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IoT systems in the process of multidisciplinary training of personnel for the digital economy and their design

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Abstract

In the context of digitalization of the most knowledge-intensive sectors of the domestic economy, the development of an industrial training system in the field of electronic instrumentation is of great importance. The key areas of its development with the use of information and communication technologies include the development and improvement of the technological basis for training and retraining of personnel in engineering educational programs. One of the elements of this basis is the service of multi-user remote access via the internet to a high-tech experimental equipment laboratory as a service based on internet of things (IoT) systems. Within the framework of this service, an urgent problem is to increase the functional saturation of automated stands/installations, which is currently characterized by a paucity of scientific research. The purpose of the research is to expand the areas of experimental research carried out in the mode of multiuser remote access based on specialized IoT systems. As a result, a method of multidisciplinary application of specialized IoT systems was developed. This consists of the technical implementation of possibilities for additional research: research into technologies underlying both multi-user distributed measuring and control systems and IoT systems in general; research into technologies used in their end-to-end computer-aided design; research into joint interaction of several geographically distributed automated stands/installations, implemented on the basis of a four level IoT reference architecture. A methodology for the design of multi-user distributed measuring and control systems as specialized IoT systems has also been developed, focused on solving multidisciplinary research problems in an interactive dialogue mode based on single sample of experimental equipment. The methodology mobilizes organizational, technical and methodological support for the process of creating such systems with specified target characteristics. In general, the method and methodology developed open up opportunities for systematically implementing the basic principles of the "Education 4.0" concept in the preparation and retraining of engineering personnel in the field of electronic instrumentation.

Key words: internet of things (IoT); IoT system; laboratory as a service; technical teaching tools; multiuser distributed measuring and control systems; design methodology.

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Introduction

The accelerated pace of digitization of various areas of human activity is reflected primarily in the meaningful, methodical and technological components of industry training systems (ITS). At the same time, a feature of the current situation in the world which imposes a number of restrictions on traditional approaches to education is the pandemic COVID-19 [1]. In these conditions, the relevance of the following current trends in ITS is increasing:

✦ system-based use in various types of information and communication technology (ICT) training;

✦ increased emphasis on personalization of learning, the introduction of flexible learning schedules and the abandonment of rigid binding of trainees to specific locations;

✦ modernization of the traditional infrastructure of educational institutions – the introduction of digital library systems, the widespread use of ICT tools and specialized systems for simultaneous lectures in many different locations for online and offline modes, the use of cyber-physical systems, as well as internet of things (IoT systems) systems, in particular, as means of conducting experiments in specialized distributed laboratories;

✦ ICT learning as a continuous process that accompanies a person throughout his life [2–10].

The Education 4.0 strategy highlights the following key aspects [11]:

✦ education on demand;

✦ personalization of education;

✦ learning at a convenient time anywhere;

✦ life-long learning.

The practical implementation of these aspects relies on the development and improvement of the ICT base for training and retraining in engineering education programs in the field of electronic instrumentation.

Thus, in the preparation and retraining of engineering personnel for the digital economy, the implementation of such aspects as "training at a convenient time anywhere" and "personalization of education" within digital educational environments are based on improving the service of access to high-tech experimental equipment and modern specialized software — "laboratory as a service" [12–14]. This service allows trainees to perform in-kind and computational experimental research in remote access mode on the internet from any location. The relevance of the development of this service is associated with an increase in its efficiency. The main areas of service efficiency include increasing the capacity of laboratory equipment that is part of remote laboratories, as well as its functional saturation in terms of experimental research, both in the context of multidisciplinary and acquired in the course of training practices. Ways to solve the problem in terms of increasing the capacity of high-tech experimental equipment by the authors of this article have already been outlined in a number of works [14–15], and the approach to solving the problem of increasing the functional saturation of experimental equipment is the subject of this article.

1. Multidisciplinary use of remotely accessible experimental equipment

Remote laboratories are based on technical training tools (TTT) [16] developed using end-to-end digital technology, including internet of things technology [2–4, 17–19]. Other TTT include multiuser distributed measuring and control systems (DMCS) that implement high-tech equipment (measuring equipment, computing equipment, automated laboratory layouts/stands/installations) based on the concept of multi-tenancy [14]. The DMCS integration scheme into the IoT's four-tiered architecture is shown in *Figure 1* [20, 21].

The process of creating DMCS samples as relevant IoT systems is based on the integration of a whole pool of digital technologies, which in turn may be the subject of individual experimental studies in addition to targeted domain research determined by appropriate automated layouts/stands/installations (*Figure 1*). In addition, advanced design technologies for such IoT systems can also serve as a separate subject of laboratory research in the context of end-to-end cycles of automated design of both individual elements and these systems as a whole. Thus, the current technical means of training in the form of DMCS (as appropriate IoT systems) are characterized by the following areas of laboratory research:

✦ in-kind experimental research in the target subject area determined by a specific ALL or their totality (purpose of the DMCS);

✦ research into the technologies underlying the functioning of DMCS (in addition to the intended purpose);

✦ research into technologies used in the design of DMCS (addition to the intended purpose).

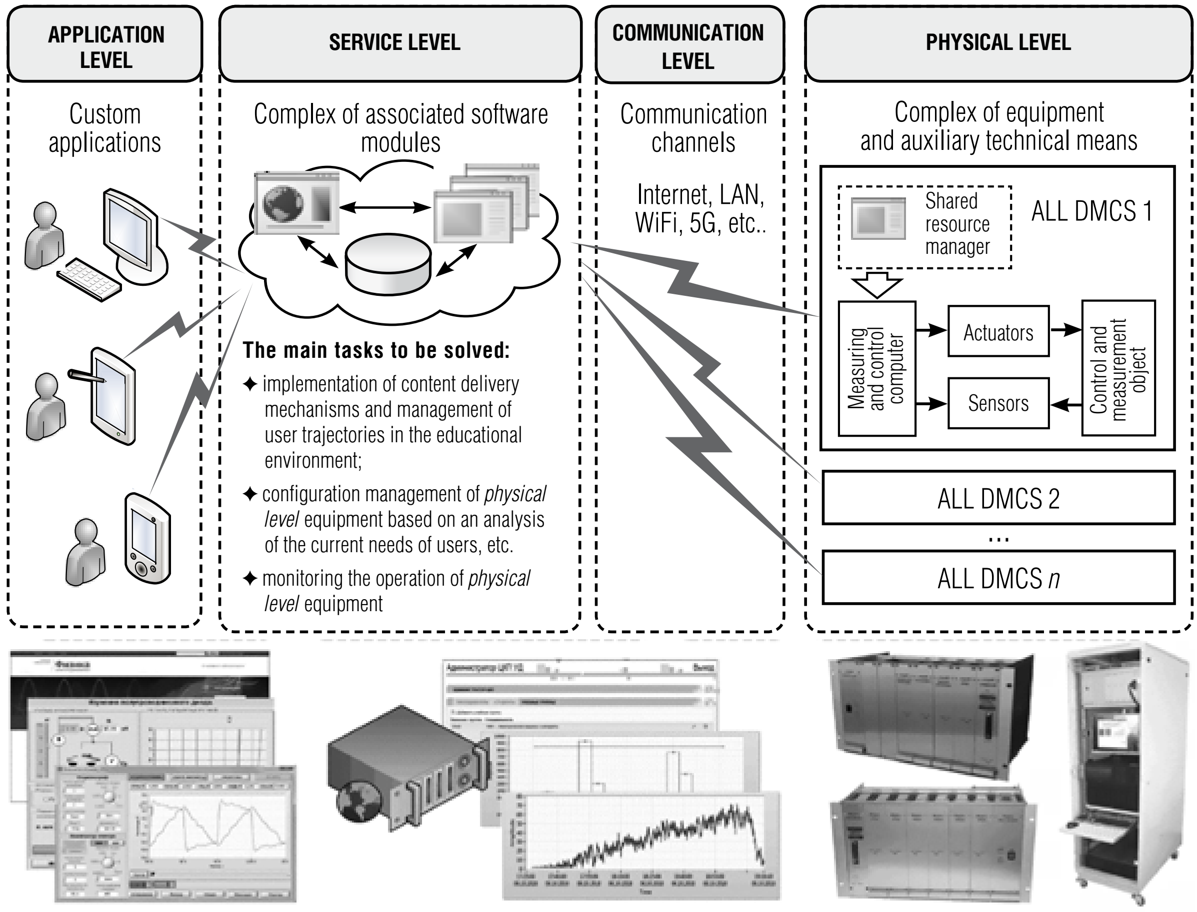
Each of these areas is characterized by a specific area of research and its own set of training practices in *Table 1.* For a more detailed analysis of the components of the experiment, *Table 1* introduces the following clarifications:

✦ a "learning experiment" is a natural experimental study provided by relevant training courses and/or discipline programs;

✦ the "scientific experiment" includes in-kind experimental studies aimed at obtaining information on new, previously unexplored processes and/or phenomena (as part of the educational process).

Taken together, these areas allow the appropriate DMCS to be used as TTT to develop multidisciplinary training courses. This, in turn, allows students to develop skills such as "systemic abilities," "cognitive abilities" and "solving complex problems" that are quite popular in the major sectors of the digital economy. In addition, a number of areas allow for contextual training, for example, in the field of research, such as end-to-end automated design technology. *Table 1.*

a



b

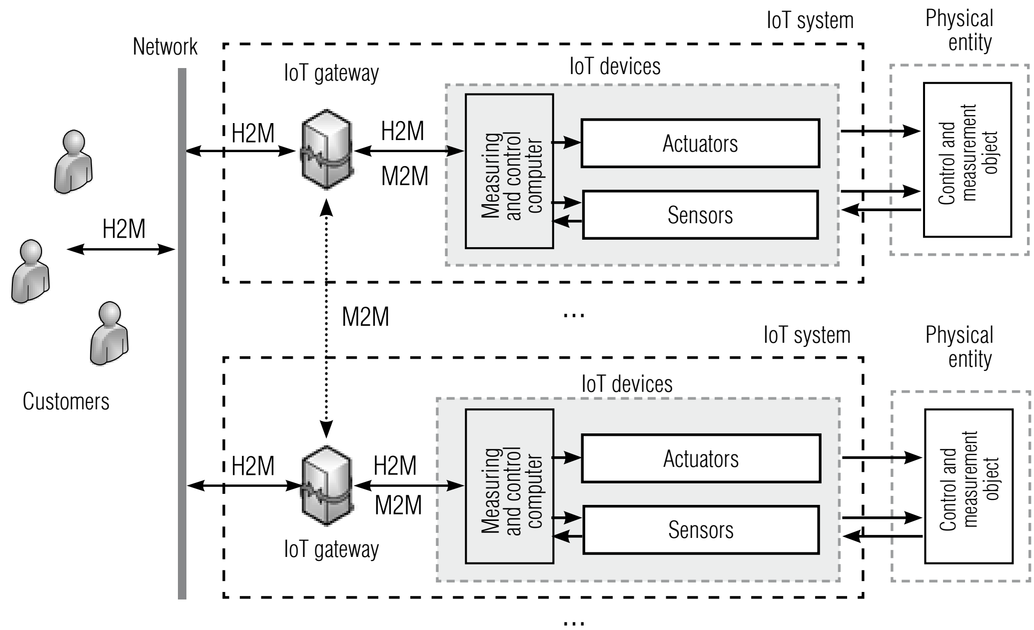


Fig. 1. DMCS as an IoT system with four–tier architecture:
a – IoT levels; *b* – DMCS as IoT system;
ALL – automated lab layout; H2M, M2M – how to organize an interaction (Human–to–Machine, Machine–to–Machine)

Table 1.

Directions of multidisciplinary research based on multiuser distributed measuring and control systems (DMCS)

No	Direction of research	Research area	Types of experimental research	Developed development/research practices
1.	The subject area defined by the TTT, as well as the properties of the DMCS as IoT systems as a whole	1.1. Physical processes or phenomena in individual functional nodes or electronic devices, as well as devices, complexes and electronic systems 1.2. Methods of organizing external (network) interaction between elements of IoT systems on the principle of M2M	Educational / Scientific	1. The use of modern information and communication technology tools to analyze the processes taking place in electronic devices. 2. Applying the principles of building IoT systems as one of the promising directions in instrumentation. 3. The use of DMCS to automate the educational and scientific experiment as a segment of the modern digital educational environment*). 4. The use of electronic pedagogy methods that improve the quality of engineering teaching*). 5. Managing individual educational trajectories in a digital educational environment*).
2.	The technologies behind the functioning of DMCS	2.1. Remote control of objects and processes over computing networks	Educational	The use of data technology in IoT systems
		2.2 Digital data technologies and protocols	Educational / Scientific	
		2.3. Statistical patterns of digital traffic transmission	Scientific	
		2.4. Operating principles and scheduling in DMCS as in interactive dialog systems (queueing systems)	Educational / Scientific	1. Applying query service disciplines with priorities in queueing systems. 2. Study of methods to increase the bandwidth of the DMCS as queueing systems. 3. The use of software to investigate the dynamics of the queueing systems.
		2.5. User behavior in ergatic (human–machine) systems	Scientific	Methods of formal description of the operator's patterns in human–machine systems.
		2.6 Functional GUI testing technologies	Educational / Scientific	Application of functional testing methods of the user GUI for human–machine systems (object control systems, virtual measuring systems, etc.)
		2.7. Methods for processing the results of experimental research	Educational	The use of specialized software for digital, statistical and other processing of experimental research results
		2.8. Computer measurement technology	Educational	The use of computer measurement technologies in the development of IoT systems

No	Direction of research	Research area	Types of experimental research	Developed development/research practices
3.	DMCS design technologies	3.1. End–to–end automated design technology / “Digital Twin”	Educational	1. Applying mathematical modeling techniques in the design process of IoT systems and cyber–physical systems in general 2. The use of methods of identification and verification of mathematical models of radio components in the process of researching electrical characteristics of electronic devices. 3. Applying methods to develop modern electronic design documentation. 4. Exploring the specifics of methodical support for end–to–end automated design of radio electronics based on CAE/CAD/CAM/PLM systems (conveyor, cyclical and iterative solution of design tasks based on specialized engineering procedures)
		3.2. Technology and tools for developing applied software (frontend / backend) of special–ized IoT systems	Educational	Application of technologies and tools for the development of applied software for automated systems (object management systems, virtual measuring systems, etc.)

*) Developing practices in the process of retraining teaching staff

As you know, the increasing functional complexity and cost of devices, complexes and systems make it difficult to properly equip training and research laboratories with modern samples as objects of appropriate experimental research [22–24]. At the same time, the use of the properties of DMCS, such as the IoT system (*Figure 1b*), namely the interaction of several DMCS, provides an opportunity to study on their basis several variants of the implementation of devices/complexes/systems in general. The organization of such research is as follows. Appropriate automated laboratory layouts which implement the variability of the performance of functional nodes/devices/complexes can be placed in one location and provide the possibility of connecting them at the physical level to organize their interaction, and can be distributed geographically across several locations. In this case, it is possible to “collect” them (to emulate the process of their joint operation) as part of a common device/complex/system at the service level (*Figure 1*) by organizing M2M interactions at the communication level. This type of interaction is realized by creating a digital “image” of relevant signals (digitization of their fragments) and then exchanging them between DMCS of different locations. In order to implement such interaction, certain instrument samples provide technical devices (means) to record digital counting of relevant signals and/or to generate signals on their digitized fragments.

As an example of such a system that implements this principle of interaction, *Figure 2* provides an example of an IoT supersystem structural scheme to ensure the process of training and retraining specialists for the aerospace industry. This system, based on the

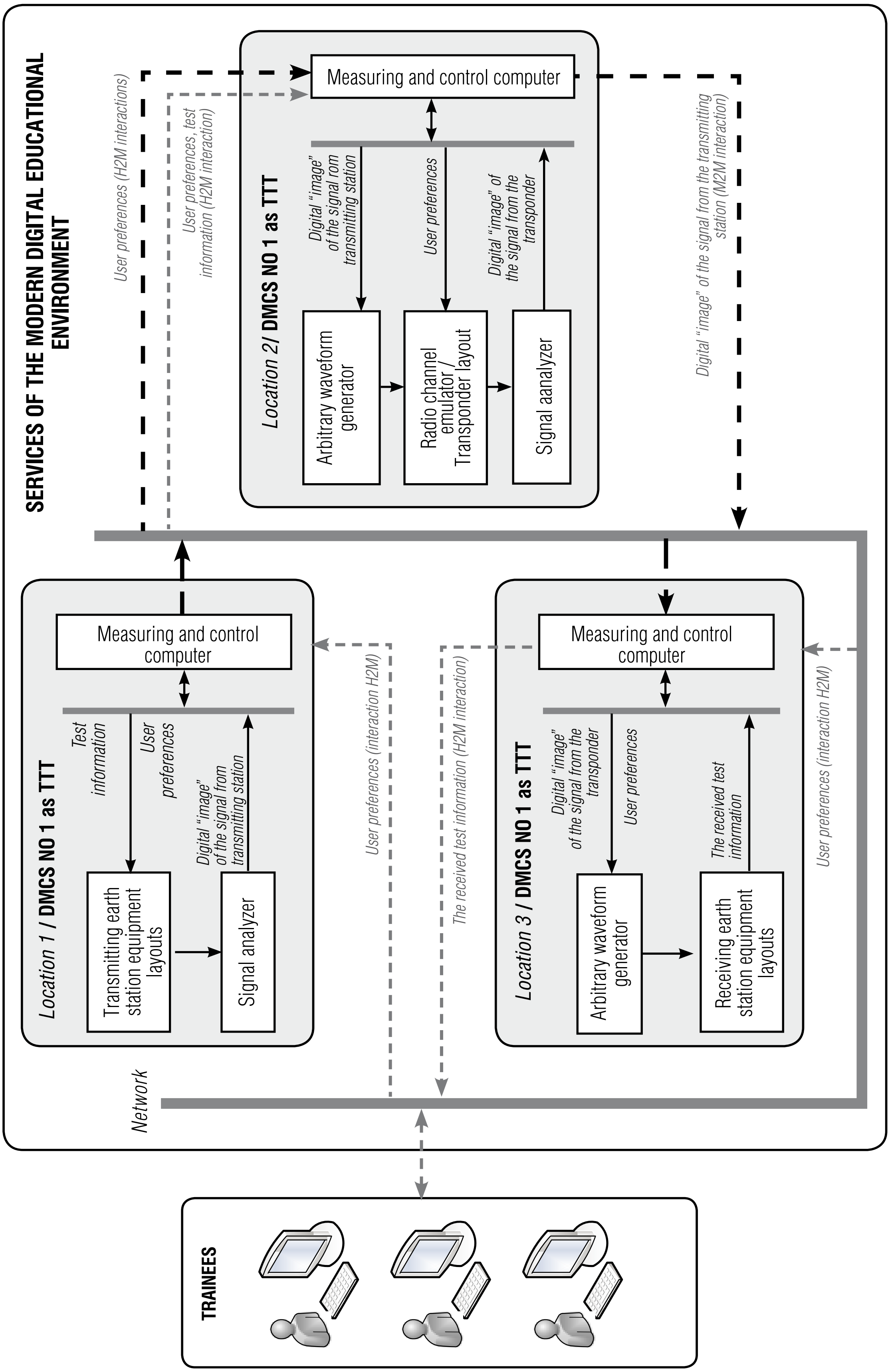


Fig. 2. An example of a research model of a satellite communications system in the form of an IoT supersystem, elements of which are individual instances of distributed location

combination of interactions H2M and M2M, implements a model of the satellite communication system through the on-board transponder of the satellite, elements of which are individual instances of distributed location DMCS.

As part of the experimental studies carried out on the basis of this system, the user is given the opportunity to form a high-frequency signal with specified parameters (the number of signals (carriers) in the band, the data transfer rate, the type of modulation used, etc.), for example, a fragment of a complex envelope which is digitized and transmitted over the computer network to location 2. In location 2, this signal is reproduced and sent to the entrance of the transponder or radio channel simulator, simulating the conditions of the signal passing in the space system, taking into account the uneven amplitude-frequency characteristics and group time delay of the transponder, the non-linearity of the amplitude characteristics of its amplifier, phase noise heterodyne and etc. A digitized signal fragment from the transponder is transmitted over the computer network to location 3. Using technical means in location 3, on the basis of the received digital "image," a signal can be formed at the entrance of the models of the equipment of the receiving station to assess the possibility of its detection, reception, processing, etc., or to evaluate the generalized qualitative characteristics of the communication system under study (bit error rate, error vector magnitude, etc.) [25].

It should also be noted that under this approach, the equipment layouts located in locations 1–3 continue to be subjects of full-fledged experimental research for each training site conducted as part of the relevant training courses.

Consider the systematic areas of experimental research in *Table 1.* The implementation of the research in accordance with items 2.1–2.2, 2.6 is based on the creation of a sample of the DMSC in the form of an open platform (with open software interfaces). Using this platform, the trainee can test and conduct functional testing of the self-developed and created user GUI to remotely control the automated laboratory layout on the basis of A pair of communication channels based on a personal computer, smartphone, laptop [26, 27] (using various software technologies and communication protocols based on various operating systems), as well as experimentally test the developed scheduling algorithms.

The study of statistical patterns and dynamics of the functioning of the DMCS as a queueing system (items 2.3–2.5) is carried out through processing the relevant statistical data. Such a given moment in time of sending and receiving the results of their implementation, the moment of arrival, beginning and end of the task on the measuring and control computer, the duration of the functional operations performed and other operations. Such data can be obtained during the operation of the DMCS, for example, by using the developed and tested software of the module which provides measurement and their centralized accumulation and storage [14].

Thus, the information content of DMCS as a TTT and their further multidisciplinary application within the designated areas should be laid down at the design stage through their implementation based on a pool of modern technologies, as well as using a scientific approach to their creation using modern computer-aided design tools. This approach should ensure the harmonization of the functional user tasks to be solved (in the corresponding subject area of ALL and the planned areas of interdisciplinary application) and the required technical characteristics of functioning as a queueing systems (average response time to user requests, the number of concurrent users, etc.).

2. Methodology for designing DMCS as specialized IoT systems

Based on the results of the research, a subject-oriented methodology for designing DMCS was developed, combining both well-known [28] and newly developed approaches:

✦ methods of increasing the efficiency of functioning (method of optimizing control operations, method of time division of multiple measurements, method of parallelizing functional operations);

✦ mathematical models of the dynamics of functioning, taking into account the heterogeneity of the behavior and service of users, the variability of the implemented scheduling algorithms, the dependence of the durations of the performed functional measurement and control operations on the parametric and functional content of tasks, etc., as well as adaptable software modules that implement them;

✦ procedures for solving particular design problems (designing hardware and software forming the boundary parameters of the dialogue scenario, calculating parametric sensitivity functions, etc.), which provide solutions to design problems in a formalized form;

✦ a set of technical solutions (a set of basic structures for hardware construction of DMCS, algorithms for scheduling a shared resource, algorithms for spectral measurement of signal parameters and software modules that implement them, basic unified virtual devices, basic design templates for a graphical user interface).

A generalized block diagram of the methodology is shown in *Figure 3*. Based on the built interaction of the components of the methodology and the complex application of modern computer-aided design tools within the DMCS design procedure as a specialized IoT system, a design solution with improved technical level indicators is sought. Additionally, in order to provide information support for the design process, the informational composition of the knowledge base of engineering solutions, accumulating and realizing the possibility of applying the experience of previous developments, is proposed.

The design results in the form of sets of electronic software and design documentation, the results of the analysis of various characteristics of DMCS, etc. are integrated as part of an interactive electronic technical manual [29]. Interactive electronic technical manual for corresponding samples of DMCS are also an auxiliary element of the educational process in the framework of the implementation of practices in the field of end-to-end computer-aided design technology. Maintenance of the process of pilot/industrial operation of industrial designs of DMCS is carried out on the basis of the proposed procedure for adapting to changing operating conditions (increase in the number of users, variability of users' thinking time, deployment of new access locations, etc.) [14].

Practical application of the proposed methodology and procedure for adapting DMCS helped to reduce the time of their design by 20–30%, allowed 3 to 6 times to expand the set of alternative design solutions synthesized in accordance with the specified requirements of the technical task, to increase in some cases the number of simultaneously served user terminals by 30% or more, as well as to create a number of industrial designs of DMCS in order to provide resources for the processes of field experimental studies of both ITS and production activities. The proposed methodology, in combination with the procedure for adaptation, makes it possible to ensure the effective use of DMCS as part of the "laboratory as a service" service while minimizing the cost of hardware and software through the implementation of the multi-tenancy concept. The high efficiency of such a service, implemented on the basis of DMCS, contributes to the wide possibilities of using the methods of electronic pedagogy in the preparation and retraining of engineering personnel for the digital economy.

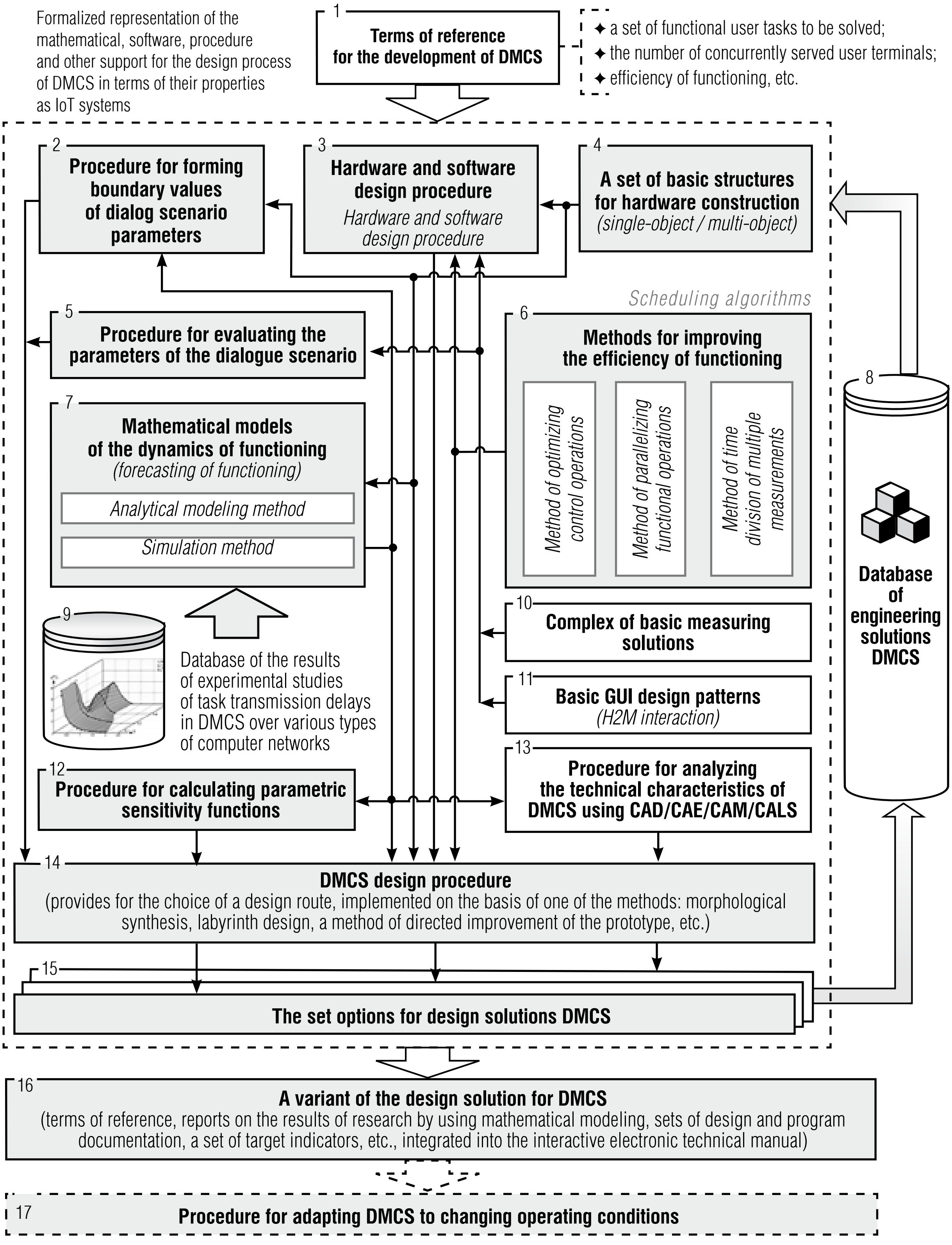


Fig. 3. Methodology for designing DMCS with specified technical characteristics:
blocks 2–7, 9–11 – solving design problems in research areas according to the items 2.1–2.8 of *Table 1*;
blocks 3, 8, 11, 13, 14, 16, 17 – solving design problems in research areas according to the items 3.1, 3.2 of *Table 1*

The “laboratory as a service” service allows several educational institutions or training centers (as operating organizations) to move from the deployment and maintenance of high-tech experimental equipment to its temporary lease and remote access via the internet (implementation of the economic model of sharing economy) [12–15, 30].

Conclusion

The directions of multidisciplinary research considered and the proposed approach to their implementation on the basis of DMCS are provided due to the following factors:

✦ a wide range of experimental laboratory studies as part of modern educational environments, allowing students to study various aspects of IoT systems (principles of operation, design methods, purpose), taking into account the key aspects of the Education 4.0 strategy and the development directions of electronic instrumentation;

✦ the development of students in the process of educational and scientific experiments, practices focused on solving a wide range of tasks in the field of digitalization of various spheres of human activity;

✦ development of students’ skills within the framework of professional competencies, such as “systemic abilities,” “cognitive abilities” and “solving complex problems” which are in demand in the main sectors of the digital economy;

✦ development of DMCS samples with specified characteristics (number of served users, response time) due to interrelated components of a domain-specific methodology which include the proposed methods, models, procedures and specialized software, and also ensure the effective use of modern computer-aided design systems;

✦ increasing the efficiency and functionality of the “laboratory as a service” service for the processes of training and retraining of personnel in the field of electronic instrumentation based on the methods of electronic pedagogy. ■

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