Chapter

Interaction of Mechatronic Modules in Distributed Technological Installations

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Abstract

The article deals with the interaction of mechatronic devices in real time through events and messages. The interaction of distributed network devices is necessary to coordinate their work, including synchronization when implementing a distributed algorithm. The approach in the development of a distributed control system (DCS) for mechatronic devices based on the IEC 61499 standard has been analyzed. Using only a LAN for interaction purposes is not always justified, since messages transmitted over a LAN do not provide transmission determinism. To eliminate this problem, a fast local network is needed, which would not utilize resources of the main computer and hardware (e.g., based on the model of terminal machines) to carry out a network communication. It is proposed to implement LAN controllers on the field-programmable gate array (FPGA) platform. Data-strobe coding (DS coding) with a signal level of LVDS was used for keeping the transmitted data intact and improving the overall reliability of the systems.

Keywords: real-time interaction, mechatronic devices, IEC 61499 standard, distributed control systems, field-programmable gate array, a distributed algorithm

1. Introduction

Technological process automation of large industrial or scientific complexes, where there is a large territorial and algorithmic distribution, is related to the development of network systems that provide interaction of individual technological installations. Usually, a telecommunications system acts as the abovementioned network system. In the general case, each installation executes its own part of a given algorithm, operating in an autonomous mode, after which it sends results to other installations. Algorithm execution can result in some informational data, materials, products, etc. A majority of industrial complexes work according to these technologies. Another case is when the result of a distributed technological system work is created by majority of technological subsystems together in real time and the technological processes are related.

The development of technology process management systems is related to building a model through input parameters and current process state parameter formalization. Real-time management of linked, territorial, and algorithmically distributed technology systems with parallel processes is pretty challenging. Additional difficulties appear when linked mechatronic devices that form mechatronic systems are used as an executive object.

Mechatronic components (MCs) can be defined as devices that combine precise mechanical units with electronic computing and management components, interface, and power modules. Such combination allows implementing new features that extend existing functions of the device. At the same time, all mechatronic units work on general task defined for all units. Over the past decades, the MC definition has significantly expanded, and mechatronics became an interdisciplinary industry that can include such disciplines as telecom, robotics, power electronics, etc.

MCs are most commonly used in industries where there are requirements like executing mechanisms' precise positioning, computers' fast response on internal and external events, increased reliability, and limited dimensions.

Very often electronic control components of MC are called embedded control system, which assumes completeness and self-sufficiency of these systems and uses software for running it. Modern MUs that are used in distributed systems have high-performance computers that work within OS environment with support of all common network protocols.

At this moment, MUs and MCs are commonly used as distributed process system (DPS) automation object. All major requirements to MCs as DPS objects are described in article [1]. MCs must have:

- Signal (event) and data interface for interacting with other MDs
- Managed process parameters I/O interface
- Dataset for keeping managed object state
- Manage algorithm for this object.

The chapter is organized as follows. Section 2 provides an analysis of work related to the design of distributed control systems (DCSs) based on the standards IEC 61131-3 [2] and IEC 61499 [3]. Section 3 discusses hardware and software solutions for the implementation of the interaction of mechatronic components. Finally, the conclusion is given in Section 4.

2. Interaction of mechatronic modules in distributed technological systems based on IEC 61131-3 and IEC 61499 standards

2.1 Centralized mechatronic objects control based on standard IEC 61131-3

The IEC 61131-3 [2] standard plays a big role in the automation of technological systems that contain mechatronic blocks. The establishment of this standard allowed unifying development languages of managing applications for programmable logic controller (PLC), which allowed to port developed projects to PLCs manufactured by various vendors. One of graphical languages described by the standard is function block diagram (FBD) language. This language uses the FB concept, which represents part of the program managing code and has an input and output interfaces. The FB interface has special entry calls—event inputs. FBs are combined into chains using interfaces. One of the disadvantages of the FBD language is that a random FB cannot be invoked from a chain.

The PLC software development technology based on the IEC 61131-3 standard is designed for centralized management, which means that direct interaction of separate PLCs is carried through the central computer. This disadvantage makes it significantly more difficult to develop applications for DCSs. When a new PLC is added to the management system or there is a change of PLC interaction algorithm, the central computer program must be changed. Therefore, configuration and scaling of such systems requires sophisticated procedures and takes significant amount of time. Besides that, there is no way to interact directly with distributed technological systems, MCs.

New developments in microelectronics and circuitry allow eliminating some of disadvantages. Thus using a system on a chip (SoC) technology, Altera (Intel) company offered to realize PLC on a crystal, by connecting high-performance dual-core ARM processor and field-programmable gate array (FPGA). This allowed processing of input events in parallel and configuring managing application algorithm remotely [4].

2.2 Distributed control systems on standard IEC 61499

In 2005, a new standard IEC 61499 [4] has been established, which defines a new way of building distributed technological process management systems. The IEC 61499 architecture is based on IEC 61131-3 definitions and uses FBs with extended interface abilities. One of the main FB extensions is an event interface, which allows defining FB execution order explicitly. Each FB can contain several encapsulated algorithms that cannot be accessed from other FBs.

A management system, based on IEC 61499, represents a set of devices that interact with each other using communication network. The management system implements functions described with applications. These applications can be distributed between several devices that can be represented by PLCs, programmable automation controllers (PACs) [5], and digital computers based on FPGA [6] platform. Each device consists of one or several resources. Resource is a functional unit that can manage its operations independently, including algorithm execution. An application is represented by several linked FBs that can be executed on different resources and management system devices.

IEC 614999 FB is an independent program unit that can be created, tested, and used separately from other FBs [3, 7]. The IEC 61499 standard defines three types of blocks: basic function block, service interface function block (mechatronic devices interact using these blocks), and composite function block (contains chain of FBs). **Figure 1** shows the IEC 61499 application model that consists of three FBs combined into one network that is used for events and data flows. FBs can be in certain states, set by function algorithm of the FB. Transfer from one state to another can be triggered by an event, received from a neighbor FB.

The main advantage of designing management systems based on the IEC 61499 standard is simplicity of reconfiguration, flexibility, and reduced development time, reusing developed components and scalability. Article [8] analyzes features of this method of developing distributed technological systems, its advantages and

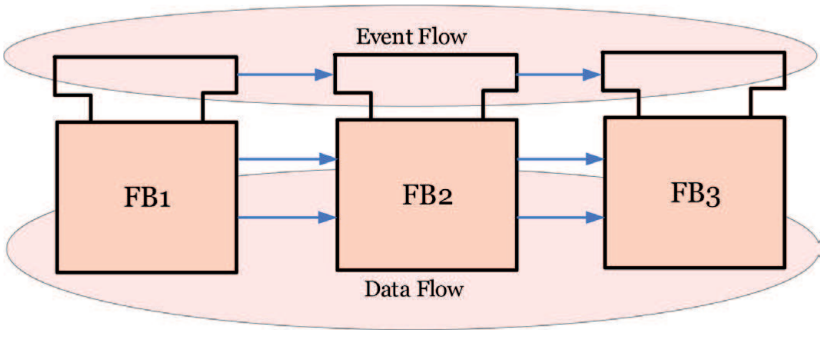

Figure 1.
IEC 61499 application model.

disadvantages. For keeping backward compatibility while moving from developing managing applications based on PLC IEC 61131-3 to applications based on IEC 61499, there is a methodology based on web technologies [9]. The main goal set in that article is to keep the identity of application behavior when launched on the IEC 61499 platform.

The DPS stability is defined by distinctness of executing applications. The IEC 61499 standard defines FB as an abstract model, which allows various FB behavior interpretations. Article [10] analyzes FB execution models. The standards sections related to the base FB semantics describe a situation, when only one FB can be active at any period of time within one network. This limitation allows to develop execution models in two directions: serial and cyclic (by analogy with PLC cyclic processing) models.

However, the evolution of multiprocessor and multicore computers allows running a parallel model. Article [11] contains suggestions about running such models. Besides, a parallel-type model can be implemented on FPGAs with the ability to use real parallelism, which is very important for mechatronic systems that are critical to the response time to incoming events.

Article [12] defines the Intelligent Mechatronic Component (IMC) and describes the conditions of using such components in DPS based on IEC 61499. Any IMC can contain the following elements:

- Be a mechatronic device, thus to represent a physical functional device with sensors, actuators, and electronic circuits

- An integrated control device, which is a computing device that includes interfaces to sensors, actuators, and communication networks, for interaction with other IMCs

- Software with data support and control logic for implementing automation functions of IEC 61499 standard

Most of the works related to the development of automation projects based on IEC 61499 are of research in nature. Despite the obvious advantages of the standard (described earlier) in the design of distributed control systems, widespread implementation in the industry has not yet happened. Article [13] describes problems of the standard that prevent it from being fully used: semantic problems, the lack of well-developed design methodologies, restrictions on the use of various execution models, and others. There is also a lack of integrated design methodologies that facilitate component-based design throughout the design cycle of automation systems [12].

The standard is being developed, and its individual provisions are being clarified. For practical use, the IEC 61499 compliance profile [14] is issued and constantly updated. There are commercial development tools for creating projects that meet the IEC 61499 standard. The most well-known project is ISaGRAF [15], in the form of a design support tool (workbench), which works with both the IEC 61131-3 and IEC 61499 standards. The nxtSTUDIO commercial system project [16] focuses exclusively on IEC 61499 and allows combining a distributed control system with HMI/SCADA. In addition, nxtSTUDIO makes it possible to automate the process of building communication channels between controllers of mechatronic devices of a distributed system.

3. Hardware and software solutions for organizing interaction of mechatronic components using local networks

The development of microelectronics and information technology allows creating miniature computers with low power consumption and high performance, which can be embedded not only in technological systems but also in individual elements of these systems, including mechatronic devices. This feature, as mentioned above, makes it possible to create intelligent subsystems combined by a global or local communication network.

The concept of the Internet of Things (IoT) [17], successfully introduced into production, gave an impetus to the development of a new direction that unites robots or robotic devices using network technologies. This direction, called the Internet of Robotic Things (IoRT), is aimed at implementing robotic technologies, by extending the functionality of IoT devices. In [18], the IoRT concept is presented, which emphasizes the tremendous flexibility in developing and implementing new applications for networked robotics while achieving the goal of providing distributed computing resources as the main utility. In these network associations (IoT and IoRT), the term "Internet" can be interpreted as a global association of computer networks that use TCP/IP protocols when interacting with each other. In addition, the participants of network associations use a huge variety of interfaces and protocols when receiving information from sensors and transmitting control signals to actuators.

By analogy with the network associations of functional devices given above, we can speak about the Internet of Mechatronic Components, a subset of which is IoRT. On the other hand, in distributed technological systems among the participants, there can be not only MCs but also, for example, self-sufficient electrical devices with integrated intelligence, that is, devices that do not include mechanics. Self-sufficiency means the ability of devices to solve independently a part of a distributed technological problem delegated to them, but which need to exchange information with other participants through the formation of events or messages. Conditionally, such devices can be called functional network connectivity (FNC).

3.1 FNC-embedded computer

Article [19] presents a methodology for creating a prototype intelligent power electronic converter (iPEC) with the ability to remotely control and interact with other DPS devices. In the developed iPEC prototype, the power module implements the function of a powerful generator of infra-low-frequency voltage. This generator can be used to power equipment (piezoelectric elements) for ultrasonic cleaning of parts or for solving geophysical tasks (cleaning of wells). An example of iPEC-type device use can be found in article [20]. This article presents solution of the technological problem of the formation of a uniform effect of ultrasonic vibrations in a liquid medium on the processed. To solve the problem, it is proposed to use a whole matrix of distributed ultrasound transducers placed in a certain way. Control signals arriving at the transducers are formed in such a way that areas with low and high pressure of the ultrasonic field arise, which causes the occurrence of directional flows and contributes to the cleaning of products. Drivers of control signals are subject to stringent requirements for response time.

The given example shows the need to create a universal built-in control module, both as part of MCs and as part of other DPS participants, that could provide execution of the following main tasks:

- Global network communication task
- Local network communication task
- Management task for the implementation of the built-in algorithm
- Sensor data processing task

In a distributed technological system, participants called as FNCs can be used as independent technological subsystems, or they can be clustered, by analogy with the composite function block (IEC 61499). On this basis, the interaction of individual FNCs can be carried out over several communication networks—global and local. The global network is available to all exchange participants, and the local network is available only to cluster devices. When interacting over a local network, an additional requirement is added—the determinism of the transmitted events and messages.

The interaction of DPS devices is necessary to coordinate their work, including synchronization when implementing a distributed algorithm. Article [19] justifies the use of the hybrid configuration of the computational control part of FNC-type devices. A device can contain several different computators, based on various calculation models. These can be computators implemented on processors with ARM architecture [21] and on the FPGA platform. Sharing two different computers gives the most flexible functionality.

Important benefits of using ARM controllers in FNC are high performance and low power consumption. This makes it possible to build a universal-embedded computer for both stationary technological systems and mobile ones. For example, in computers based on the Smart Mobility ARChitecture (SMARC) standard [22], ARM controllers are widely used.

ARM controllers used in the FNC solve the following tasks: communication over a global network, downloading computer configurations, implementing an embedded algorithm, implementing cloud technologies, video processing of objects for machine vision, etc. Global network controllers must support TCP/IP protocols, which are typically present in modern embedded computers. The exchange between mobile autonomous objects, for example, automatic guided vehicle (AGV) [23], requires a wireless network controller as part of the network module.

The ideology of random access to the network is not suitable for solving the problem of interaction between FNC-cluster devices, since it is impossible to ensure the determinism of message delivery. Therefore, a fast local network is needed, which would not utilize resources of the microcontroller and hardware (e.g., based on the model of finite automata) to carry out a network exchange. Also, it is necessary to use a special encoding at the signal level when transmitting events and messages, for keeping the transmitted data intact and improving the overall reliability of the systems. Controllers of such a network are usually implemented on the FPGA platform. When creating equipment based on FPGA for technological installations of the accelerator complex [24], the implementation of the exchange based on data-strobe coding (DS coding) network signals with the signal level LVDS [25] showed a good result. LVDS levels have high noise immunity and energy efficiency. DS coding allows you to transfer data at high speeds without first agreeing the speeds between the calculators of the two devices. At a speed of 100 Mb/s, the length of the communication line can be within 30 m. DS coding has been successfully applied in the aerospace industry within the framework of the SpaceWire standard, where increased requirements are applied to the reliability of transmitted data [26]. Another option for organizing a local network can be using the MIL-1553 interface. Article [27] describes a network for transmitting events and messages for technological subsystems of the accelerator complex.

Figure 2 shows an example of the simplified structure of the FNC computer, which includes support for communication over local and global networks. The computer contains:

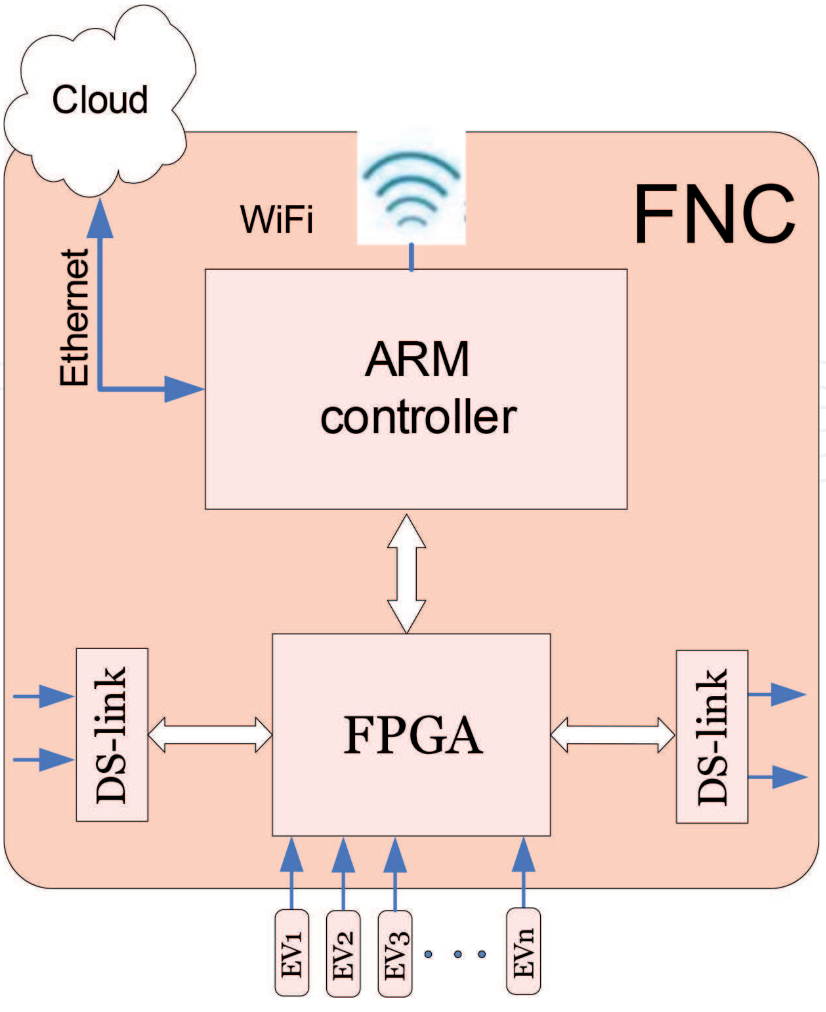

Figure 2.
FNC-embedded computer.

- ARM controller for wired and wireless networking with other members of the global network
- LAN controller on the FPGA platform
- FPGA signal level converters to LVDS levels (DS links).

FPGA FNC-embedded computer receives events (EV1.EVn) that must be transferred to other FNCs of the cluster. **Figure 2** does not show network support for the lower level of the sensors. Thus, we can conclude that, for full-fledged work as part of a distributed technological system, each FNC should have at least three levels of network support.

3.2 Communication network configuration

The choice of the type and number of communication networks in DPS is determined by many factors: the technological problem to be solved, the network configuration chosen, geographical distribution of the interacting subsystems, and so on. Article [28] justifies a circular network configuration consisting of series-connected MCs. Serial network is formed using a single duplex DS link. Messages are transmitted sequentially from one MC to another using a DS interface and can have a broadcast status or contain the address of a particular MC. To control the

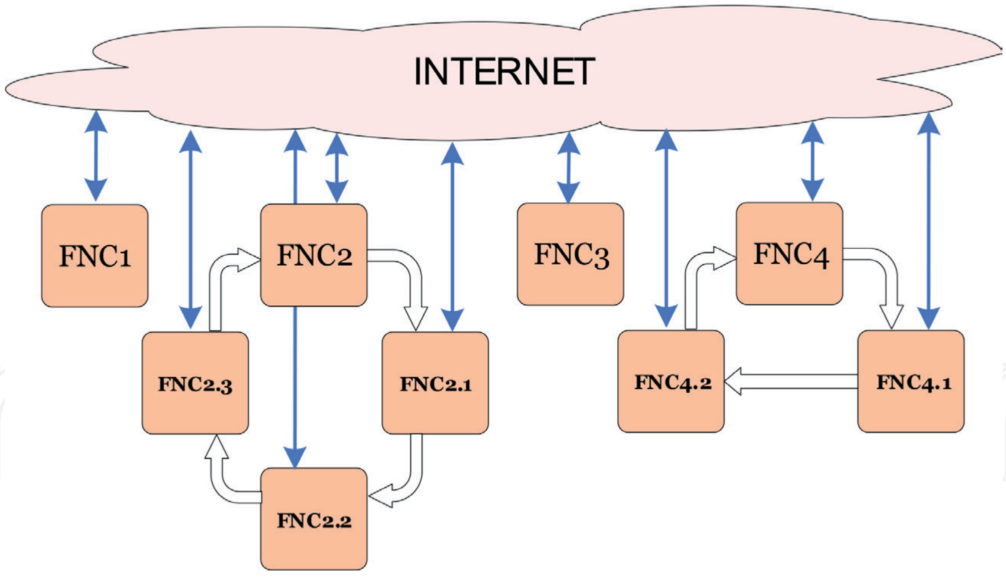

Figure 3.
FNC networks.

passage of messages, the last MC is connected to the first. The advantages of a ring serial network are as follows:

- DS link of each MC is a network repeater and amplifier that allows you to maintain a high speed with a large number of mechatronic devices.

- It is possible to control the transmitted message for accuracy and transmission time upon return after passing through the entire network.

- Message transmission time is strictly determined.

Figure 3 shows the structure of a distributed technological system with two communication networks—global and local. Each FNC device may be a specific functional technological unit. It can be a mechatronic module, individual components of a robotic system, or a power converter. The devices FNC2, FNC2.1, FNC2.2, and FNC2.3 and FNC4, FNC4.1, and FNC4.2 are clustered.

Each FNC device has access to the global network to perform tasks that require access to common databases: reconfiguration, transfer of measured process parameters or video data, and so on. Only FNC1, FNC2, FNC3, and FNC4 exchange event control via the global network. Devices within clusters transmit messages sequentially within the cluster.

4. Conclusion

Intellectualization of mechatronic devices allows expanding the functionality of technological systems. The intelligence of the MCs is provided by the increased computational performance of the controllers, the additional real-time video processing capability, and high sensory sensitivity. Many algorithmic problems that were previously solved with the involvement of a centralized computer can now be solved at the level of the mechatronic component itself. The increased intelligence of the MCs adds increased requirements for organizing the design of distributed control systems, complicating the solution of the problem of interaction of distributed technological subsystems. A rather long implementation of the IEC 61499 standard showed the complexity of the problem to be solved. The development of mechatronic components as network devices goes toward the unification of embedded computers on the proposed computing and communication services. Standards for the design of distributed control systems are being implemented, which determine the ideology of the interaction of a distributed algorithm of a technological problem.

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References

[1] Panjaitan S, Frey G. Functional control objects in distributed automation systems. IFAC Proceedings Volumes. 2007;**40**(3):259-264

[2] International Standard IEC 61131-3 (edition 2.0): Programmable Controllers/ International Electrotechnical Commission; Geneva; 2003. p. 230

[3] International Standard IEC 61499. Function blocks for industrial-process measurement and control systems. Part 1: Architecture/International Electrotechnical Commission; Geneva; 2005. p. 245

[4] Integrating PLC Systems on a Single FPGA or SoC. Available from: https://www.intel.com/content/dam/www/programmable/us/en/pdfs/literature/po/ss-plc-on-a-single-chip.pdf [Accessed: 28 May 2019]

[5] Programmable Automation Controller. Available from: http://www.cannonautomata-products.com/programmable-automation-controller.html [Accessed: 28 May 2019]

[6] O'Sullivan D, Heffernan D. VHDL architecture for IEC 61499 function blocks. IET Computers and Digital Techniques. 2010;**4**(6):515-524

[7] Dubinin V, Vyatkin V. On definition of a formal model for IEC 61499 function blocks. EURASIP Journal Embedded Systems. 2008;**2008**:1-10

[8] Vyatkin V. IEC 61499 as enabler of distributed and intelligent automation: State of the art review. IEEE Transactions on Industrial Informatics. 2011;**7**(4):768-781

[9] Dai W, Dubinin VN, Vyatkin V. Migration from PLC to IEC 61499 using semantic web technologies. IEEE Transactions on Systems, Man, and Cybernetics. 2013;**44**(3):277-291

[10] Vyatkin V. The IEC 61499 standard and its semantics. IEEE Industrial Electronics Magazine. 2009;**3**:40-48

[11] Vyatkin V, Dubinin V, Ferrarini LM, Veber C. Alternatives for execution semantics of IEC61499. In: 5th IEEE Conference on Industrial Informatics; Vienna; 2007. pp. 1151-1156

[12] Pang C, Vyatkin V. IEC 61499 function block implementation of intelligent mechatronic component. In: 8th IEEE Conference on Industrial Informatics (INDIN 2010); 2010. pp. 1124-1129

[13] Thramboulidis K. IEC 61499 in factory automation. Advances in Computer, Information, and Systems Sciences, and Engineering. 2006: 115-124. Available from: https://doi.org/10.1007/1-4020-5261-8

[14] IEC 61499 Compliance Profile for Feasibility Demonstrations. Available from: https://www.holobloc.com/doc/ita/index.htm [Accessed: 28 May 2019]

[15] ISaGRAF Technology. Available from: https://www.rockwellautomation.com/global/detail.page?pagetitle=Isagraf&content_type=tech_data&docid=209076c017d6dd586c895e9e3a4856e4&redirect_type=tld&redirect_url=www.isagraf.com [Accessed: 28 May 2019]

[16] nxtSTUDIO. Available from: https://www.nxtcontrol.com/en/engineering/ [Accessed: 28 May 2019]

[17] Javed B, Iqbal MW, Abbas H. Internet of things (IoT) design considerations for developers and manufacturers. ICC2017

[18] Ray PP. Internet of robotic things: Concept technologies and challenges. IEEE Access. 2017;**4**:9489-9500

[19] Kokovin V, Diagilev V, Halik J, Uvaysova S. Intelligent power electronic converter for wired and wireless distributed applications. In: Proceedings of the IEEE International Conference SED-2019; 23-24 April 2019; Prague: IEEE; 2019. (in the press)

[20] Dostanko AP, Avakov SM, Ageev OA. Tekhnologicheskie Kompleksy Integrirovannykh Protsessov Proizvodstva Izdeliy Elektroniki [Technological Systems Integrated Production Processes of Electronics Products]. Belorusskaya nauka: Minsk; 2016. pp. 5-25

[21] Available from: https://www.arm.com/ [Accessed: 28 May 2019]

[22] Smart Mobility ARChitecture Hardware Specification. Available from: https://sget.org/standards/smarc/ [Accessed: 28 May 2019]

[23] Available from: http://www.roboticautomation.com.au/agvs [Accessed: 28 May 2019]

[24] Kalinin AY, Kokovin VA, Kryshkin VI, Skvortsov VV. An absolute intensity beam monitor. Instruments and Experimental Techniques. 2016;**59**(4):536-358

[25] ANSI/TIA/EIA-644-1995. Electrical characteristics of low voltage differential signaling (LVDS) interface circuits; 1995

[26] SpaceWire Standard. ECSS—Space Engineering. "SpaceWire—Links, nodes, routers and networks." ECSS-E-ST-50-12C; Rev1 Draft D; November 2014

[27] Komarov V, Antonichev G, Kim L, Kokovin V, et al. Modernization of U-70 general timing system. In: Proceedings of ICALEPCS-2005; Geneva, Switzerland; 10-14 October 2005

[28] Kokovin VA, Evsikov AA. Event-related interaction of mechatronic modules in distributed technological installations. Mechanical Engineering Research and Education. 2018;**5**:12