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DESIGN OF INFORMATION AND MEASUREMENT SYSTEMS WITHIN THE INDUSTRY 4.0 PARADIGM

The subject *of the study is the process of Information and Measuring System (IMS) designing as a component of the Cyber-Physical System (CPS) in the paradigm of Industry 4.0 (I4.0).* ***The aim*** *of the study is to develop methodological support for the design of IMS and Automatic Control Systems (ACS) as components of production CPS (CPPS), in particular, for Digital Factory.* ***Objectives:*** *to determine the conceptual model of IMS; choose the IoT model for structural synthesis, select the appropriate regulatory (sets of standards and implementation models) and hardware; perform R&D of IMS based on NB-IoT sensors; formalize the procedure for integrating components into the CPPS, develop the Asset Administration Shell. The methods used are: heuristic synthesis methods, experimental planning theory. The following* ***results*** *were obtained. The key role of optimally designed IMS level 4.0 in increased decision-making accuracy in CPPS management and control processes is demonstrated. The quality of control is improved both by quickly obtaining accurate information for updating models in cyber add-ons, and at the physical level, in ACS. The universal model of IMS implementation in CPPS was proposed. The stages of choosing the concept, structure, hardware and communication protocols of the IIoT ecosystem IMS + ACS have been performed. The methodology was tested during the development of the NB-IoT Tech remote monitoring system, which has a decentralized structure for collection data on resources consumed. The integration of the ecosystem as a component of CPPS at the appropriate levels of the architectural model RAMI 4.0 has been performed. Regulatory support has been formed and the functional aspect of the Asset Administrative Shell for CPPS integration has been developed.* ***Conclusions.*** *Scientific novelty: it is proposed to design the IMS as a component of the AAS of the cyber-physical system, according to the implementation methodology of its subsystems at the corresponding levels of RAMI4.0 and the selected IoT model. The new approach, called "soft digitalization", combines the approaches of Industry 3.0 and 4.0, it is designed for the sustainable development of automated systems to the level of cyber-physical systems and is relevant for the recovery of the economy of Ukraine. Practical significance of the results: the IoT-Tech system based on Smart sensors has been developed and tested. This information and measurement system is non-volatile and adapted to measure any parameters in automated systems of various levels of digitization.*

Keywords: *Cyber-physical production system; Industrial internet of things; architectural model; regulatory support; Information and measurement system; NB-IoT technologies; Asset administration shell.*

Introduction

The fourth industrial revolution [1] is characterized by the fact that "things" (cars, houses, enterprises, even entire cities) and means of human interaction in various spheres of life are beginning to undergo digital transformation. Summarizing, we can call it Objects 4.0 and Movements 4.0. The digital transformation of industrial enterprises is their targeted transition to a state that corresponds to the concept of Industry 4.0 (I4.0) [2], and the transformation of energy systems corresponds to the concept of Energy 4.0. The transformation of human relations is described by the concepts of E-Gov, e-Health, etc. Quite often, the preposition Smart appears in the name of 4.0 objects, as they are characterized by revolutionary intellectualization, thanks to the use of "Disruptive Technologies" [3] during their design and production: Artificial intelligence (AI), Internet of Things (IoT), Simulation, Cloud computing, Augmented reality, Big Data, Blockchain etc.

The goal of digital transformation is to transform objects into cyber-physical systems (CPS) [4], which are characterized by extreme quality, efficiency, and competitiveness. The CPS are different from the third industrial revolution automated systems (level 3.0) that synergistically combine the virtual (cyber) and physical components by means of advanced information and communication technologies (ICT). Information and measurement systems (IMS) are a significant part of ICT.

The fundamental difference between level 4.0 IMS and level 3.0 IMS is that the received data is used for intelligent CPS add-ons, including for parametric optimization of models [5]. This allows to clarify tactical

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decisions in control systems and strategic decisions in management systems and ultimately leads to a dramatic increase in system efficiency. The term "management" here is more related to cyber add-ons (for example, digital platforms MES and ERP [6]), and the term "control" refers more to material assets (equipment, product etc.).

The scale of digital transformation can be different: from the structurally and conceptually complete transformation of the object into a cyber-physical system, which actually means the synthesis of a new system, to the integration of only some CPS-components of level 4.0 into the existing system of level 3.0 [7]. Regardless of the scale of the transformation, IMS are fundamentally necessary components that integrate all physical and virtual aspects of CPS.

Publications on CPS and IoT are increasing every year, but the process of standardization and harmonization of principles for developing CPS components and IoT ecosystems began only recently (about 5 years ago). In Ukraine, many standards have not yet been adopted [8] and there is no support for strategic decisions that form the basis of Industry 4.0, although the movement in this direction is already carried out by both state institutions and public organizations, for example, APPAU [9].

The recovery of the Ukrainian economy will require revolutionary solutions, and one of them is the implementation of cyber-physical systems, the main element of which is IMS, based on sensors 4.0. In Ukraine, the foundations are gradually being formed, in particular methodological ones [10] for developing IMS and automatic control systems as components of the CPS: these are smart sensors [11] and 4G technologies implemented by Ukrainian mobile operators [12], hardware and digital platforms developed by INTECH, IT-Enterprise, ACS Engineering and other engineering and industrial companies [13-15].

In most cases, the authors of the publications present either the final product, the design stages of which are a commercial secret, or previous studies, such as in the study [16], dedicated to the development of an IoT air quality monitoring system integrated with Smart House. The focus of research was on system integration and the ability to connect a large number of sensors. In the study [17] the specific example of designing an IoT platform for vibration diagnostics of industrial equipment was shown, but it would be interesting to investigate the possibility of its integration into CPPS. In the study [18], issues related to the application of IoT technologies for cyber-physical systems and the types of IoT platforms for Smart Enterprises CPPS were analyzed. It should be noted that CPPS is one of the variants of CPS, the operation of which is based on the Industrial Internet of Things (IIoT) [19, 20]. In the study [21] the specific example of designing an IoT platform for vibration diagnostics of industrial equipment was shown, but it would be interesting to investigate the possibility of its integration into CPPS. In [22] justified the choice of structure and parameterized the option of a "smart jacket" as an assistant to production personnel in the I4.0 concept, but it remains to be clarified the issue of matching this system with modern standards.

Thus, the goal of this study is the solution of the following urgent tasks: the selection of regulatory framework, hardware, software, the development of methodological and information support for the design of IMS as components of CPPS in the I4.0 paradigm.

1. IMS in CPPS: problems and tasks

IMS are of great importance for the functioning of the CPPS, as they not only work at the lower levels of the ACS (the key difference of modern IMS), but also fill the “intelligent” superstructure with information and form the basis for decision-making at all levels of the CPPS and at all stages of the product life cycle. Therefore, the concept of IMS intended for CPPS is fundamentally different from the standard measurement system for three-level ACS. If we compare CPPS with a person, IMS not only ensures adequate work of the autonomic nervous system (this work in technical systems is performed by ACS), but also of the central nervous system (this work in technical systems is performed by cyber add-ons).

For the design of IMS as a part of the industrial ACS of computerized production, the reference Purdue model [23] was traditionally used. However, the Purdue model has a clear demarcation between IT (Information Technology) and OT (Operational Technology) networks, which no longer exist in CPPS/Digital Manufacture [24]. Therefore, the task of developing a design methodology and models for the implementation of IMS in CPPS arises.

Let's consider the technology of the synthesis of a cyber-physical system through the prism of determining the role of IMS for its proper functioning. The first stage of synthesis of the virtual part of the CPPS (for example, Digital Twins), is the acquisition and collection of data on the state and processes of the simulated production system. This data can be obtained from personnel, equipment sensors or from end devices that signal a malfunction. They can also carry data about operating conditions, environment, etc. Collection and transfer of data were performed using IMS. Data after filtering and preprocessing are converted into information in the sensors themselves, if they are 4.0 objects (Smart sensors) [25-28], or in controllers, if level 3.0 sensors are used in IMS. Both types of sensors fill the database of

SCADA (Supervisory Control and Data Acquisition) as well. In Figure 1, the arrows indicate these connections.

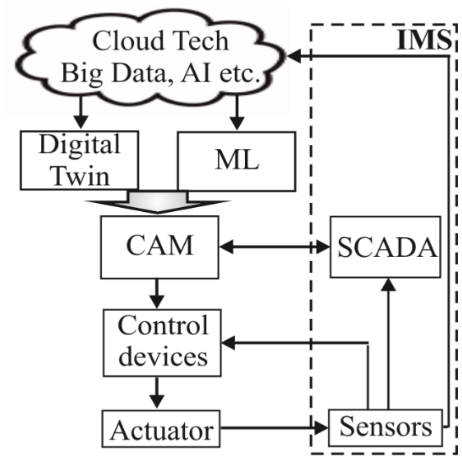

Fig. 1. IMS in CPPS

Processed data are stored in databases on local or Cloud servers. After processing by Cloud Tech, Big Data and AI (Fig.1), were used to build, retrain, and update behavioral empirical models for Machine Learning (ML) and for parametric optimization of physical models (Digital Twins) of assets and processes. The use of specified models allows us to optimize all processes in the simulated object, prevent accidents, predict and warn about malfunctions, etc. This occurs through both machine (model-based) and human decision-making based on visualized information in human-machine interface (HMI), SCADA systems, and other cyber assistants in CAM (Computer Aided Manufacturing) [22, 29]. The influence zones of IMS are highlighted in Figure 1 and the interconnections among CPPS-components are shown. It is obvious that IMS is the main component and carries information to all levels of CPPS and this is the starting point for the design of IMS.

The new IMS must be developed according to the same criteria as the CPPS, and the only way to develop existing ACS is intellectualization. This goal is achieved by introducing additional control loops in ACS and expanding IMS functions. The main problem when designing new IMS is the need to ensure the activity of the CPPS as a single "organism", so the IMS sensors must provide all the completeness of information for the functioning of Digital Twins, ML, and for HMI, as human decision-making remains a part of the CPPS. As the role of "intelligence" in today's automated systems grows significantly, IMS that provide all input information now determine the adequacy of the whole system.

Thus, functioning of the entire CPPS depends on the quality of the synthesized IMS and accuracy of the data collected in the IMS. At the same time, the task of optimality of IMS synthesis must be solved within the framework of the accepted I4.0 paradigm and a set of relevant standards (normative support) for compatibility with other CPPS components. In addition, the optimal structure of the IMS contributes to the speed and stability of the whole system, which is important for the operation of Digital Twins operating in real time.

2. IMS models in the I4.0 paradigm

At the upper levels of abstraction, the synthesis of CPPS components is carried out in two stages: first, a conceptual model is generated, then, with the help of heuristic approaches, structures are synthesized within the accepted models. The main idea when designing the IMS in the I4.0 paradigm is that the IMS is a "component" (subsystem) of the CPPS, that is, end-to-end integration should be ensured on the basis of current rules and regulations. I4.0 regulatory support includes standards and their structural compositions, which are called "implementation models".

The conceptual model of CPPS and its components is based on the RAMI 4.0 metamodel (registered as standard DIN SPEC 91345:2016-04 [29]), which defines all the main aspects of I4.0 and allows CPPS to be decomposed. RAMI 4.0 is a three-dimensional system, the right horizontal axis of which includes hierarchical levels of enterprise architecture according to IEC 62264 [30] and IEC 61512 [31] standards. These standards normalize the structure and rules of system integration: from the primary functions of production units (Product+Field Devices) to the interconnection of CPPS through IoT with external objects 4.0 at the Connected World level [32]. The left horizontal axis of RAMI 4.0 outlines the equipment and product life cycles according to the IEC 62890 standard [33]. There are concepts of Type and Instance here: a Type becomes an Instance after the R&D stage of the product is completed and series production begins. Layers on the vertical axis represent: market, functional, information, communication and integration aspects of CPPS components [34, 35].

IMS level 4.0, which is based on smart sensors and IIoT, penetrates all levels of CPPS and provides them with the information they need. Figure 2 shows the information paths of IMS influence at different hierarchical levels of RAMI 4.0. At the upper levels, this information is necessary for the functioning of CRM (Customer relationship management), MES (Manufacturing Execution System), ERP (Enterprise Resource Planning) and other cyber add-ons [35], for example, the Ukrainian automated data collection and reporting system M.E.Doc [36].

IMS level 3.0 can not cover all levels of CPPS, communicates only with the hardware part of automated systems, and provides HMI in the best case. However,

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under the condition of using modern SCADA [28], which are equipped with artificial intelligence algorithms for dynamic monitoring of malfunctions, warnings about potential threats, and predictive maintenance, such a system can be considered IMS level 3.5. In our opinion, the implementation of such SCADA is one of the means of "soft digitalization" [7].

The universal model of implementation of IMS in CPPS has been developed (Fig. 2). It is based on the RAMI4.0 architecture and takes into account different concepts of CPPS construction: based on Digital Twins, ML or modern SCADA, or as a composition of all these approaches.

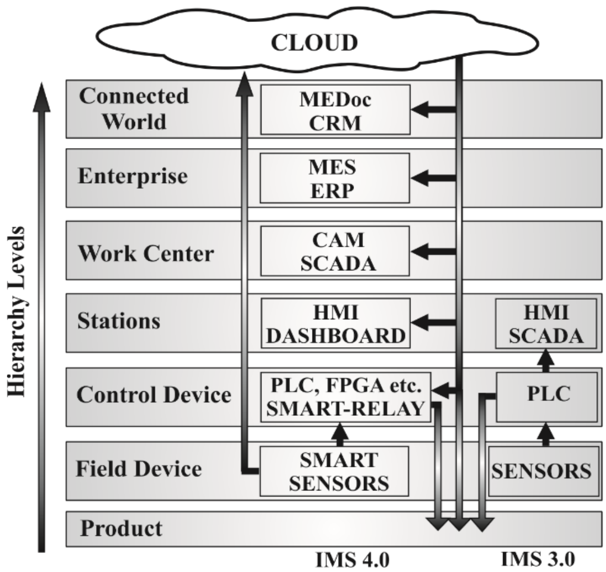

Fig.2. Model of IMSs implementation on RAMI 4.0 levels

Communication of IMS 4.0 with all levels of CPPS is possible thanks to the use of IIoT, therefore, at the stage of structural synthesis of the component, it is necessary to use one of the structural models of IoT: reference model (RM) ISO/OSI (standard ISO/IEC 7498) [32], or others that based on it. More specialized IIoT models detailing the requirements, technologies, standards and solutions for CPPS networks were developed by the IIC consortium (IINF IICF, IIRA) [19, 20].

At each of its hierarchical levels, RAMI 4.0 characterizes access to information throughout the entire production cycle, and IoT models, which are associated with the integration and information levels of RAMI 4.0, embody ICT tools, forming an IIoT "ecosystem". Table 1 shows the IoT Stack Model [38] and the Internet Model (RFC 1122) for comparison with the OSI reference model.

For any IIoT model, the movement of information in the CPPS can be represented by a linear algorithm:

1) measurement, primary transformation at the physical level;

2) collection, pre-processing and transfer of data using ICT;

3) data conversion into information suitable for use by the physical part of the CPPS (for control), the cyber part of the CPPS (for management) and for visualization in the HMI;

4) practical application of information using control and management, impact on CPPS subsystems.

Table 1

Comparison of IoT model layers

Layer	OSI Model	IoT Stack Model	Internet Model
7	Application	Application/ Framework	Application Layer
6	Presentation		
5	Session		
4	Transport	Transport	Transport
3	Network	Internet	Internet
2	Data Link	Network/Link	Link Layer
1	Physical	Physical Layer	

Next, the algorithm is cyclically (but at a different stage of the product life cycle) repeated. This generalized information model emphasizes the need for continuous data collection throughout the life cycle to improve products, machines and other I4.0 assets according to the IEC 62890 standard [33].

One of the important tools for integrating subsystems into CPPS according to IEC 62832 CD2 Part 1 [39] is the component model I4.0, which combines data on the properties and functions of a component with data on its digital twin during the life cycle and contains information necessary for communication with other CPPS subsystems. In this model, a component ("thing" in the world of the Internet of Things) is designated as an asset. The model jointly embodies the physical and digital forms of the asset through the administration shell (Asset Administration Shell, AAS) [40] and provides interaction between management and control CPPS-subsystems. The rules for the formation of AAS are given in [41].

The AAS model consists of sub-models representing different aspects of the asset: identity, communication, functional, cyber security, energy efficiency, etc. To enter the unified AAS database in CPPS, each submodel must be standardized, which facilitates multivariate search and allows finding the optimal component for a specific application. A submodel contains a structured number of properties that can reference data and functions. The properties are given according to the IEC 61360 standard [42]; although this data and functions are available in different formats.

Thus, various aspects of the IMS implementation model are based on the I4.0 regulatory framework. In particular, the conceptual model must be formed on the basis of RAMI4.0, the structural model must be formed on the basis of the adopted IoT model and the proposed generalized model, the formation of IMS component sub-models for integration with CPPS is regulated by IEC TR 62794 [43], IEC 62832 Digital Factory [39] and ANSI/ISA-95.00.04-2018 [44] standards. These and other standards must be used at the appropriate RAMI4.0 levels (see Fig. 2) and stages (will be considered in the third chapter) of IMS design.

Additionally, it takes into account the proposed approach of "soft digitalization", where the addition of cyber applications (at the top three levels of RAMI 4.0) and intelligent sensors transforms an extensive automated system into a cyber-physical system (this is especially important for the recovery of the Ukrainian economy). Structures 3.0 can complement CPS, forming level 3.5 objects (it is shown in Fig. 2 on the right).

3. Methodology of development IMS IoT-Tech

Let's consider in a methodical sequence the stages of IMS synthesis in the I4.0 paradigm using the example of IMS IoT-Tech, which was developed by ASU Engineering (Zaporizhzhia, Ukraine) in cooperation with the authors of the article.

3.1. Concept development

According to the technical task, the system should autonomously measure and register data on resource consumption from sensors, generate warnings and instructions through SCADA, evaluate and display information in HMI. IMS also has to be integrated with the physical level of the CPPS, with ACS, that generate and transmit control signals to the actuators, and with the cyber add-ons of the CPS, in particular, with the M.E.Doc digital platform. Therefore, a conceptual model based on RAMI4.0 was adopted for IoT-Tech. CPS, like each of its parts, is characterized by the level of integration, stability, functionality, economy and intelligence, therefore the IoT-Tech system was developed based on these criteria.

3.2. Structural synthesis

At the stage of structural synthesis, variants of centralized and decentralized structures were analyzed. With a centralized approach, each sensor communicates with a control component (PLC), and the central communication element behaves as an edge device [45].

This approach was widely used in IMS 3.0. For a better implementation in CPPS, a decentralized approach and smart sensors were chosen, which according to the IEEE 1451.0-2007 standard [46] provide functions exceeding the minimum sufficient to perform measurements. Sensors 4.0 communicate on the CPPS layers (see Fig. 1) with personnel and/or machines, and data can be sent to the Cloud or to a local CPPS server. Hardware 4.0 can also be called IoT-devices because they receive and exchange data with other nodes and applications using protocols according to the chosen IoT model.

For the implementation of IoT-Tech, the IoT Stack Model with the principle of wireless data transmission was chosen. The main technologies for wireless data transmission from IoT devices to Cloud servers by LPWAN (Long Power Wide Area Network) networks are NB-IoT, Weightless, LoRa, SIGFOX and others [47]. The IoT-Tech system was synthesized, in particular, according to the criteria [48] on the basis of the cellular communication standard NB-IoT/LTE-CAT (Narrow-band IoT) [49], created for telemetry devices with low data transmission volume, which guarantees a battery life of up to 10 years due to low power consumption. NB-IoT has a wide coverage area, the ability to quickly upgrade the network, as well as high reliability.

Typically, sensors 4.0 consist of four subsystems: measurement, calculation, transmission and power. In IoT-Tech, the computing subsystem based on STM32L051K8U6 is isolated and receives data from 5 sensors, the set of which can be varied to adapt to the production task. This topology corresponds to the Fog Computing paradigm, which extends cloud computing and services to the edge of the network [50]. This way of processing data from sensors significantly speeds up the exchange of information for real-time simulation, which is the basis for operating digital twins.

Each such block has 2 analog inputs (4-20mA) and 3 discrete, for connecting sensors using current loop technology (range – up to 500 m), thanks to the built-in transmitter and internal DSP controller with spectral analysis algorithms, it transmitted using NB-IoT technology from MTC [13] for further processing in the cloud service Impler Cloud. Normalized data already cleared of noise can be used in various areas and digital platforms of CPPS: from resource planning in ERP to the global coordination of production resources [35].

A convenient and visual web interface has been implemented for the staff through Dashboard Impler on a smartphone; SCADA development (Station & Work Center RAMI4.0 levels) is ongoing. IMS transfers information to the M.E.Doc automated data collection and reporting system (Enterprise & Connected World RA-MI4.0 levels). IMS communication models with Digital Twin are currently under development.

3.3 Parameterization of the system. Hardware and protocols

IoT-Tech consists of a set of measuring and computing units and is an autonomous non-volatile IMS subsystem that integrates with other CPPS components

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and physical assets through Cloud services and devices for interactions, which must meet the criteria:

- support a range of IoT model protocols;
- programming should be simple;
- must have means of communication with ACS;
- must ensure data security.

The above requirements are met by Arduino, Raspberry Pi, and ESP32. Arduino is equipped with an analog-to-digital converter and has an advantage if it is necessary to receive information from analog sensors. The ESP32 has advantages over sensor networking capabilities, thanks to its small form factor, low cost, and wireless connectivity capabilities. Raspberry Pi3 on the ARM platform (Linux operating system) was chosen for this project due to the following set of advantages [44]:

− higher performance compared to other development boards in terms of storage and calculation speed (clock frequency up to 1.5 GHz);

− has 40 general-purpose digital inputs/outputs, built-in Wi-Fi, BLE, and Ethernet port modules;

− can be turned into a computer (the board can be connected to a monitor via an HDMI port, a standard mouse and keyboard via a USB port);

− languages C, C#, C++, Python, and PHP, combined with a sufficiently large amount of RAM (up to 8 Gb), allow you to create an IoT server;

− makes it possible to use software for data exchange according to industrial protocols, according to IEEE 802.11 standards; IEEE 802.15.4; BLE 4.0, IEEE 802.3ab, application-level protocols, for example, to host a web client for HMI and an OPC-UA server [51].

Raspberry Pi allows us to use standard Modbus TCP client functions, for each of them there are two main protocol data blocks (request and response), which are elementary packets on the Physical Layer of the IoT model, PDU (Protocol Data Unit), which in turn, are packed into individual ADUs (Application Data Units) of the Transport Layer protocol. Modbus TCP is a common protocol for communication between field and control devices in server-client architecture. At the transport level, the IoT Stack Model (TCP technology stack) and the Ethernet standard at the Link Layer implement this.

IMS on Raspberry Pi can be integrated with various ACSs. A fairly economical and simple way to implement ACS is Smart Relay, for example, the easyE4 series relay from Moeller [52], which has up to 11 expansion modules to increase the number of inputs/outputs, a wide range of supply voltages, both direct and alternating current. EasySoft app provides the use of four different programming languages and provides preliminary system simulation. An integrated web server and an Ethernet interface allow easyE4 to be integrated into the IIoT architecture. The easyE4 relay has the function of deploying a Modbus TCP server, with which, in turn, the Raspberry Pi can interact via the Ethernet port. Eaton MFD multifunction display is used to implement HMI at the Control level and reprogramming easyE4. An input expansion module for analog signals is also connected to the easyE4 basic device.

A NanoMono TA63A network analyzer has been added to the IMS hardware power circuit, which provides important indicators not only for ACSs at the Control+Field RAMI 4.0 level, but also for higher levels of digital production. In addition to the main parameters (frequency, current and voltage), this device transmits consumption indicators in the form of power components and a moto-clock for product cost calculations to the MES and ERP digital platforms.

To communicate the NanoMono network analyzer with the Raspberry Pi, a Modbus RTU server is implemented on it. Modbus RTU has the same PDU and ADU structure as Modbus TCP, but uses different physical layer standards (RS-485, RS-232, RS-422) that implement serial data transmission. In this project, NanoMono is connected to a microcomputer via RS-485 with the help of an interface expansion board. The packet checksum is used to verify the correctness of the data.

IMS can be deployed on a wired industrial Internet or on wireless data transmission protocols, in accordance with the requirements for cyber security and structural features of digital production [35]. The MQTT (Message Queue Telemetry Transport) or OPC-UA protocol can be used for telemetry, but the IMS structures will be different. OPC-UA is selected for Raspberry Pi communication with «Cloud Impler» server as a client, HTTP server is used for data transfer to HMI, the client is a smartphone with an installed Dashboard that functions as an AAS. This mini-SCADA displays the measured parameters for technical personnel at the Control level of RAMI4.0. The client can also be workstations, on which full-fledged SCADA should be deployed for engineering personnel at RAMI4.0 Station/Work Center levels, which receive data from IMS IoT-Tech regarding resources and from IMS on Raspberry Pi regarding technological processes.

Thus, IMS CPPS consists of several subsystems: IoT-Tech, which processes data from sensors installed in hard-to-reach places (in pipes with gas, liquids), and IMS on Raspberry Pi, integrated with automatic control systems for actuators, the state of which are monitored by level 3.0 and 4.0 sensors. The latest IMS has a mixed, hybrid structure that corresponds to the concept of "soft digitalization" when only some components and technologies of I4.0 are introduced into production [7].

In this system, it is possible to adjust the frequency of measurement and data upload. The system is non-volatile (powered by a large-capacity battery). Tests of NB-IoT sensors were carried out in conditions of low temperature, high humidity (even under water) and showed their high metrological reliability.

3.4 Integration of the component to CPPS

The integration of IMS as a CPPS component on the corresponding layers of RAMI4.0 and the transport layer of the IoT Stack Model is shown in Figure 3. Taking into account all the layers of the IoT model will make this framework multidimensional. Figure 4 shows the AAS of this component called IoT-Tech, which consists of two parts: a header (DF asset header) and a body (DF asset body). AAS can be run on a cloud server to which the HMI is connected as a client. The AAS body depends on the aspect (Basic views), in this case it contains the structural and functional aspects (Local view) [40] of the component. AAS can also contain relationships between elements. For each component, an AAS folder must be created for each aspect and installed in the CPPS resource library. The header should indicate the identifier, serial number and purpose of the asset in the structure of CPPS.

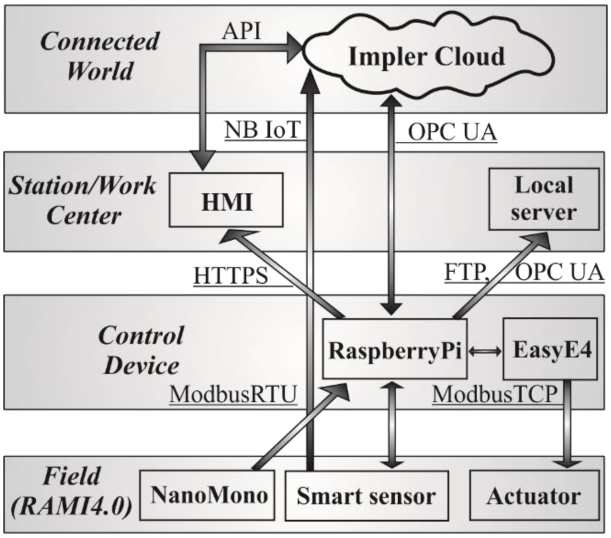

Fig. 3. Integration of the IMS IoT-Tech components on the RAMI4.0 levels

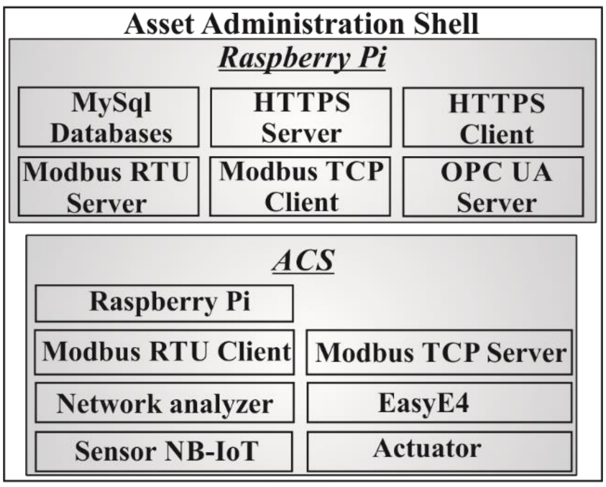

Fig. 4. AAS IMS IoT-Tech

IoT-Tech research has shown reliability, stability and the necessary functionality, taking into account the possibilities of adaptation to a wide range of production tasks. Functional and economic indicators were studied during field tests of systems, in particular, at the Kryvyi Rih Waterworks. IoT-Tech accurately and quickly identifies network failure points and current water consumption figures. Simultaneously, the sensors consume almost no electricity, as they go into hibernate mode after sending information.

Conclusions

The concept and structures of IMS change during the transition to the I4.0 paradigm: they become the basis of adequate CPPS work, as they must provide information to both cyber superstructures and physical assets. All stages of the synthesis of such IMS should be based on the developed models (conceptual, informational, structural, implementation, etc.).

The sequence of stages and models of IMS design as a CPPS component is presented. This methodology can be applied to the design of any physical asset related to automation. This approach will allow their integration with other digital production systems and platforms based on the AAS model. We recommend using the IMS structural and implementation diagrams (Fig.1 and Fig.2) and methodology for designing cyber-physical systems of various degrees of intellectualization based on machine learning, Digital Twins or modern SCADA.

The IMS IoT-Tech subsystem is implemented based on 4.0 sensors, NB-IoT and Fog Computing technologies, which ensures high efficiency of remote monitoring of resources and increases the speed, efficiency of management and control in industrial CPS. The synthesis is based on the appropriate I4.0 regulatory framework, RAMI4.0 and IoT models. A model of the integration of this system with other IMS and ACS CPPS has been developed. A smart system can also be implemented as part of the concept of "soft digitalization".

A set of Industry 5.0 requirements, such as increasing the environmental friendliness of systems (no waste, saving resources, reducing pressure on the environment), was also taken into account when designing the IMS. Thus, the developed IoT-Tech system not only helps to save resources due to their precise control, but also practically does not consume electricity.

Directions for further research

The development of IMS communication mechanisms with the «Digital Twin» cyber superstructure is ongoing. In the realities of economic

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recovery. The interaction with scientists and practitioners united by the INDUSTRY4UKRAINE platform continues, including the basis for the integration of components for the "soft digitization" of level 3.0 objects.

Author contributions: development of the concept and information model, structural synthesis, design of research results – **Olga Vasylenko**; hardware selection and software development, system parameterization, prototype development and testing – **Sergii Ivchenko**; selection of regulatory support, analysis of experimental research results, registration of research results – **Hennadii Snizhnoi**.

All the authors have read and agreed to the published version of the manuscript.

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ПРОЄКТУВАННЯ ІНФОРМАЦІЙНО-ВИМІРЮВАЛЬНИХ СИСТЕМ В ПАРАДИГМІ ІНДУСТРІЇ 4.0

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Предметом дослідження є процес проєктування інформаційно-вимірювальної системи (IMS) як компоненту кібер-фізичної системи (CPS) в парадигмі Індустрії 4.0 (I4.0). **Метою** є розробка методичного забезпечення проєктування IMS та систем автоматичного керування (САК) як компонентів промислових CPS (CPPS), зокрема, для цифрового виробництва. **Завдання:** визначити концептуальну модель IMS; обрати модель IoT для структурного синтезу; підібрати відповідне нормативне (набори стандартів та моделей впровадження), програмне та апаратне забезпечення; виконати R&D IMS на базі датчиків NB-IoT; формалізувати процедуру інтеграції компонентів до CPPS, розробити адміністративну оболонку активу. Використовуваними **методами** є: евристичні методи синтезу, теорія планування експериментів. Отримані такі **результати.** Продемонстрована ключова роль оптимально спроєктованої IMS рівня 4.0 в підвищені точності прийняття рішень в процесах керування та управління в CPPS. Якість керування покращується як за рахунок швидкого отримання точної інформації для актуалізації моделей в кібер-надбудовах, так і на фізичному рівні, в САК. Універсальна модель імплементації ІМС в кібер-фізичну систему була запропонована. Формалізовано етапи вибору концепції, структури, апаратного забезпечення та протоколів зв'язку IIoT-екосистеми IMS+САК. Методику апробовано під час розробки системи віддаленого моніторингу NB-IoT Tech, яка має децентралізовану структуру для збирання даних щодо споживаних ресурсів. Виконано інтеграцію екосистеми як компоненту CPPS на відповідні рівні архітектурної моделі RAMI 4.0. Сформовано нормативне забезпечення та розроблено функціональний аспект Адміністративної оболонки активу для інтеграції у CPPS. **Висновки.** Наукова новизна: запропоновано проектувати IMS як складову ААС кіберфізичної системи, згідно методології реалізації її підсистем на відповідних рівнях RAMI4.0 та обраної моделі IoT. Новий підхід під назвою «м'яка цифровізація» поєднує в собі підходи Індустрії 3.0 і 4.0, він призначений для сталого розвитку автоматизованих систем до рівня кіберфізичних систем і є актуальним для відновлення економіки України. Практичне значення результатів: розроблено та протестовано систему IoT-Tech на основі Smart сенсорів. Ця інформаційно-вимірювальна система є енергонезалежною та адаптована для вимірювання будь-яких параметрів в автоматизованих системах різного рівня цифровізації.

Ключові слова: промислова кібер-фізична система; промисловий Інтернет речей; архітектурна модель; нормативне забезпечення; інформаційно-вимірювальна система; технології NB-IoT; адміністративна оболонка активу.

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