS layers providing the necessary intensity of information flows. The result of these studies should be the basic data acquisition and retrieval principles at the CPS layer 2, the basic decision-making principles at the CPS layer 4 concerning data acquisition and retrieval and, as a result, basic protocols of data acquisition and retrieval.

As the hardware basis for the data acquisition and retrieval tools we suppose to use the distributed systems based on autonomous exploration stations, consisting of autonomous measuring and computing nodes. To create these distributed systems the research in some new directions must be undertaken, particularly in the architecture of the multilevel configurable distributed systems, in the methods and algorithms for structural adaptation of the measurement and computing processes, in the algorithms for decentralized planning and distribution of the measuring and computing problems, in the algorithms and methods of the autonomous measuring and computing nodes collective behavior, in the methods of the adaptive measurement and computing processes organization. The result of these investigations should be the protocols for control and monitoring of the autonomous measuring and computing nodes and protocols of their interaction ensuring the decentralized control and self-organization.

C. Information processing tools

Information processing tools are intended for real-time information processing received from the physical world components characteristics measuring tools and from the physical world components monitoring tools with the aim of the useful information selection and forming for the CPS layer 4 and also to raise the level of protection, data transmission speed, reducing the volume of storage, dispatch reliability and so on.

Information processing tools include a wide range of hardware and software that provide centralized and distributed processing of large data streams on complex algorithms. The CPS specifics indicate that there are at first worth considering tools reachable through the computer networks. There should be viewed such modern data processing technologies as grid systems, cloud technology, big data, which are based on the computer networks technologies and high-performance computing.

At this layer at first there must be held research into the methods and tools for real-time information processing received from the physical world components characteristics measuring tools and from the physical world components monitoring tools, the result of which should be the basic principles of information processing at the CPS layer 3. In addition, it is necessary to develop the methods, tools and protocols for interactions with other CPS layers with consideration of the information flow intensity. Particular attention in the process of this layer tools creating need to be paid to big data technology, adaptive hardware and to research and development of evolvable hardware. It is clear that it is important there to continue the research into configurable and self-configurable high-performance computer systems creating including signal and image processing and analysis tools and information protection tools. When designing these tools, the emphasis is to be made on the use of cloud technology and mobile computing. An important research area is the development of methods and tools for the research objects processing models, their hardware and software virtualization.

D. Decision making tools

Decision making tools are intended to create statistics and decision making based on the user requests and the results of real-time information processing received from the physical world components characteristics measuring tools and from the physical world components monitoring tools.

CPS implementation at this level requires detailed knowledge on the investigated or controlled physical world object, which requires creation of the expert systems with elements of self-learning and other artificial intelligence technologies to help users make the right decision. At this level the feedback from cyberspace to physical word is formed so that CPS is able to self-organize, self-configure and adapt to the solved problems. Corrective and preventive solutions can be applied there. Therefore, the priority of research at this level should include the methods and tools for decision making creation on the basis of real-time information processing from the physical world components characteristics measuring tools and from the physical world components monitoring tools to create the basic principles of information processing at the CPS layer 4. Another important issue is the study of the decision making tools interaction with other CPS layers, taking into account the information flow intensity in order to develop the interaction protocols.

To ensure the high level of research such advanced technologies as decision support systems, data mining, and big data, machine learning must be implemented at this layer. The methods of measuring, computational and research problems planning and scheduling, including multi-user mode and multi-agent technologies, must be used there taking into account the CPS specifics.

E. Personal service tools

Personal service tools provide user interaction with CPS and provide them with services according to the CPS destination. They include access servers, mobile computer tools, particularly personal digital assistants with the appropriate software. The main research problems of this layer are the personal service methods and tools creating the same as the basic principles of received information processing, research and development of generalized models of user interaction (groups of users) with autonomous CPS. Another challenge is research of personal service tools from the perspective of their interaction with the other CPS layers taking into account the information flow intensity to create the basic interaction protocols. Also, the methods for user behavior predicting and methods of user interaction interfaces adapting to CPS must be researched and developed.

Another issue of this layer is the study of the problems of the targeted CPS creating designed in particular to provide the protection and monitoring services on the CPS multilayer platform, environment monitoring services, GIS and transport logistics services, payment and access control services, social interaction of users support service, minerals searching services, objects identification and others.

Organization of protected interlayer information interaction

The organization of protected interlayer information interaction is one more issue in CPS design. Resolving this issue requires the development of the methods and tools of information protection taking into account the CPS specifics. It is necessary to define the requirements to the levels of information security in CPS, justify the necessary level of interlayer exchange security and build information security system in CPS on the basis of confidentiality, integrity, authenticity and models of secure information exchange in a multilayer CPS. The result of these studies should be the principles of secure exchange, processing and storage of measurement and service information, including the methods to ensure confidentiality, integrity and authenticity of information, technical and cryptographic protection of information links between the CPS components and control of the access to them, methodological principles of informational and functional safety.

VII. EXPECTED RESULTS FROM THE MULTILAYER PLATFORM INTRODUCTION

Creating the proposed multilayer platform should significantly influence the overall CPS development. On this basis the CPS of various applications could be built, including transport, medical, agricultural, exploration, military. The above mentioned main CPS research challenges, namely the possibility of a large number of different types of components integrating, high efficiency of operating, high level of service and others. The new scientific knowledge of CPS design will be obtained, including new methods and tools for: integrating the sets of sensors inside one sensor system, combining measurement information, intellectualizing the tools for interaction with the physical world, interactive CPS-user interaction; information CPS interlayer interaction; real-time information acquisition, monitoring the physical world components, data retrieval to the physical world components monitoring tools and to the physical world components production facilities; structural adaptation of the measurement and computing processes, decentralized planning and distribution of the measurement computing problems, organization of collective behavior of the measurement and computing autonomous nodes, organization of adaptive measurement and computing processes; organization of the real-time information processing from the tools of interaction with the physical world and making decisions on the result of its processing; CPS personal service, user interaction with autonomous CPS, prediction of the user behavior and adaptation of the user-CPS interaction interfaces; secure information exchange in the CPS, processing and storage of the measurement and service information.

The created bases of the CPS multilayer platforms, the new methods of integration and interaction organization of the CPS measurement, computing and executive components will provide high efficiency of planning and executing the complex problems of target objects research and management that cannot be solved with the help of today available tools. The obtained results will be a foundation for future generation CPS development. They can be used to build arbitrary CPS, including industrial and military applications.

VIII. CONCLUSIONS

The problems of CPS creating and directions of their development in accordance with the achievements and modern concepts of computer, information and telecommunication technologies applications have been considered. The challenges of CPS design have been outlined and the principles of their multilayer platform have been suggested. The research framework within the CPS multilayer platform has been formed and the expected results from its implementation have been defined.

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