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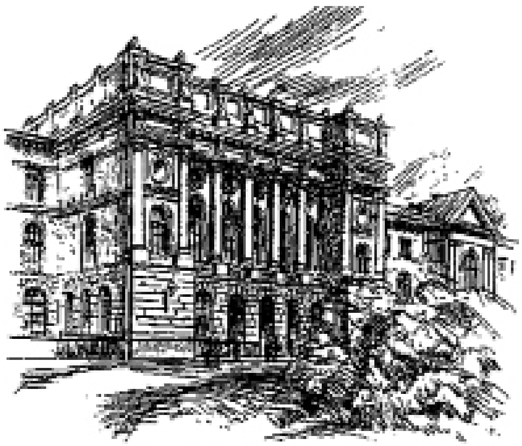

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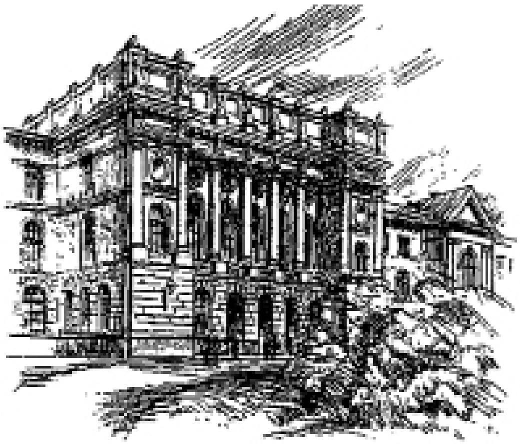
МИНИСТЕРСТВО НАУКИ И ВЫСШЕГО ОБРАЗОВАНИЯ РОССИЙСКОЙ ФЕДЕРАЦИИ



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Том 13, № 4
2020

Санкт-Петербургский политехнический
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2020

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INFORMATION MODELING FOR CULTURAL PRESERVATION: PORTICO OF THE NEW HERMITAGE AND ATLAS SCULPTURES. PART 2. METHODS AND ALGORITHMS

A.A. Fedotov[1], V.L. Badenko[1], T.V. Prazdnikova[2], V.K. Yadykin[1]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation;

[2] The State Hermitage Museum, St. Petersburg, Russian Federation

This article presents the results of interaction between SPbPU and the State Hermitage in a promising direction of using the latest achievements in the field of information technology in solving problems of preserving cultural heritage, using the example of information modeling of the Portico of the New Hermitage building and Atlas sculptures based on laser scanning data. This part of the work presents the results of the development of digital technologies for solving urgent problems of preserving cultural heritage objects. One of the main symbols of St. Petersburg, the Portico of the New Hermitage building, was chosen as the object of testing the technique. The authors present the developed methodology for collecting and processing spatial data about the elements of a cultural heritage object to build an adequate digital model of the object based on appropriate digital technologies. The following results of the technique approbation are analyzed: creation of a hybrid points cloud of Portico as the basis for the formation of an information model; creation of high-precision models of Portico Atlas sculptures based on point clouds; creation of a parametric families library of the Portico individual elements; creation of the Portico informational model; creation of a finite element model of the main elements of the Portico for stress analysis. The approbation showed the robustness of the proposed method.

Keywords: digital model, BIM, HBIM, laser scanning, cultural heritage, Historical Building Information Modeling, Hermitage, photogrammetry.

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ИНФОРМАЦИОННОЕ МОДЕЛИРОВАНИЕ ДЛЯ СОХРАНЕНИЯ КУЛЬТУРНОГО НАСЛЕДИЯ: ПОРТИК ЗДАНИЯ НОВОГО ЭРМИТАЖА И СКУЛЬПТУРЫ АТЛАНТОВ. ЧАСТЬ 2. МЕТОДЫ И АЛГОРИТМЫ

А.А. Федотов[1], В.Л. Баденко[1], Т.В. Праздникова[2], В.К. Ядыкин[1]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация;

[2] Государственный Эрмитаж, Санкт-Петербург, Российская Федерация

В статье представлены результаты взаимодействия СПбПУ и Государственного Эрмитажа в перспективном направлении использования последних достижений в области информационных технологий при решении задач сохранения культурного наследия, на примере информационного моделирования портика здания Нового Эрмитажа и скульптур атлантов на основе данных лазерного сканирования. В данной части статьи описаны результаты разработки цифровых технологий решения актуальных задач по сохранению объектов культурного наследия. В качестве объекта апробации методики выбран один из главных символов Санкт-Петербурга – портик здания Нового Эрмитажа. Представлена разработанная методика сбора и обработки пространственных данных об элементах объекта культурного наследия для построения адекватной цифровой модели объекта на основе соответствующих цифровых технологий. Проанализированы следующие результаты апробации методики: создание гибридного облака точек портика в качестве основы формирования информационной модели; создание высокоточных моделей скульптур атлантов портика на основе облака точек; создание библиотеки параметрических семейств отдельных элементов портика; создание информационной модели портика; создание конечно-элементной модели основных элементов портика для проведения анализа напряжений. Апробация показала робастность предложенной методики.

Ключевые слова: цифровые модели, BIM, HBIM, лазерное сканирование, культурное наследие, информационное моделирование, Эрмитаж, фотограмметрия.

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Introduction

The application of BIM technology to historical buildings and cultural heritage sites in the world is called HBIM (from the English Historical / Heritage Building Information Modeling) [1]. Information modeling of existing buildings, structures and other objects of historical and cultural value begins with obtaining high-precision non-destructive remote sensing geometry of the object [2, 3]. When choosing adequate survey methods, it is the accuracy that plays a decisive role, since the reliability of the model and the degree of its applicability depend on it [4, 5]. In practice, the following shooting methods have successfully proven themselves: laser scanning, digital photogrammetry technology and high-precision 3D scanning [6]. Each method has its own indicators of accuracy, features and limits of applicability [7]. Laser scanning (LS) is the most modern and actively developing type of remote sensing (RS) [8]. The drug belongs to the active remote sensing method [9]. The principle of operation of laser scanners, regardless of their type and purpose, is based on measuring the distance from a laser pulse source to an object [10]. The laser beam leaving the emitter is reflected from the surface of the examined object. The reflected signal enters the scanner's receiver, where the required distance is determined by the time delay (pulse method) or phase shift (phase method) between the emitted and reflected signal [11]. Typically, the laser scan results in a point cloud containing 3D coordinates of the points and the intensity of reflected signal. Currently, modern technologies allow points in this cloud to store information about the color, we will call such clouds hybrid [5]. Point clouds can be obtained not only using direct measurements, but also by calculating distances from images using special algorithms. This technique is called digital photogrammetry, which uses overlapping 2D images to create a 3D point cloud. Combining images and converting them to the cloud takes place automatically. Shooting can be carried out with a hand-held camera or from an unmanned aerial vehicle (UAV). On the basis of hand-held images, high-precision reconstruction of the full-size texture of the surfaces of interior rooms [12], complete reconstruction of the internal geometry of rooms [13, 14], as well as small three-dimensional objects outside the scanner's field of view [15] is possible. UAV photographs are used to photograph the roofs and facades of relatively tall buildings, where a person cannot go with cameras or scanners [16]. Most often, photogrammetric point clouds are used in conjunction with the results of laser scanning [17]. In addition, high-precision 3D scanners based on laser triangulation technology are used for small architectural forms and sculptures, which a ground laser scanner is not capable of capturing in high resolution and full volume [18].

HBIM serves as a universal platform for storing and sharing information about the current state of a structure. Defects that are inherent in any cultural heritage object are included in the model by adaptive components that are linked to the corresponding elements. An adaptive component has a value parameter representing what it is: mold, destruction, crack, etc. Further, the component has its own color, depending on what it is, and the legend gives a decoding of the color designation [19]. Most defects, such as discoloration, a loose element, or a crack, are easy to detect visually. However, there are defects that require special instruments and algorithms to be detected. For example, the following methods are used to determine the moisture content of a material:

• Contact method: a high-precision moisture meter is applied to the object evaluating the moisture content in it. The readings are recorded and a map of the distribution of moisture values over the surface is built. The map is superimposed on the corresponding surface to obtain a visual picture of potentially hazardous areas where the water content in the material exceeds the average permissible value [20].

• Non-contact method: the intensity value of the cloud points obtained as a result of laser scanning is processed according to an algorithm that shifts the values with respect to the histogram, and as a result a moisture parameter is assigned to each point [21].

Remote sensing and room modeling techniques are proving to be extremely useful in surveying and reconstructing buildings after natural disasters [22]. HBIM is also the basis for all kinds of simulations: finite element analysis of structures, determination of the risk of collapse under conditions of an earthquake, deformations and other influences [23], heat engineering calculation and verification of insolation norms. In addition, HBIM can act as a basis for the development of a project for the reconstruction of an object and a repository of all historical and up-to-date documentation in all possible forms: from written sketches to drawings [24]. Designing utility systems in historic buildings is a particularly complex task that requires a modern approach. Digital information modeling technologies allow capturing the current state of networks and designing new ones, avoiding collisions [25]. Over the past decade, virtual and augmented reality technologies have become very popular and widely available, and specialists around the world have learned to apply them in their fields. In the field of preserving cultural heritage, technology allows not only to service buildings more efficiently, but also to provide tourists with expanded opportunities for visiting and studying monuments [26]. HBIM can be used to organize virtual tours through the VR platform. The user has the ability to move around the model, inspect it, interact with its elements, receive relevant and historical information [27] and enter rooms that are physically closed to visitors. VR even helps engineers in building maintenance, as it makes it possible to accurately understand the situation without leaving the office and to plan work as efficiently as possible [28]. This technology can be used in the field of education of specialists, historians and restorers [29].

This paper explores the possibilities of using modern digital technologies in relation to the preservation of a cultural heritage site, one of the main symbols of St. Petersburg: the Portico of the New Hermitage building.

This study has the following objectives:

• to develop a methodology for collecting and processing spatial data for cultural heritage sites using digital technologies;
• to create a resulting hybrid points cloud of Portico to preserve the object of cultural heritage;
• to create high-precision models of Atlas sculptures based on the data obtained;
• to create a library of parametric families of individual elements of the Portico;
• to create an information model of the Portico;
• to create a finite element model of the main elements of the Portico;
• to analyze the deformations of the main elements of the Portico caused by their own weight.

Materials and methods

In general, the developed methodology for cultural heritage objects (Fig. 1) includes a collection of spatial data reflecting the up-to-date geometry of the Portico elements (1), their processing (2), creation of an information model based on the processed data (3) and modeling of processes and phenomena at the facility, including finite element analysis of the elements (4).

Depending on the type of analysis carried out, different requirements are imposed on the level of elaboration of the HBIM and its individual elements. For example, when calculating insolation, there is no need for full compliance of the model geometry with its real state, and an assessment of the cultural heritage object VAT, on the contrary, requires an accurate model of the object. Taking into account the fact that HBIM is created from elements obtained on the basis of point clouds, it is possible to formulate certain quantitative requirements for the data obtained in the course of the study (Table 1).

Table 1

Quantitative requirements

Data Type	Element	Quantitative requirements
Point clouds	Complex architectural forms	Density $\geq 10^6$ dots/ m^2, % blind spots $\leq$ 10 %
	Metal constructions	Density $\geq 10^4$ dots/ m^2, % blind spots $\leq$ 70 %
	Reinforced concrete structures	Density $\geq 10^2$ dots/ m^2, % blind spots $\leq$ 50 %
	Basic dimensional elements (walls, floors)	Density $\geq$ 5 dots/ m^2, % blind spots $\leq$ 50 %
NURBS surfaces	Basic dimensional elements (walls, floors)	Number of splines $\geq$ 5, spline density $\geq$ 1 vertices/ m^2
Meshes	Complex architectural forms	Number of polygons ~ 1/3 on the number of points
Revit families	Replicated elements (windows, doors)	Number of parameters $\geq$ 2
HBIM	Model granularity	LOD100 – LOD500

In addition to the listed requirements, there may also be additional requirements for the semantic classification of point clouds and for the geographic referencing of data. Polygonal models can be subject to requirements for the absence of topology artifacts (double vertices, incorrectly oriented polygons, missing polygons) and for topology optimization (retopology).

Data collection. Depending on the requirements for the initial data, data collection can be carried out using terrestrial, mobile or aerial LiDAR systems. Individual elements can be captured using close range photogrammetry, or high-resolution 3D scanning systems based on LiDAR or stereo cameras. To improve accuracy and data binding, GCPs are surveyed with a total station or GNSS receiver.

Data processing. After completing all field measurements, independent datasets of laser scanning, photogrammetric surveys and additional control measurements are formed. They are then converted to point clouds and control point coordinates. As a result of this conversion, irregular data arrays with different spatial density are obtained, containing hundreds of millions of laser reflection points, including the so-called "false" reflections resulting from the reflection of a laser beam from the surface of water, mirrors, etc., as well as unwanted points reflected from foreign objects in the scanning area. To simplify further work with such clouds, as well as to ensure fast data transfer between all project participants, it is necessary to reduce the number and density of points and eliminate unwanted points. Therefore, various algorithms for filtering and thinning point clouds are used based on the open PCL library [30]. Each dataset is processed

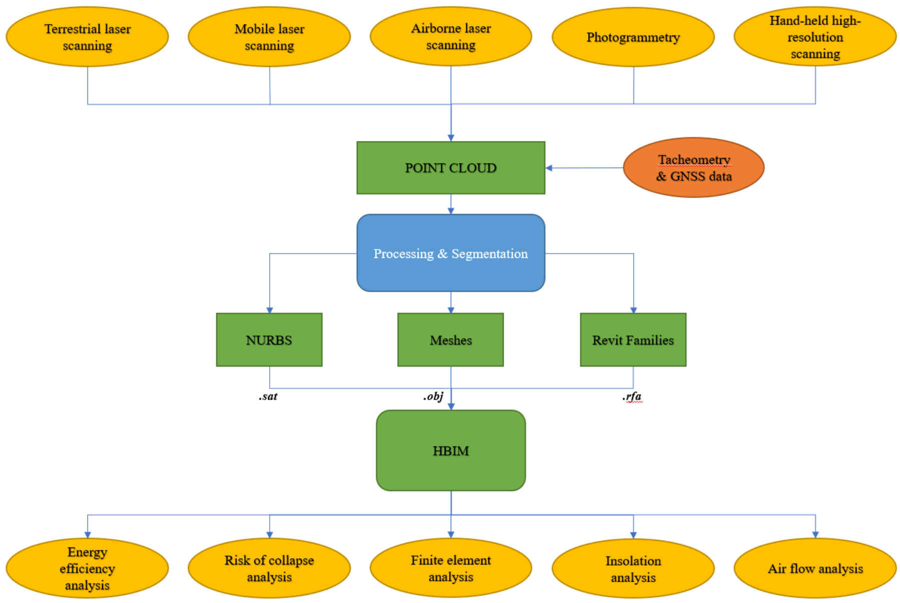

Fig. 1. Block diagram of the developed technique

independently of each other, then the resulting point cloud is formed to reduce blind spots. For the convenience of further work, segmentation of individual elements from the cloud is performed.

BIM. The most common cultural heritage information modeling (HBIM) software is Autodesk Revit [31]. Information Modeling in Revit uses system and user-defined families. System families create features such as walls and floors and cannot be modified, but you can customize the layer structure and settings. Their main disadvantage in a BIM context is regular geometry. However, this disadvantage can be partially eliminated due to the possibility of creating system families based on NURBS surfaces. Custom families create elements such as columns, beams, facade decorative elements, etc. Despite the greater flexibility of modeling compared to system families, their main disadvantage is also the regularity of the geometry. However, this problem also has a solution: for elements of complex shapes, it is possible to create families based on imported polygonal models. Thus, using the basic principles of Revit, a model is created that reflects the actual geometry of the object under study. HBIM includes not only geometry, but also information about materials obtained by instrumental methods, as well as the necessary documentation, results of energy efficiency calculations, structural analysis, etc. Documentation and the formation of the results of various calculations are performed using standard Revit tools, depending on the requirements for a specific project. The resulting model is a database of the object, containing all the available information and is the basis for planning and carrying out future work, as well as for creating a digital twin of the object.

Analysis. On the basis of the resulting information model of the cultural heritage object, various types of analysis are carried out, including analysis of the energy efficiency of a building, analysis of the stress-strain state of an object, modeling of air flows, calculation of insolation, and so on. The use of the information model as a basis for certain calculations is ensured due to the compatibility of the computational software systems with the three-dimensional geometry of which HBIM consists.

Results

To obtain accurate results, fully reflecting the actual geometry of the Portico elements, we performed laser scanning of the object and digital photogrammetric photography of its individual sections. Terrestrial laser scanning was carried out using a Leica BLK 360 laser scanner, which was controlled using an iPad Pro tablet. The scanning accuracy was 4 mm.

The survey was carried out in 2 stages. At the first stage, the main elements of the Portico were scanned, but as a result of the analysis of the data obtained, blind spots were identified in the narrow spaces between the columns and sculptures, as well as in the upper parts of the sculptures. To eliminate the identified blind spots, an additional stage of surveys was carried out using digital photogrammetric photography. Photogrammetric shooting was carried out using Nikon D610.

The processing of the received data begins with bringing individual scans to a common coordinate system. Registration was performed in the local coordinate system using paper stamps in Cyclone Register 360 software. The number of points after registration was about 200 million. For further processing, it is necessary to optimize the number of laser reflection points. In doing so, it is also necessary to maintain a high density of points related to the sculptures. For this, the points related to the Atlas sculptures were segmented from a common cloud. Then, the rest of the cloud was optimized, so that the distance between adjacent points was 5 mm. Then the points were filtered to improve their decoding properties and reduce noise. The data was filtered using the SOR algorithm. Next, the remaining noise was removed based on the TLO roughness parameter. To automate data preprocessing, the command line mode of the CloudCompare software was used. Due to different data density requirements, the points describing the surfaces of the sculptures were processed separately.

Photogrammetric surveys were processed automatically using Metashape software. Optimization of the alignment of images was carried out using the coordinates of paper stamps obtained on the basis of a cloud of laser scanning points. The dense cloud was built automatically. Then all non-sculpture points were removed. A dense point cloud, like a raw laser scan point cloud, is too dense and therefore requires preprocessing. Its preliminary processing was carried out in the same way as processing the cloud of laser scanning points. After independent processing, the resulting clouds were combined into a resulting point cloud based on the common coordinates (Fig. 2).

Thus, the collection and processing of data can be summarized as follows:

- first of all, data are collected using laser scanning and digital photogrammetry methods, it is necessary to provide for the survey of areas between sculptures and columns, and also for the visibility of at least 3 paper stamps at each scanning station to improve the registration accuracy;
- preliminary processing of points related to sculptures must be performed independently of other points;
- preprocessing (registration, optimization and filtering) can be automated using the CloudCompare command line mode;
- combining data into the resulting point cloud should be based on the shared coordinates.

To create an information model of the New Hermitage Portico, Autodesk Revit software was used. First of all, the cloud was segmented into separate parts, and then, using Revit tools, 12 parametric families of elements of a historical object were formed based on point clouds: windows, columns, pilasters, capitals, pedestals, Atlantean statues, etc. The families of Atlas sculptures were created based on their triangulation models. Model elements such as walls with significant deviations from the plane were modeled with Revit tools based on NURBS surfaces, which in turn were generated automatically from the point cloud in Rhinoceros software. The resulting information model reflects the actual state of the Portico with accuracy of 1 cm (Fig. 3).

Thanks to modern software systems, it is possible to obtain a finite element model based on the geometry obtained from the information model. In this case, ANSYS software was used to solve this problem, for it supports the import of models saved in the ACIS geometric modeling format. The export of information model components from the Revit environment for their finite element analysis in ANSYS was performed in the .sat format. The finite element mesh was generated automatically based on the geometry of the information model. After setting the boundary conditions and loads, we carried out an analysis of the deformations of the Portico elements, including the Atlas sculptures. The analysis result is shown in Fig. 4.

Fig. 2. The resulting point cloud

Fig. 3. Information model

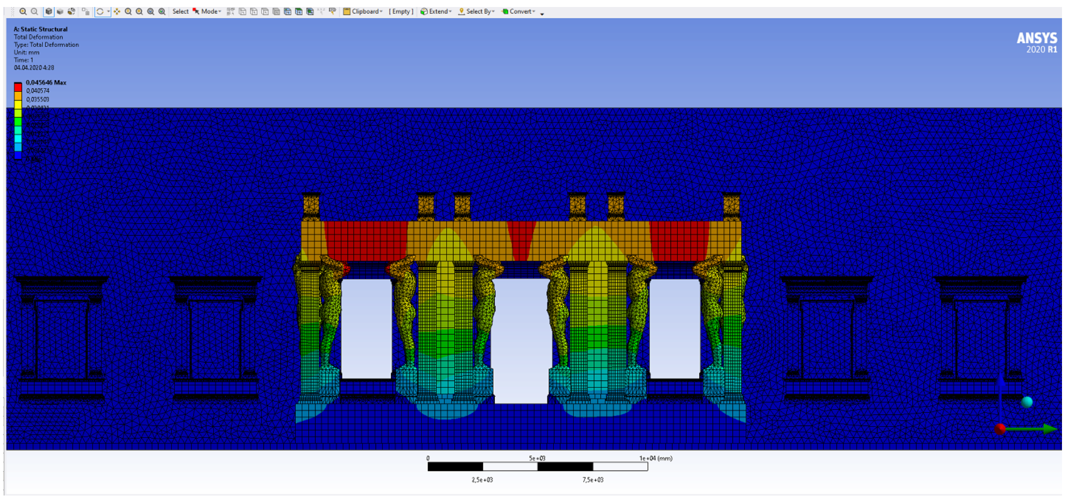

Fig. 4. Analysis result

As a result of the finite element analysis based on HBIM, the maximum deformation values of the Portico elements were calculated to be 0.04 mm. Taking into account the main assumptions within the framework of which the calculation was performed, it can be concluded that the local maxima of the deformation diagrams of the longitudinal beams of the Portico are of the greatest interest. According to the analysis results, their location coincides with the location of the sculptures cracks during field observation. This suggests that the formation of cracks in the sculptures could have occurred as a result of deformations of the structural elements of the Portico and the transfer of load to the sculptures themselves.

Conclusion

This work is the second part of [32], which presents the results of the development of digital technologies for information support for the preservation of cultural heritage sites. One of the main symbols of St. Petersburg, the Portico of the New Hermitage building, was used as an object of approbation. The following results of method approbation are analyzed:

- creation of a hybrid points cloud of Portico as the basis for the formation of a digital model;
- creation of high-precision models of Portico Atlas sculptures based on point clouds;
- creation of a library of parametric families of individual elements of the Portico;
- creation of an information model of the Portico.

The results of the finite element analysis of the deformations of the elements of the Portico of the New Hermitage building are presented on the basis of the information model of the cultural heritage object (HBIM) obtained from the laser scanning results. The main advantage of the proposed technique in comparison with traditional methods of object inspection and corresponding finite element analysis is the completeness and speed of measurements, as well as increased adequacy and accuracy of the results.

Numerical comparison of the proposed methods with the traditional approach based on the use of tacheometric measurements allows us to draw the following conclusions. Thus, the accuracy of the tacheometric survey of the individual points coordinates is approximately 0.5 mm. In turn, the accuracy of the individual points coordinates measuring by laser scanning is 4 mm. However, it should be noted that the density of tacheometric measurements is hundreds of thousands of times inferior to the proposed methods; therefore, when using only discrete measurements, most of the information on the object elements geometry under study is absent, which inevitably leads to a decrease in the processed results absolute accuracy. Thus, based on the expert judgment, it can be concluded that the absolute accuracy of the simulation results based on the proposed methods is several times higher (depending on the scanned surfaces geometry homogeneity) compared to the simulation results based on tacheometric measurements. For a complete capture of the scanned scene using the proposed methods, it will take about 2-3 times less time compared to using tacheometric survey. This is achieved due to a high degree of measurement automation by the proposed laser scanning methods. In addition, it should be noted that, due to the complex geometry, shooting the Atlas sculptures using the tacheometric method is impossible in principle. A similar comparison can be made with the photogrammetric survey approach. The result of such surveys is also a point cloud. However, in the case of laser scanning, the coordinates of the points are obtained by direct measurements, while in case of photogrammetry, the coordinates of the points are obtained by calculating distances based on two overlapping images. Therefore, this method of calculating coordinates is subject to distortion which negatively affects the final accuracy, which, among other things, depends on many factors (illumination, surface material, equipment, shooting mode, processing parameters). Thus, the final accuracy of the proposed methods in comparison with the use of photogrammetry is 5-10 times higher. According to expert estimates, the speed of photogrammetric surveys is also at least 2 times inferior to the proposed methods. This is due to the fact that for a complete photogrammetric shooting of an object, it is necessary to make about 5 thousand images with the required overlap, and also to provide the absence of strangers in the frame. It should be noted that the existing experience, for example, of obtaining a high-precision digital model of the sculpture of David Michelangelo and others, is usually associated with the transfer of objects to special rooms and / or the installation of devices to strengthen scanning cameras [33–36]. In our case, the survey was carried out in real "field" conditions. It should also be noted that the proposed method includes all the advantages of the traditional methods that are used for additional shooting of the necessary elements. For example, tacheometric survey of control points is used for more accurate registration of point clouds, and photogrammetric survey is used for partial survey of blind spots.

In addition, an information model with the up-to-date state of elements can become the basis for creating a digital twin of an object. The main difference between the proposed data processing methods lies in the significant automation of the preliminary processing of point clouds, as well as in the increase in the decoding properties of laser reflection points. The proposed methods for creating an information model based on point clouds, including the use of NURBS surfaces, increase the degree of model adequacy in comparison with traditional modeling methods.

As a result of the work we obtained:

- a point cloud to preserve the object of cultural heritage,
- informational model of the Portico, reflecting its up-to-date state at the time of shooting,
- results of finite element analysis in the ANSYS software package.

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THE AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Fedotov Alexander A.
Федотов Александр Александрович
E-mail: alexandrefedotov@gmail.com

Badenko Vladimir L.
Баденко Владимир Львович
E-mail: vbadenko@gmail.com

Prazdnikova Tatiana V.
Праздникова Татьяна Владимировна
E-mail: prazdnikova.t@gmail.com

Yadykin Vladimir K.
Ядыкин Владимир Константинович
E-mail: v.yadikin@gmail.com

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MODERN POSSIBILITIES OF USING AI METHODS IN THE ANALYSIS OF BIOMEDICAL DATA

I.A. Gasanova[1], *D.S. Prelovskii*[1], *V.A. Yurkin*[1],
P.D. Drobintsev[1], *A.O. Drobintseva*[2]

[1] Peter the Great St. Petersburg Polytechnic University,
St. Petersburg, Russian Federation;

[2] Saint Petersburg State Pediatric Medical University,
St. Petersburg, Russian Federation

Nowadays, one of the key indicators that have a great impact on the evolution of society is artificial intelligence. AI and Big Data technologies are widely used to analyze biomedical data. This article describes what artificial intelligence and Big Data are and what are the modern possibilities of using their methods and technologies. The statistics showing the growth in the use of Big Data and AI technologies in medical research are presented. The main types of artificial neural networks used in this area are considered, as well as examples of the successful use of Big Data technologies in medicine. The effectiveness of the use of special computer programs in the field of health care, which allows detecting diseases at early stages, are demonstrated. The key technological and ethical problems of introducing artificial intelligence technologies into medicine are considered, the difficulties of implementation, integration and dissemination of technologies are shown. Special attention is paid to the use of AI in the fight against the global pandemic, the COVID-19 coronavirus infection. The methods of using AI in various countries for collecting data, analyzing and then building a model of the spread and mutation of coronavirus under various scenarios of the development of the situation and the introduction of special restrictive measures, as well as predicting their effectiveness are analyzed.

Keywords: Big Data, predicative analysis, healthcare, cancer detection, neural networks.

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СОВРЕМЕННЫЕ ВОЗМОЖНОСТИ ИСПОЛЬЗОВАНИЯ МЕТОДОВ ИИ В АНАЛИЗЕ БИОМЕДИЦИНСКИХ ДАННЫХ

И.А. Гасанова[1], *Д.С. Преловский*[1], *В.А. Юркин*[1],
П.Д. Дробинцев[1], *А.О. Дробинцева*[2]

[1] Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация;

[2] Санкт-Петербургский государственный педиатрический медицинский университет,
Санкт-Петербург, Российская Федерация

На сегодняшний день одним из ключевых показателей, оказывающих большое влияние на эволюцию общества, является искусственный интеллект (ИИ). ИИ и технологии Big Data широко применяются для анализа биомедицинских данных. В статье рассказывается о том, чем является искусственный интеллект и Big Data и каковы современные возможности использования их методов и технологий. Приведена статистика, показывающая рост использования технологий Big Data и ИИ в медицинских исследованиях. Рассмотрены основные типы искусственных нейронных сетей, используемых в этой области, а также приведены примеры успешного применения технологий Big Data в медицине. Продемонстрирована эффективность использования специальных компьютерных программ в сфере здравоохранения, позволяющих выявлять заболевания на ранних стадиях. Рассмотрены ключевые технологические и этические проблемы внедрения технологий искусственного интеллекта в медицину, показаны трудности реализации, интеграции и распространения технологий. Отдельное внимание уделено использованию ИИ в борьбе с глобальной пандемией – коронавирусной инфекцией COVID-19. Изучены способы применения ИИ в различных странах для сбора данных, анализа и последующего построения модели распространения и мутации коронавируса при различных сценариях развития ситуации и введения специальных ограничительных мер, а также прогнозирование их эффективности.

Ключевые слова: Большие данные, предикативный анализ, здравоохранение, обнаружение рака, нейронные сети.

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Introduction

Nowadays, the whole world and his wife talk about Big Data, but only a few actually know what it is and how it works. Big data technology is a set of various tools, approaches, methods for analyzing structured and unstructured information and on its basis the subsequent production of new information to solve specific problems and goals defined by the customer (market, consumer, etc.). In 2011, research and consulting company Gartner noted Big Data as the number two trend in the information technology infrastructure (after virtualization) [1]. At present, Big Data technologies can no longer be unambiguously attributed to the IT sphere, since they have become an important part of the structures of management, business, industry, medicine and science, constantly increasing their share of participation.

According to the Russian IT holding IBS, in May 2015, the global amount of data exceeded 6.5 zettabytes. By 2025, it is predicted that humanity will generate 400–440 zettabytes of information, according to a report by The Data Age 2025, which was prepared by analysts at the American research company IDC [2]. The report notes that most of the data will be generated by the enterprises themselves, and not ordinary consumers. By 2027, the global Big Data market is projected to grow to $ 103 billion, more than double its expected market size in 2018. The growth is projected to be up to (about) 8 billion US dollars per year, or 10–15 % of the total market turnover. The largest share of 45 % will be achieved in the field of software production, and will be the largest share on the market [3] (Fig. 1).

Big Data is a part of the information that can be obtained by digitizing the entire spectrum of sources available to us, which can be processed by any means and recorded using sensors. The rationality and prospects of the application of Big Data technologies in medicine, as well as in the whole health concept in recent years has been widely discussed by the professional community. In the field of healthcare, Big Data technologies are used to analyze and process information about the health status of a population or individuals, and potentially increase the likelihood of timely identification of diseases and predispositions to them stored in the human genome. Because prevention is always cheaper than treatment, such technologies have great potential, and will soon have to be applied to every person. In most medical institutions of the future, all medical information about a person from the moment of his birth will have to be stored in an

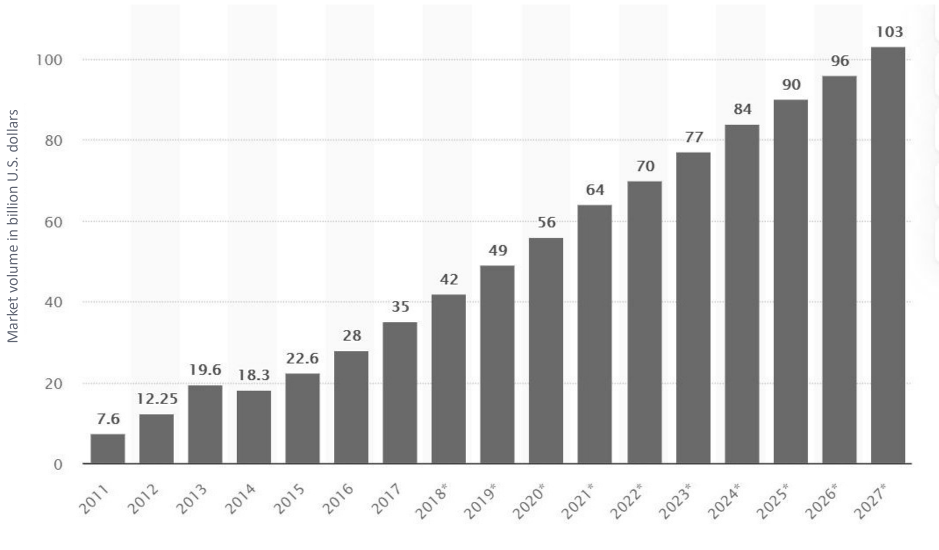

Fig. 1. Big Data market size revenue forecast worldwide from 2011 to 2027

electronic database. The issuance of forecasts, medical indications and recommendations for patients will be promptly implemented through the use of machine learning algorithms that can determine statistical correlations in an array of medical data collected from medical institutions around the world.

The initial analysis of the data and the collection of necessary information about the patient can be transferred from a person to an automated system, thanks to this, a significant part of the time can be saved. For the correct diagnosis of the disease, a large amount of data about the patient is required, namely: his purchases, diagnoses, risks of the condition, etc. Having performed this analysis, we will come to a new personalized and preventive medicine. So, thanks to the results of using Big Data, it is quite possible to predict the risks of mental or psychological diseases of a particular person and prevent diseases such as depression, psychoses, etc. These methods of individual and preventive medicine, which is based on monitoring patients remotely, will entail significant cost reductions, as well as increase the quality of life of the observed patients. For example, a medicament will not have any effect on 90 % of the observed patients, however, a certain group of patients must be offered it directly, and to another group, on the contrary, it is required to refuse this medicine, since the risk of an allergic reaction is increased. Another example is the medical examination on a certain group of people (or all, without exception) once a year, and personally, for each patient according to an individual schedule developed in connection with the risks of his condition. In the modern world, a single doctor has a large number of patients; accordingly, having received some background information, he may not notice that the patient is cutting off episodes of his life, which can be crucial. For example, in order to identify the distant spread of cancer on the bone, information about various injuries is needed, but due to the workload of the doctor and, accordingly, understatement on the part of the patient, information about the absence of injuries can be obtained, but at the same time asking a more correct and accurate question, you can find out the opposite.

Recently, the use of Big Data technologies in pharmaceutics has gained considerable importance. At the moment, Big Data tools and AI technologies are actively used in the production and marketing of medicines. Nowadays, the main 4 areas of implementation of Big Data technologies in pharmaceuticals are actively discussed, these include:

1. The development of new drugs. Big Data technology focuses on finding trends and models that otherwise would be difficult, expensive and even impossible to find using traditional methods of collecting and processing information [4].

2. Collection of clinical information about patients. Among pharmaceutical manufacturers, there is fierce competition for the right to get first access to patients medical data. Obtaining such information is characterized by transactions with large technology companies engaged in research in the field of database analysis. For example, the holding pharmaceutical company Roshe Group collaborated for a long time, and then acquired the Flatiron Health company, which is the market leader in the collection of clinical information specializing in cancer research [5].

3. Improving the quality and control of clinical trials. Corporations can increase the effectiveness of clinical trials through the use of Big Data methods. For example, searching for patients with certain parameters in a large database.

4. Detection of intolerance to medical drugs. The use of an analytical system with Big Data approaches for segregating drugs with certain medical properties can reduce costs for companies and save the lives of more patients [6].

In addition, one of the cutting-edge discoveries that contribute to monitoring the health of each person is various devices (for example, fitness trackers, smart watches). These devices contain a number of sensors that monitor the pulse, blood pressure, counting steps, in addition, through these gadgets it is possible to control the rate of breathing, as well as create a varied and balanced nutrition menu. All information from these devices can be instantly transferred to the appropriate application on the phone in order to keep all your indicators under special control, which will allow the user to draw up a daily regimen, nutrition, help monitor physical activity, water balance, and health in general. In some cases, this information can save the user's life, but if the user is healthy, the zettabytes of the collected data form continuously expanding information databases. The interdisciplinary interaction of Big Data specialists and medical professionals is facilitated by the high information potential of wearable smart devices. In the middle of 2015, two largest US corporations, Apple and IBM, decided to consolidate their efforts in the use of Big Data technologies in healthcare [7]. The companies have integrated the data received from owners of iPhone smartphones and Apple Watch smart watches with the IBM Watson Health cognitive system. The above examples of the use of smart devices for collecting medical indicators show that this area is being intensively developed by Big Data technology specialists. This is a rapidly developing area which has great potential to expand.

The provided statistics demonstrates high growth rate of the use of Big Data technologies in medical research. Large financial investments emphasize the high interest of medical and IT companies in collaborative research, the result of which is to increase the efficiency of the use of resources in the healthcare sector and improve medical statistics data.

Artificial Intelligence Algorithms for Big Data analysis

Since the size of medical data is growing rapidly, humanity comes to the logical conclusion that our health and quality of life depend on the speed and quality of their analysis. And that all this is a job for artificial intelligence. In this article, by the term AI, we understand the ability of machines to model rational behavior of people, that is, their ability to navigate in a changing context, on the basis of which they makes the most appropriate choice to achieve their goals.

To date, two AI technological processes are widely used: expert systems and neural networks. At the same time, expert systems are becoming obsolete, neural networks have flooded the market due to their ability to learn. A neural network means a sequence of neurons, which are connected to each other by synapses that serve to transmit a nerve impulse. In a computer form, artificial neural networks (ANNs) represent a graph with three or more layers of neurons. The layers are interconnected according to the selected algorithm, depending on the task. Each link has its own specific weight. These weights play a crucial role in training of an ANN. Most often, ANNs are used to solve such types of problems as classification, prediction and recognition, etc.[1]. There are quite a few types of neural networks for solving problems specific to various fields. This article describes different types of basic ANNs.

[1] Rashchenko J.V. Application of modified artificial neural networks in machine vision problems. 2018. Available: http://hdl.handle.net/11701/12215 (Accessed: 15.01.2021).

1. Shallow neural networks. This type of ANN consists of only 1 hidden layer of the perceptron. The number of neurons in the hidden layer may vary. Collaborative filtering is considered one of the examples of this type of ANN: a method of forecasting in recommendation systems. In medicine, this type of ANN can be used to create a classifier that can distinguish cancer and manage patients from mass spectrometry data [8].

2. Multilayer perceptron is a type of direct distribution ANNs. They consist of many input nodes of one or more hidden layers and one output layer of neurons. The number of input and output elements in a multilayer perceptron is determined by the conditions of the problem. This type of ANN is used in the tasks of forecasting, managing agents of classification, approximation, etc.

3. Convolutional neural network (CNN) is a type of deep ANNs, most often used for the analysis of visual images. It uses certain characteristic features of the visual cortex, in which two types of cells with different features were discovered. Simple cells tend to react to straight lines at different angles, and complex – to activate a specific set of simple cells.The network structure is unidirectional, basically multilayer. It is used in problems with image recognition, classification, analysis of medical images, natural language processing, etc. [9]. There are various CNN architectures available, which were key in the construction of algorithms that provide and should ensure the operation of AI as a whole in the foreseeable future. Some of them are listed below: LeNet, AlexNet, VGGNet, GoogLeNet, ResNet, ZFNet.

4. A recurrent neural network (RNN) is a class of artificial neural networks, where connections between nodes form a directed graph along a time sequence. This allows it to process a series of events over time. RNNs are called recurrent because they perform the same task for each element of the sequence, and the output depends on previous calculations. Recurrent neural networks add memory to artificial neural networks, but the implemented memory is short – at each step of the training, the information in memory is mixed with new and after several iterations is completely overwritten. It is applied to such tasks as non-segmented handwriting recognition with connection or speech recognition.

5. A network with long-term and short-term memory is an artificial recurrent neural network used in the field of deep learning, capable of studying long-term dependencies. Long short-term memory (LSTM) modules are designed specifically to avoid the problem of long-term dependency by storing values for both short and long periods of time. This is because the LSTM module does not use the activation function inside its recurrent components. Thus, with the method of back propagation of errors in time during network training, the stored value does not blur in time and the gradient does not disappear [10]. It is used in tasks related to image processing, video, and speech recognition.

6. Networks based on attention. The key point of the proposed attention-based model is that it takes into account the influence (interconnection) that exists between different parts or words or the whole one input sentence with another, and provides an interdependent representation of a pair of sentences that can be used in subsequent tasks. Many hierarchical patterns of attention are called transformers. These transformers are most effective for stacks running in parallel, so they provide the most innovative results with relatively minimal data and a period of time for training. This model is mainly used when working with text data.

7. Generative-competitive network is a machine-learning algorithm without a trainer, created in the composition of 2 neural networks, one of which, called a generator, creates new instances, and the other, the discriminator, evaluates them for authenticity, seeks to distinguish true (genuine) examples of samples from erroneous. Widely used in tasks related to the generation of images, video and audio. In a sense, they are robotic artists, and their result is impressive, but they can also be used to create fake media content [11].

Currently, there is a tendency to increase the number of publications on the successful use of neural networks in parallel with the development of AI technologies based on neural networks in the healthcare sector. Despite many years of attempts at application, the main directions of the use of neural networks remain unchanged and include: classification, forecasting and diagnostics. The most commonly used type of ANNs in these tasks is a neural network with direct connection. In addition, the study revealed a significant share of hybrid models used.

The aforementioned examples of artificial intelligence usage in the medical field show the leading position of two types of neural networks: hybrid and feedback. Both of them are used to solve the main problems of data classification, recognition of medical markers on images and data arrays, and predicting the occurrence of relevant diseases.

Big Data case studies

Consequently, AI may (at least at the current stage of the technology development) not replace a doctor, but be – has already become – a useful tool, an assistant in the process of diagnosis and treatment. The examples are listed below.

One striking example is IBM Watson for Oncology (WFO), a program based on the power of the IBM Watson supercomputer that uses natural language processing and machine learning to provide recommendations for the treatment of cancer. In the course of its work, it is involved in data processing (structured and unstructured) from literature, medical records, images, all kinds of pathology reports, laboratory data, expert knowledge, etc. [12]. Each patient, with the help of IBM Watson, is offered a personalized course of treatment, which is aimed at those factors that led to the development of a cancerous tumor in a particular person, taking into account his genome. This allows increasing the chances of a successful recovery, and each new case increases the likelihood even more. The Watson Cancer application has already been used to help more than 20,000 people around the world.

A study launched in China found that different types of cancer are common various conformities as recommended by doctors. For example, recommendations for treating gastric cancer had the lowest chance of being agreed with your healthcare providers. Morbidity and pharmaceuticals may be the main causes of disagreement. In order to comprehensively and quickly apply this technology in China, WFO needs to accelerate localization [13]. At the moment, another project from IBM Watson is under development – IBM Medical Sieve – a cognitive assistant system for radiologists and cardiologists that can detect abnormalities using holistic clinical information obtained from images, text or medical data [14].

In 2016, Optellum startup was created. They are developing lung cancer prediction AI (Optellum LCP) software for the diagnosis and treatment based on computed tomography. The company's solution is based on artificial intelligence and machine learning technologies used in the world's largest clinical data set. The software provides expert-level clinical decision support, which can improve the doctor's ability to correctly diagnose nodules in the lungs [15].

Modern classifiers based on convolutional neural networks are able to systematize images of skin cancer along with dermatologists, which makes it possible to guarantee an early diagnosis of the disease. Software products that use this type of ANN are already trained using a large data set; during their work, they improve the data characteristics for systematizing skin lesions and demonstrate better efficiency with currently available limited data sets [16]. Currently, there is an O-network under development, a convolutional network that is a combination of two convolutional U-networks. These networks are combined on the coding layer and disconnected at the decoding level, which allows the convolution/reverse convolution process to be used with another core of the structure, which is aimed at searching for elements with different parameters. This type of architecture shows promising results in the field of detection of breast cancer using mammography, but needs to be improved [17].

Due to the rapid population growth over the past years, prevention and control of lung cancer has become increasingly important. The use of risk factors for lung cancer in the elderly and their quantitative analysis of the degree of influence using deep neural network models can be used as a tool for identifying risk factors, and for other types of cancer to help doctors who make decisions on cancer prevention diseases [18].

Adverse reactions to medications are becoming more common and are considered the main factor causing more than a million injuries, disabilities, anomalies and deaths per year. The best known method for identifying adverse drug reactions is to rely on spontaneous reports of them. A model has now been developed based on a fully connected neural network that uses chemical and biological information and biomedical drug data to detect adverse reactions. The purpose of this product is to identify potentially dangerous reactions to the drug and to predict possible adverse reactions to new drugs. The results of the work show that the use of this model helps to detect potential reactions to drugs, regardless of whether they were registered in the past [19].

The significance of research in the diagnosis of lung cancer is associated with social relevance, this type of disease and its leading position in the structure of cancer. An intelligent automated diagnostic system using a combined algorithm based on machine learning methods, such as deep forest and Siamese neural network, was developed in the scientific cluster of the St. Petersburg Peter the Great Polytechnic University. It is a more effective approach with a small sample of training data and optimal in terms of reproducibility. The algorithm uses the data of the St. Petersburg Clinical Scientific and Practical Center for Specialized Types of Medical Care (Oncology), which includes only computer tomograms of patients with verified diagnoses of lung cancer. The developed software is considered innovative and has already been patented. The software provides the ability to quickly recognize and detect all neoplasms without exception, which after processing the data are highlighted in a certain color, which allows the system to interpret the neoplasm as malignant or benign. Comparing information about one patient with a large amount of previously accumulated knowledge, the model discovers relationships that previous methods or doctors overlooked [20].

There is a common problem for many studies, which impedes the full realization of their potential. Such a problem for researchers working in the field of artificial intelligence is the quality of the data they use. AI can analyze and interpret scanned images or pathological images only if the data are of good quality and in large volume. Therefore, if the data quality is poor, then AI systems generate inaccurate and biased results.

The implementation of Big Data analysis technologies can significantly improve the quality and speed of diseases detection in the early stages according to medical data. This information in turn entails a reduction in the burden on doctors, providing the opportunity to redistribute efforts to other problems requiring human involvement.

Problems, difficulties of implementation, dissemination of Big Data technology in healthcare

It is important to mention, that the use of artificial intelligence algorithms in dermatology and general medicine is not fiction from distant future, but a part of modern reality. Doctors who are the first to take advantage of new opportunities will take their diagnostic skills to a whole new level and significantly increase the prestige in the eyes of patients. Once this happened with ultrasound diagnostic devices, then the turn of popularity of computed tomography came.

A Big Data system, usually characterized by size, variety, reliability and speed, goes beyond the boundaries of a data type and contains the nuances of data analysis, such as generating hypotheses, but not hypothesis testing. Big medical data has a number of features that distinguish them from Big Data from other disciplines. Big Data technology has many applications in healthcare, such as predictive modeling and clinical decision support, disease or safety surveillance, public health and research.

Integration of heterogeneous data sources (medical records, research data, laboratory test results, the Internet, biometric readings, medical images, etc.) leads to an increase in data size, incompleteness and complexity [21]. To cope with the growth of data volumes, organizations turn to a number of different technologies, such as compression, deduplication, etc. Database support requires constant funding, which creates an additional barrier to the implementation of Big Data [22]. The idea of data integration is closely related to the idea of data validation. There are cases when there are no values in the data set, and as a rule, the easiest way is to delete incomplete information. The disadvantage of this method is the reduction in the amount of data required for analysis, which leads to inefficiency.

Big Data has a number of problems associated with the data itself, which should be taken into account when analyzing them.

The presence of a linear relationship between variables, the complexity of the model, the re-equipment of its data with large computational costs accompany the technology of Big Data and affect most quantitative analyses.

In the healthcare sector, confidentiality and security of patients data is an important aspect, because large data warehouses can attract the attention of fraudsters [23].

Another problem in introducing Big Data technologies is a lack of specialists in this field, which has led to an increase in demand for the Big Data experts [24].

The companies with experience in working with Big Data are for the most part satisfied with the results of their work, however, without exception, everyone faces difficulties in maintaining competitiveness and turning into digital enterprises [25].

Many problems, including legal, ethical, integration ones, must be overcome in order to implement large medical data as a combustible material for a continuously learning healthcare system that will help improve the condition of patients and reduce time and material costs in this area [26].

The adoption of artificial intelligence technologies in other fields of science can contribute to implementation problems solution, which leads to increase in the number of specialists in this field. The quality of medical data will be inevitably improved with the growth and spread of electronic medical systems in the world. The development of data storing and analyzing devices will lead to a reduction in the cost of this technology and an increase in the efficiency of its use in the future.

AI approaches in COVID-19 pandemic

The current global COVID-19 pandemic is the most acute topic around the world. Government authorities in all countries are trying to take measures to contain and fight the virus. A significant role in this process is taken by mathematical models, algorithms and methods in the field of technologies for human movement and identification.

To determine the COVID-19 markers, specialized software is used. For instance, Infervision, which is based on deep learning technology, using the results of computed tomography in the process. While it usually takes a few minutes for a healthcare professional to read and explain the results of a CT scan, a dedicated AI application can complete such the procedure in seconds. The system is already implemented in over 100 hospitals in China and in many countries worldwide [27].

We can also note the use of Big Data technologies in the iOmniscient's iQ-Fevercheck system, which uses cameras with temperature and recognition sensors. This software contributes to the detection of people susceptible to infection in real time in the stream, with further fixation and tracking of the face by cameras. This process takes places until they are next to a medical worker who receives a message about an infected person for further assistance. Protective medical masks do not interfere with tracking, and the system's temperature recording accuracy is up to 0.5 degrees [28].

In addition to the topic of the coronavirus, it is important to note the key factors that underlie care for healthcare providers and allied professionals. These factors are the transparency of the data and the adequacy of statistics. According to them, it is possible to determine the features of a specific extreme situation, which determines the necessary measures for their timely adoption. At the current moment, many interactive systems that provide a web interface for tracking operational information on the situation with COVID-19 have been created. For example, Yandex presented its dashboard with a global picture and detailing by regions of Russia, which uses Russian Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing (Rospotrebnadzor) reports and data from Johns Hopkins University in the USA [29].

In the Republic of South Korea, potential carriers of coronavirus infection are monitored using mobile phones and satellite technology. A similar application works in the Russian Federation, for example, on the territory of Moscow: the social monitoring application. It is used primarily by those who have been diagnosed with coronavirus infection and by people who cohabit with such patients. Patients sign a consent to receive home healthcare or an order from the Chief Sanitary doctor. In these documents, you must indicate the phone number and address at which they undertake to be isolated within 14 calendar days from the date of signing. After signing the contract, instructions for installing the application are sent to the patient's phone. In case patients have a phone, they are given a smartphone that is focused only on this application, it will not be possible to use it for other purposes, all other functions are blocked. Technical means of monitoring the location make it possible to quickly record cases when a person who is required to be isolated leaves the house and endangers other citizens of the city.

At this moment, we can note the widespread use of machine learning and other Big Data methods in the development of vaccines and drugs. For example, the AlphaFold neural network predicted the possible structure of some COVID-19 proteins using matrix population modeling technology. The synthesis of drugs for the treatment of diseases caused by coronavirus requires precise knowledge of the component and structural composition of the virus. The data obtained during the research have not been experimentally confirmed at the current stage, but based on the available materials, scientists can judge the functioning of the virus, which allows them to create hypotheses regarding the effectiveness of a particular therapy.

This pandemic has several applications for Big Data technologies, for which AI is of key importance. These examples include biomedical research, natural language processing, social networks.

Based on an epidemiological simulator with the implementation of the SEIR mathematical compartmental model, which can help outline the dynamics of the spread of the disease, Sberbank predicted an increase in the number of infected people in accordance with the use of protective measures [30]. This model calculates data both for the capital and for the whole of Russia and considers four possible scenarios when residents comply with the measures, sometimes or often violate them, or behave as usual.

Conclusion

Peter the Great St. Petersburg Polytechnic University researchers were able to predict the development of the Coronavirus epidemic using mathematical modeling methods. Periodically incoming new data give an ability to correct and refine the forecast. For the developed mathematical model, the so-called calibration of the mathematical model of the spread of the coronavirus infection is used. During the work, the specialists step by step examined and described with a high degree of accuracy the situation regarding the ongoing spread of the coronavirus infection in the Wuhan metropolitan area in China, on the Diamond Princess liner, in Italy and in the USA. This, in turn, made it possible to significantly improve the forecasting accuracy in Russia. After the adoption of measures to reduce restrictive and control measures due to the slowdown in the spread of the infection, the process of mathematical modeling and forecasting for the specialists of the NTI (National Technology Initiative) Center has become much more complicated. However, experts are closely monitoring the changing situation and adjusting forecasts taking into account its development.

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THE AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Gasanova Ilakha A.
Гасанова Илаха Адалет Гызы
E-mail: ilaha.gasanova@yandex.ru

Prelovskii Dmitrii S.
Преловский Дмитрий Сергеевич
E-mail: dimaprelovski@gmail.com

Yurkin Vladimir A.
Юркин Владимир Андреевич
E-mail: arhimondled@yandex.ru

Drobintsev Pavel D.
Дробинцев Павел Дмитриевич
E-mail: drob@ics2.ecd.spbstu.ru

Drobintseva Anna O.
Дробинцева Анна Олеговна
E-mail: anna.drobintseva@gmail.com

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PHASE NOISE OF A MICROSTRIP MICROWAVE OSCILLATOR WITH VARACTOR FREQUENCY TUNING 6–12 GHz

A.B. Nikitin, E.I. Khabitueva

Peter the Great St. Petersburg Polytechnic University,
St. Petersburg, Russian Federation

This work presents the results of a study of the microwave oscillator's active device biasing influence on the oscillator phase noise. The paper considers a hybrid voltage-controlled oscillator (VCO) with an octave frequency tuning (6–12 GHz), based on a low-noise SiGe-heterojunction transistor. The simulation of the VCO in the AWR Design Environment (AWR DE) allowed one to evaluate the choice of the transistor operating point influence on the oscillator phase noise. Based on the data obtained, an experimental study of the fluctuation characteristics of several samples of the hybrid microwave VCOs, differing in the operating mode of the active devices, was carried out. The results of the research carried out make it possible to determine a number of conditions (the value of the collector current, the ratio between the currents of the transistor base and the resistive divider, determining the mode of the active device), which provide the best oscillator characteristics. It is shown that the smallest average level of the phase noise power spectral density is –95 dBc/Hz at 100 kHz offset from the carrier with a minimum change in its level in the tuning range within ± 2.5 dB.

Keywords: microwaves, voltage-controlled oscillator, VCO, phase noise, fluctuation characteristics.

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ФАЗОВЫЙ ШУМ МИКРОПОЛОСКОВОГО СВЧ-ГЕНЕРАТОРА С ВАРАКТОРНОЙ ПЕРЕСТРОЙКОЙ ЧАСТОТЫ 6–12 ГГц

А.Б. Никитин, Е.И. Хабитуева

Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация

Описаны результаты исследования влияния режима работы активного элемента СВЧ-генератора, управляемого напряжением (ГУН), на его флуктуационные характеристики. Рассмотрен автогенератор с октавной перестройкой частоты выходного колебания (6–12 ГГц), выполненный на основе гибридной технологии на базе малошумящего SiGe-гетеропереходного транзистора. Проведённое моделирование ГУН в среде AWR Design Environment (AWR DE) позволило оценить влияние выбора рабочей точки транзистора на уровень фазового шума автогенератора. На основе полученных данных проведено экспериментальное исследование флуктуационных характеристик нескольких образцов перестраиваемых генераторов, отличающихся режимом работы активного элемента. Определён ряд условий (величина коллекторного тока, соотношение между токами базы транзистора и резистивного делителя, определяющего режим активного элемента), обеспечивающих наилучшие флуктуационные характеристики. Показано, что наименьший средний уровень спектральной плотности мощности фазовых шумов (СПМ ФШ) составляет –95 дБн/Гц на частоте отстройки от несущей 100 кГц при минимальном (в пределах ±2,5 дБ) изменении СПМ ФШ в диапазоне перестройки.

Ключевые слова: СВЧ, генератор, управляемый напряжением, ГУН, флуктуационные характеристики, фазовый шум.

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Introduction

Design of a stable wideband microwave source based on frequency synthesizers with phase-locked loop (PLL) implies the use of low-noise voltage-controlled oscillators (VCOs) with ultra-wide band (octave or more) frequency tuning range in such systems [1–7]. At the same time, fluctuation characteristics of VCOs are to a significant degree determined by the choice of oscillator’s active device. For example, in hybrid microwave oscillators is advisable to use SiGe-heterojunction bipolar transistors characterized by the lowest levels of phase noise with oscillation frequencies up to 10–15 GHz [7].

In addition, oscillator’s operation heavily depends on the mode of the active device related to the choice of the transistor’s operating point and bias circuit. Thus, for example, in the simplest circuit with fixed current bias, the operating point position, and therefore, the oscillator’s characteristics are significantly affected by the specific transistor and environment temperature [8].

One of the ways to eliminate this negative effect is to use bias circuit with emitter resistor, that provides (be means of serial DC-coupled negative feedback in the circuit) stability of the operating point position, and therefore, the oscillator’s parameters in a wide range of temperatures. This also allows to replace an active device without the consequent replacement of the whole circuit [8].

It should be noted that in scientific publications, this kind of circuit is most frequently considered in terms of its application not in oscillators, but in various amplifiers [9–14]. Indeed, paper [14] presents general recommendations as to the choice of the bias circuit parameters and describes their influence on operation of amplifiers built on the basis of bipolar transistors.

In the papers devoted to the topic under consideration, the authors, in general, describe monolithic microwave integrated circuit (MMIC) oscillators. In addition, the study of hybrid microwave VCOs permitting the use of simpler manufacturing process is usually restricted to considering devices intended for operation in the frequency range significantly less than an octave [1, 15–20]. At the same time, the tuning of VCOs in wide and ultra-wide band (octave or more) frequency range results in a considerable change in the conditions of active device operation which hinders the choice of the mode providing the best fluctuation characteristics.

Moreover, publications often present results of analyzing the influence of active device circuit and mode on oscillator’s characteristics (frequency response, fluctuation, etc.) without any experimental verification which puts limitations on practical application of such data [1, 21, 22].

This article contains study results on the dependence of phase noise power spectral density $S(F)$ of octave microwave oscillator in the 6–12 GHz range on active device operating mode [23, 24]. The tunable oscillator is hybrid based on low-noise SiGe-heterojunction bipolar transistor NESG3031M14 [25].

Computation of VCO parameters

Fig. 1*a* shows a layout of the microwave oscillator under consideration. Fig. 1*b* presents a fragment of its simplified circuit which contains a transistor and resistive elements determining active device operating mode (R_1, R_2 и R_E). Fig. 1*c* shows characteristics of the VCO.

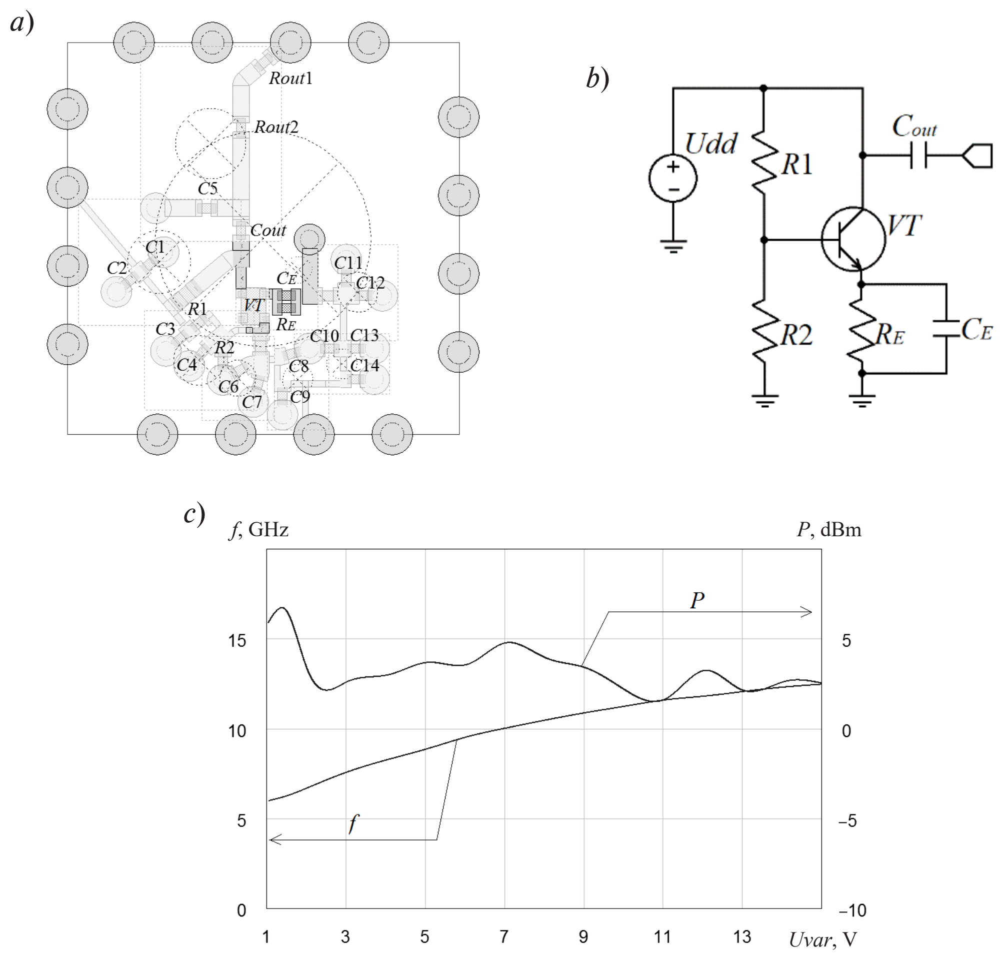

Fig. 1. VCO: *a* – layout; *b* – simplified circuit without frequency control elements; *c* – dependence of oscillation frequency *f* and power *P* on control voltage *Uvar*

To compute resistance values of resistors R_1, R_2 and R_E, determining transistor mode *VT* (Fig. 1), we use the following expressions [1, 14]:

$$R_1 = \frac{U_{R1}}{I_1} = \frac{U_{dd} - U_{R2}}{I_1} = \frac{U_{dd} - U_{R2}}{kI_B^0}, \quad (1)$$

$$R_2 = \frac{U_{R2}}{I_2} = \frac{U_{R_E} + U_{BE}^0}{I_2} = \frac{U_{R_E} + U_{BE}^0}{(k-1)I_B^0}, \quad (2)$$

$$R_E = \frac{U_{R_E}}{I_E} = \frac{U_{dd} - U_{CE}^0}{I_C^0 + I_B^0}, \quad (3)$$

where U_{dd} is supply voltage of the VCO; U_{R1}, U_{R2} and U_{RE} are voltage across resistors R_1, R_2 and R_E, respectively; I_1, I_2 and I_E are current across resistors R_1, R_2 and R_E; I_B^0 and I_C^0 are base and collector current of the transistor; U_{BE}^0 and U_{CE}^0 are base-emitter and collector-emitter voltages of the transistor; k is coefficient of proportionality between I_1 and I_B^0 values.

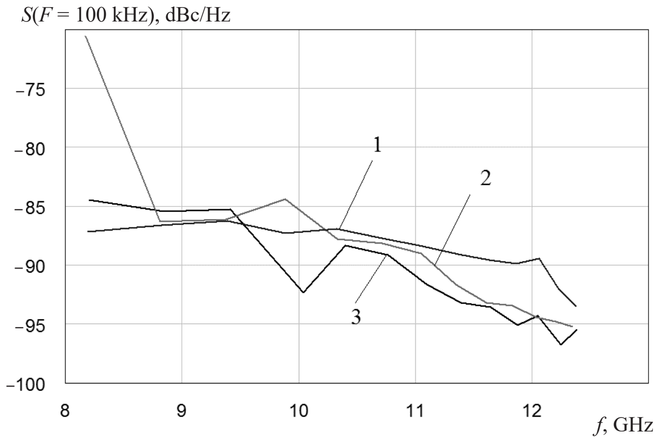

Fig. 2. VCO's simulation characteristics

To minimize possible unwanted spectral components in the output oscillations, the value of U_{CE}^{0} needs to be approximately half of the VCO supply voltage. Moreover, for the NESG3031M14 transistor, I_{B}^{0} and I_{C}^{0} values should be more than 20 μA and 6 mA, respectively [8].

To enhance bias voltage stability supplied to the transistor base (using voltage divider R_1–R_2, see Fig. 1), it is advisable that the value of the current across resistors R_1 and R_2 was sufficiently high, which requires increasing k parameter value (expressions (1), (2)). However, one should make allowance for the fact that excessively high divider current may result in inadequate power consumption and, consequently, a drop in efficiency.

Keeping in mind these remarks, as well as parameters of NESG3031M14 transistor used in the 6–12 GHz VCO [25], we obtained several options of oscillator's circuit configuration corresponding to different positions of the operating point. As an example, in Fig. 2, we demonstrate a diagram of dependence of $S(F = 100$ kHz) on VCO's frequency values obtained as a result of modeling in AWR DE [26], for several options of transistor point position.

The dependencies presented in Fig. 2 correspond to the following cases:

- curve 1: I_{C}^{0} = 11 mA, U_{CE}^{0} = 2 V, I_{B}^{0} = 40 μA, U_{BE}^{0} = 0.845 V, $k = 5$ (R_1 = 5.8 kOhm, R_2 = 22 kOhm, R_E = 240 Ohm);
- curve 2: I_{C}^{0} = 20 mA, U_{CE}^{0} = 2 V, I_{B}^{0} = 80 μA, U_{BE}^{0} = 0.87 V, $k = 5$ (R_1 = 2.9 kOhm, R_2 = 11 kOhm, R_E = 130 Ohm);
- curve 3: I_{C}^{0} = 30 mA, U_{CE}^{0} = 2.5 V, I_{B}^{0} = 140 μA, U_{BE}^{0} = 0.875 V, $k = 5$ (R_1 = 2.3 kOhm, R_2 = 5.5 kOhm, R_E = 75 Ohm).

Fig. 2 shows that reduction of $S(F)$ (for the same value of k parameter) is possible if collector current I_{C}^{0} is increased. Thus, for example, a change in I_{C}^{0} value from 11 mA up to 20 mA allows to reduce the level of $S(F)$ by (2–4) dB in the most part of the tuning range.

At the same time, it should be noted that voltage values between the collector and transistor emitter U_{CE}^{0} = 2.5 V and U_{CE}^{0} = 2 V do not provide the required octave (6–12 GHz) tuning range of the oscillator's output frequency.

Further research of the VCO revealed that reduction of $S(F)$ (by several dB) is possible in case of an increase not only in the collector current, but in parameter k as well.

Thus, the modeling of several VCO circuits corresponding to different positions of the operating point performed in AWR DE showed that the phase noise reduction is connected with the increase of collector current and coefficient k. In addition, to provide the needed tuning range of the oscillator, it is necessary that U_{CE}^{0} > 2.5 V.

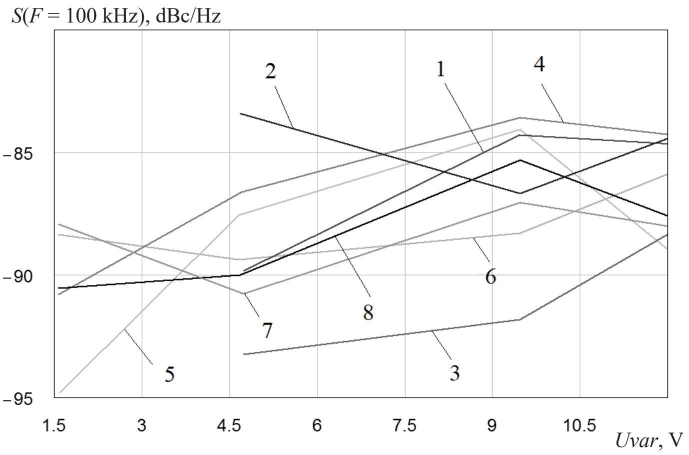

Fig. 3. VCO's measured characteristics

Experimental study of VCO's phase noise

For the experimental study of the VCO samples, we used N9000A CXA series signal analyzer by Keysight Technologies [27], designed for operation in the range from 9 kHz to 26.5 GHz.

In Fig. 3 we present measured VCO's fluctuation characteristics for several options of transistor point position.

The dependencies presented in Fig. 3 correspond to the following cases:

- curve 1: $I_C^0 = 11$ mA, $U_{CE}^0 = 2$ V, $I_B^0 = 40$ µA, $U_{BE}^0 = 0.845$ V, $k = 5$ ($R_1 = 5.8$ kOhm, $R_2 = 22$ kOhm, $R_E = 240$ Ohm);
- curve 2: $I_C^0 = 20$ mA, $U_{CE}^0 = 2$ V, $I_B^0 = 80$ µA, $U_{BE}^0 = 0.87$ V, $k = 5$ ($R_1 = 2.9$ kOhm, $R_2 = 11$ kOhm, $R_E = 130$ Ohm);
- curve 3: $I_C^0 = 30$ mA, $U_{CE}^0 = 2$ V, $I_B^0 = 140$ µA, $U_{BE}^0 = 0.88$ V, $k = 5$ ($R_1 = 1.65$ kOhm, $R_2 = 6.4$ kOhm, $R_E = 90$ Ohm);
- curve 4: $I_C^0 = 20$ mA, $U_{CE}^0 = 2.5$ V, $I_B^0 = 80$ µA, $U_{BE}^0 = 0.85$ V, $k = 5$ ($R_1 = 4.02$ kOhm, $R_2 = 7.5$ kOhm, $R_E = 75$ Ohm);
- curve 5: $I_C^0 = 30$ mA, $U_{CE}^0 = 2.5$ V, $I_B^0 = 140$ µA, $U_{BE}^0 = 0.875$ V, $k = 5$ ($R_1 = 2.3$ kOhm, $R_2 = 5.5$ kOhm, $R_E = 75$ Ohm);
- curve 6: $I_C^0 = 30$ mA, $U_{CE}^0 = 3$ V, $I_B^0 = 140$ µA, $U_{BE}^0 = 0.875$ V, $k = 5$ ($R_1 = 3$ kOhm, $R_2 = 4.5$ kOhm, $R_E = 56$ Ohm);
- curves 7 and 8: $I_C^0 = 33$ mA, $U_{CE}^0 = 3$ V, $I_B^0 = 160$ µA, $U_{BE}^0 = 0.88$ V, $k = 5$ ($R_1 = 2.7$ kOhm, $R_2 = 4.02$ kOhm, $R_E = 51$ Ohm).

Fig. 3 shows that:

1. For the voltage values across the transistor collector $U_{CE}^0 < 3$ V, it is impossible to provide the required frequency range tuning to the VCO: 6–12 GHz. Moreover, for $U_{CE}^0 = 2.5$ V in the lower end of the range (when *Uvar* < 1.4 V), we can observe a spectrum collapse. Therefore, in order to provide the oscillator under consideration with frequency tuning across the whole bandwidth, the operating voltage U_{CE}^0 needs to be no less than 3 V.
2. The level of the phase noise power spectral density drops as the collector current I_C^0 increases. Taking this fact into account, as well as keeping the transistor data, limiting the maximum value of the collector current, the operating value of I_C^0 needs to be no more than 30 mA.

We carried out further experiments for the purpose of studying the influence of the ratio between the base current I_B^0 and resistive divider R_1–R_2 on VCO's phase noise for the selected values of collector-emitter voltage and collector current: $U_{CE}^0 = 3$ V, $I_C^0 = 30$ mA.

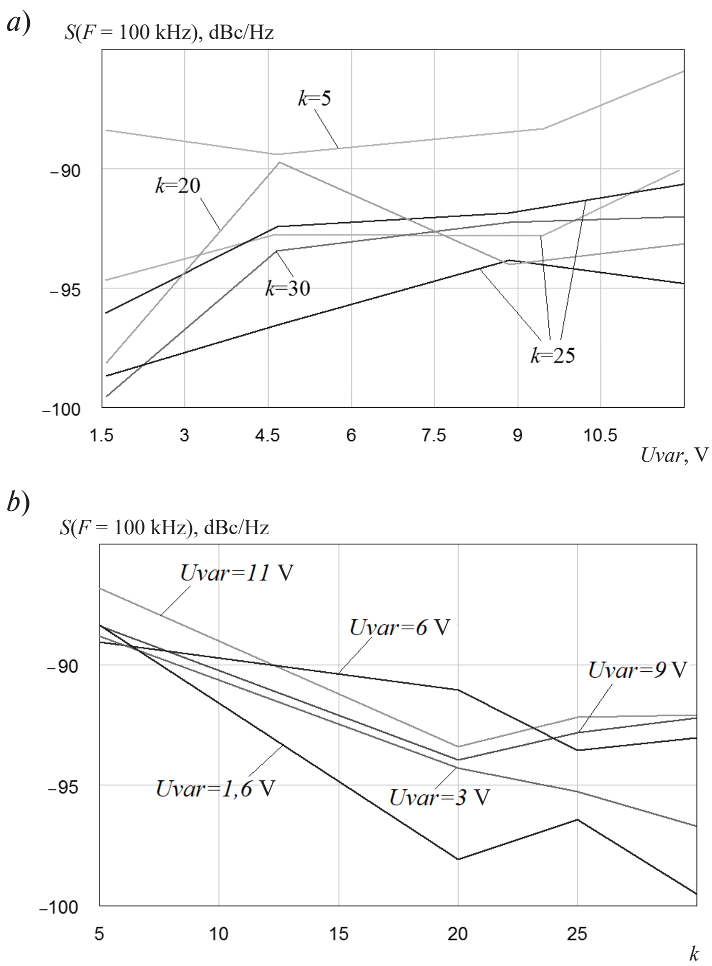

Fig. 4. VCO's measured characteristics for different k values

Fig. 4 shows VCO's measured characteristics at U^0_{CE} = 3 V and I^0_C = 30 mA.

Fig. 4*a* shows that for constant values of collector voltage and current of the transistor, the ratio between the base and resistive divider currents may have significant influence on the fluctuation characteristics of the VCO. For example, in the lower end of the tuning range an increase of the parameter k from 5 to 30 allows us to reduce the noise level by more than 10 dB. At the same time, the minimum level of $S(F)$ amounts to a value of –100 dBc/Hz order at 100 kHz offset from the carrier.

Fig. 4*b* shows that when k = 25, we observe the lowest change in $S(F)$ in the tuning band: around ±2.5 dB with the average level around –95 dBc/Hz. Note that the obtained results are on a par with characteristics of foreign VCO samples of the similar application [28].

Thus, the data obtained as a result of experimental research of the fluctuation characteristic of a 6–12 GHz microwave oscillator are in full compliance with the results of computer modeling of the VCO in the AWR Design Environment. For instance, the identified dependencies of phase noise level on the value of collector current and parameter k, according to which a reduction of VCO's phase noises in possible if I^0_C and k increase, were proved experimentally: the computations showed that an increase in collector current from 11 mA up to 30 mA (curves 1 and 3 in Fig. 3) provides a reduction of $S(F)$ by more than 4 dB.

Conclusion

As a result of studying a hybrid microwave VCO with an octave frequency tuning, we determined its operating conditions providing the best fluctuation characteristics. The paper showed the mode of the oscillator's active device based on a SiGe-heterojunction transistor, which provides the minimal level of phase noise of the output oscillation in the range of 6–12 GHz, is achieved if the following conditions are satisfied:

- Maximum possible collector current: $I_C^0 = 30$ mA.
- Voltage U_{CE}^0 ensuring the entire range of frequency tuning: $U_{CE}^0 = 3$ V.
- Ratio of divider and base currents of the transistor $k = 25$. Such a value of coefficient k ensures the minimum average level of phase noise: around –95 dBc/Hz at 100 kHz offset from the carrier with a minimum (within ± 2.5 dB) change in $S(F)$ in the tuning range.

The obtained results could be used in design of hybrid microwave oscillators providing frequency tuning in a range of an octave or more.

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THE AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Nikitin Aleksandr B.
Никитин Александр Борисович
E-mail: nikitin@mail.spbstu.ru

Khabitueva Ekaterina I.
Хабитуева Екатерина Исаковна
E-mail: habitueva.ei@edu.spbstu.ru

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SUB-6 GHz IP BLOCKS FOR 5G TRANSCEIVERS IN 65 nm CMOS

I.A. Rumyancev

Peter the Great St. Petersburg Polytechnic University,
St. Petersburg, Russian Federation

This paper presents the development results of a vector modulator, a low-noise amplifier and a power amplifier for the 4.80–4.99 GHz. It is planned to deploy fifth-generation communication systems in this frequency band in the Russian Federation. Circuits, layouts and simulation results of the designed IP blocks are presented and compared with state-of-the-art works. All circuits are inductorless to improve bandwidth and reduce the layout area. Thus, the vector modulator area, which has the largest dimensions, is only 0.4 sq. mm. The use of a vector modulator that combines the functions of an attenuator and a phase shifter in the transceiver modules makes it possible to calibrate the amplitude-phase states to minimize the influence of the technological process parameters variation. According to the simulations results, the designed IP blocks allow implementing the transceiver for the whole sub-6 GHz band (3–5 GHz).

Keywords: vector modulator, power amplifier, low noise amplifier, CMOS, calibration, 5G.

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IP-БЛОКИ ДЛЯ ПРИЁМОПЕРЕДАТЧИКОВ СЕТЕЙ 5G НА ОСНОВЕ 65 нм КМОП-ТЕХНОЛОГИИ

И.А. Румянцев

Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация

В статье представлены результаты разработки интегральных схем векторного модулятора, малошумящего усилителя и усилителя мощности для приёмопередающих модулей диапазона частот 4,80–4,99 ГГц, в котором планируется развертывание систем связи пятого поколения в Российской Федерации. Представлены принципиальные схемы, топологии и результаты моделирования IP-блоков, проведено сравнение полученных характеристик с аналогичными разработками. Разработанные интегральные схемы не содержат индуктивных элементов, что позволяет значительно расширить полосу рабочих частот и уменьшить площадь топологии. Так, площадь топологии векторного модулятора, имеющего наибольшие габариты, составляет всего 0,4 кв. мм. Использование векторного модулятора, объединяющего в себе функции аттенюатора и фазовращателя, в приёмопередающих модулях позволяет обеспечить возможность калибровки амплитудно-фазовых состояний для минимизации влияния разброса параметров технологического процесса. Согласно результатам моделирования, на основе разработанных IP-блоков можно реализовать универсальный приёмопередатчик для всего диапазона до 6 ГГц (3–5 ГГц) систем 5G.

Ключевые слова: векторный модулятор, усилитель мощности, малошумящий усилитель, КМОП-технология, калибровка, 5G.

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Introduction

The fifth generation (5G) communication systems, in comparison with the existing ones, have significant advantages, such as lower latency, higher data rates and connection density, better energy and spectral efficiency [1]. To provide these benefits, multiple frequency bands and electrically scanned antennas are used. According to GSMA information, the frequency spectrum of 5G systems is divided into three bands [2]: sub-1 GHz (~ 600–700 MHz), sub-6 GHz (~ 3–5 GHz) and above 6 GHz (~ 24–29 GHz and higher). However, specific frequency ranges in these bands may differ from country to country. In the Russian Federation the 4.80–4.99 GHz range is allocated for the 5G in the sub-6 GHz band [3], while in most other countries the 3.4–3.8 GHz range will be used.

There are three main electronically scanned antenna architectures [4]: digital, analog and hybrid. The last two use phase shifters (PS) as a key element. A hybrid architecture that combines analog and digital parts is considered by the scientific community and commercial companies as the most promising due to the higher flexibility compared to pure analog architecture and lower power consumption compared to purely digital architecture. Among the possible ways to build hybrid electronically scanned antenna, two approaches can be distinguished:

- based on high power amplifiers with power dividers/adders and phase shifters;
- based on many transceiver modules with low and medium power amplifiers.

The first approach seems promising due to fewer power amplifiers. However, in practical implementation problems associated with high insertion losses of power splitters/combiners and GaAs or GaN phase shifters. The second approach is more complicated, but allows to process low power RF signals by silicon integrated circuits and then amplify them if necessary [5]. Silicon technology makes it possible to integrate RF circuits with mix-mode circuits, such as analog-to-digital converters [6, 7] and digital-to analog converters [8], and with digital circuits in one die. Digital circuits can also be implemented in GaAs, but with lower energy efficiency [9]. Thus, the development of silicon IP blocks for the 5G transceiver modules in the 4.80–4.99 GHz range is an urgent task, the solution of which is presented in this paper.

CMOS RF IP blocks: circuits, layouts, simulation and comparison

The designed low noise amplifier (LNA) circuit is shown in Fig. 1*a* and consists of an input amplifier based on a feedback inverter, an active balanced-to-unbalanced signal converter, and a common-source output stage. The LNA is implemented on the basis of the noise canceling technique [10] to ensure low noise figure in a wide frequency range. The dimensions of the LNA layout are 150 x 335 um (Fig. 1*b*).

The results of computer simulation after parasitic parameters extraction are shown in Fig. 1*c*. Taking into account the influence of the input bonding wire, the developed low-noise amplifier in the frequency band of 1.1–7.7 GHz provides a gain of 12.2–15.2 dB, a noise figure (NF) of 2.45–2.80 dB, an input and output return losses better than –10 dB.

In the 4.80–4.99 GHz range, the forward transmission coefficient S21 is more than 13.8 dB, the noise figure is below 2.53 dB, the input and output return losses are below –20.4 dB and –13.4 dB consequently. The power consumption of the circuit is about 14.4 mW with the input 1 dB compression point –21.4 dBm. The performance comparison of the designed low-noise amplifier with similar solutions is presented in Table 1.

The designed two-stage power amplifier circuit is shown in Fig. 2*a*. Each stage is based on a pair of *N*-transistors in a cascode connection to double the circuit supply voltage and increase the output power

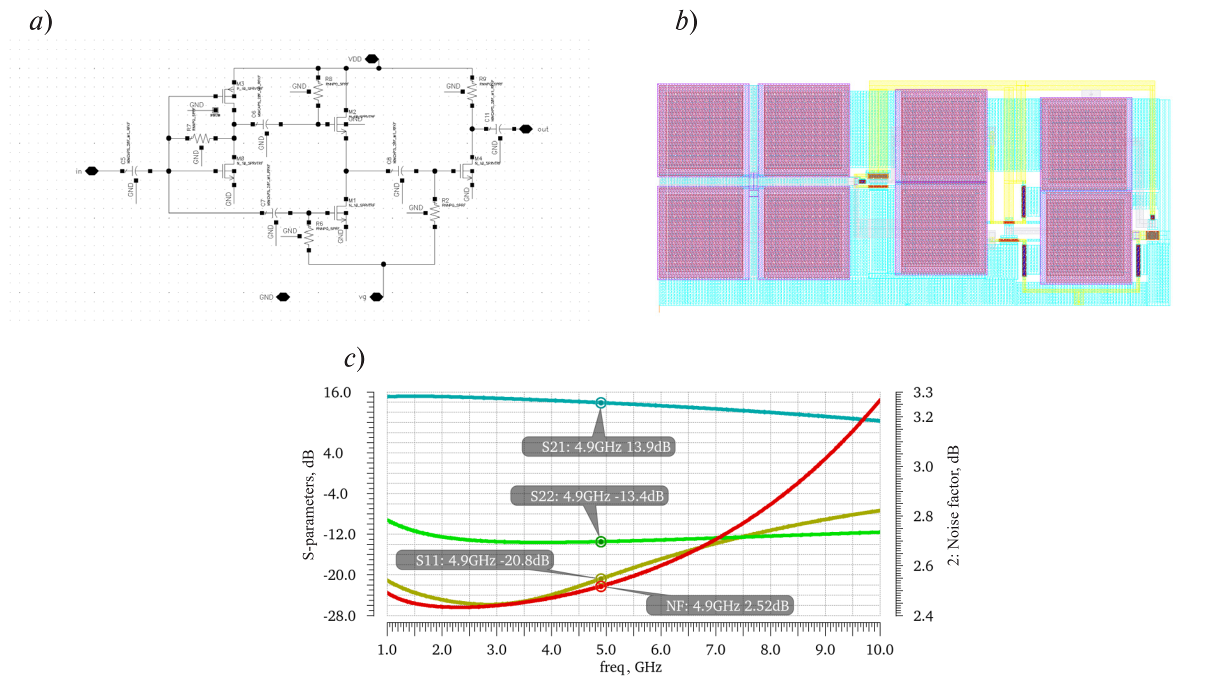

Fig. 1. Low noise amplifier schematic (*a*), layout (*b*), *S*-parameters and NF versus frequency (*c*)

Table 1

Performance Comparison of the LNAs

	[11]	[12]	[13]	[14]	[15]	[16]	This work
Technology, nm	180	130	180	350	130	180	65
Frequency, GHz	3–10	0.2–3.3	3.4–3.8	3.3–3.8	2.3–2.7	2.0–5.0	1.1–7.7
Gain, dB	11	13.8	15.3	23.1	18.7	14.9	15.2
Input CP1dB, dBm	–15	–19.6*	–13.5	–18	–17.2	–12.0	–21.4
Power consumption, mW	11.5	19.0	9.3	27.6	9.4	14.0	14.4
NF, dB	3.2	3.4	1.35	2.5	0.85	3.2	2.8
Area, sq. mm	N/A	0.15	N/A	N/A	N/A	1.35	0.05

*Estimated

level. The dimensions of the power amplifier layout are 280 x 190 μm (Fig. 2*b*). The results of computer simulation after parasitic parameters extraction are shown in Fig. 2*c* and Fig. 2*d*. Taking into account the influence of the output bonding wire, the power amplifier in the 2.0–15.9 GHz frequency range provides 24.1–24.7 dB gain with the input and output return losses better than –10 dB. In the frequency range of 4.80–4.99 GHz, the input 1 dB compression point is better than –10.0 dBm, while the output power is 13.9 dBm with 13.3% power-added efficiency (PAE). The state-of-the-art linear power amplifiers characteristics comparison is given in Table 2.

The block diagram of the developed vector modulator is shown in Fig. 3*a* and consists of an input active balun (UnBal) that converts an unbalanced signal to a balanced form, a second-order passive polyphase

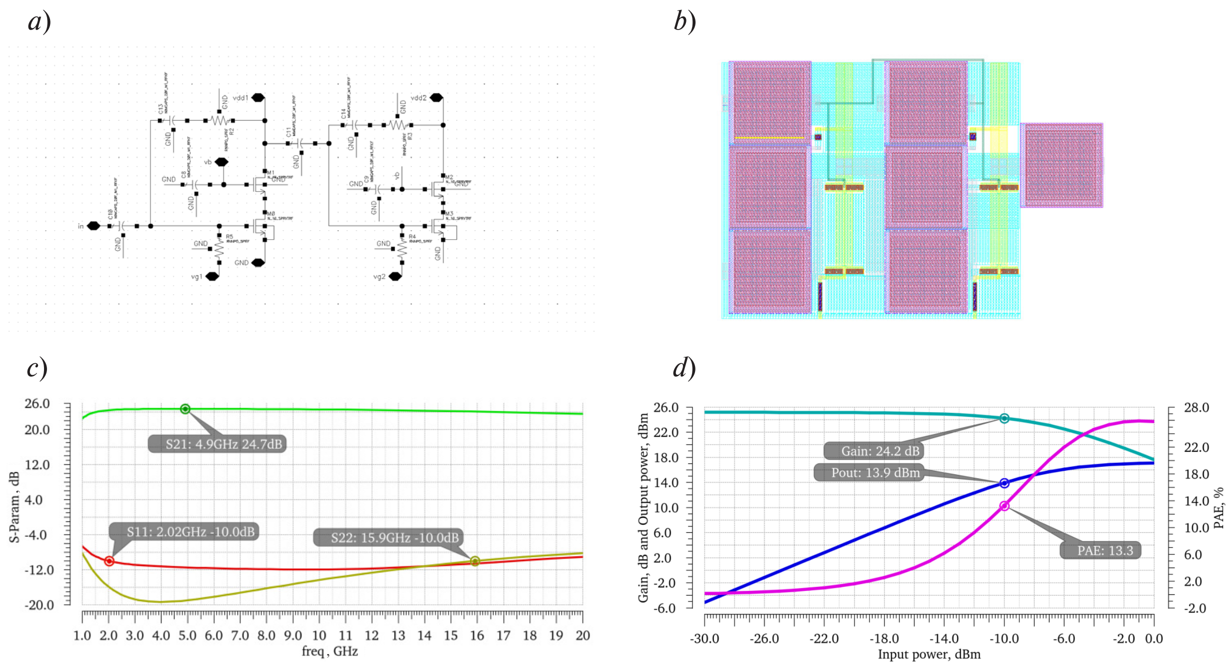

Fig. 2. Power amplifier schematic (*a*), layout (*b*), *S*-parameters versus frequency (*c*), gain, output power and PAE versus input power (*d*)

Table 2

Performance Comparison of the Power Amplifiers

	[17]	[18]	[19]	[20]	[21]	[22]	This work
Technology, nm	180	65	65	180	130	180	65
Frequency, GHz	3.1–10.6	2.5–2.6	2.4	1.8–2.6	6.0–9.0	3.0–10.6	2.0–15.9
Gain, dB	15	30	13.5	22	8	11.5	24
Output CP1dB, dBm	4.3	22*	6	21*	7	9	14
Power consumption, mW	14.4	1250	171	818	22	34	189
PAE, %	18	12.6	2.4	15.4	22.7	23.5	13.3
Area, sq. mm	0,53	2.98	1.7	1.33	0.86	0.81	0.05

*Estimated

RC filter (PPF), an adder based on Hilbert cells, an output active converter from a balanced signal to an unbalanced signal (Balun) and an output amplifier. Schematics of the listed circuits are presented in [23]. The dimensions of the vector modulator layout are 1050 x 410 µm (Fig. 3*b*).

The developed vector modulator has a maximum gain of 10.7 dB. In the frequency range of 4.80–4.99 GHz, the transmission coefficient of the circuit varies from minus 0.1 dB to plus 0.5 dB. The input 1 dB compression point is about –5 dBm while the power consumption of the circuit is less than 40 mW. The calibration procedure [24] has been performed to obtain 6 bit phase resolution and 5 bit amplitude resolution. The designed modulator controls gain from 0 dB to –8 dB with 0.5 dB steps. Simulation results of the vector modulator gain and phase versus frequency are presented in Fig. 3*c* and Fig. 3*d* respectively. The maximum amplitude and RMS phase errors calculated from the simulation

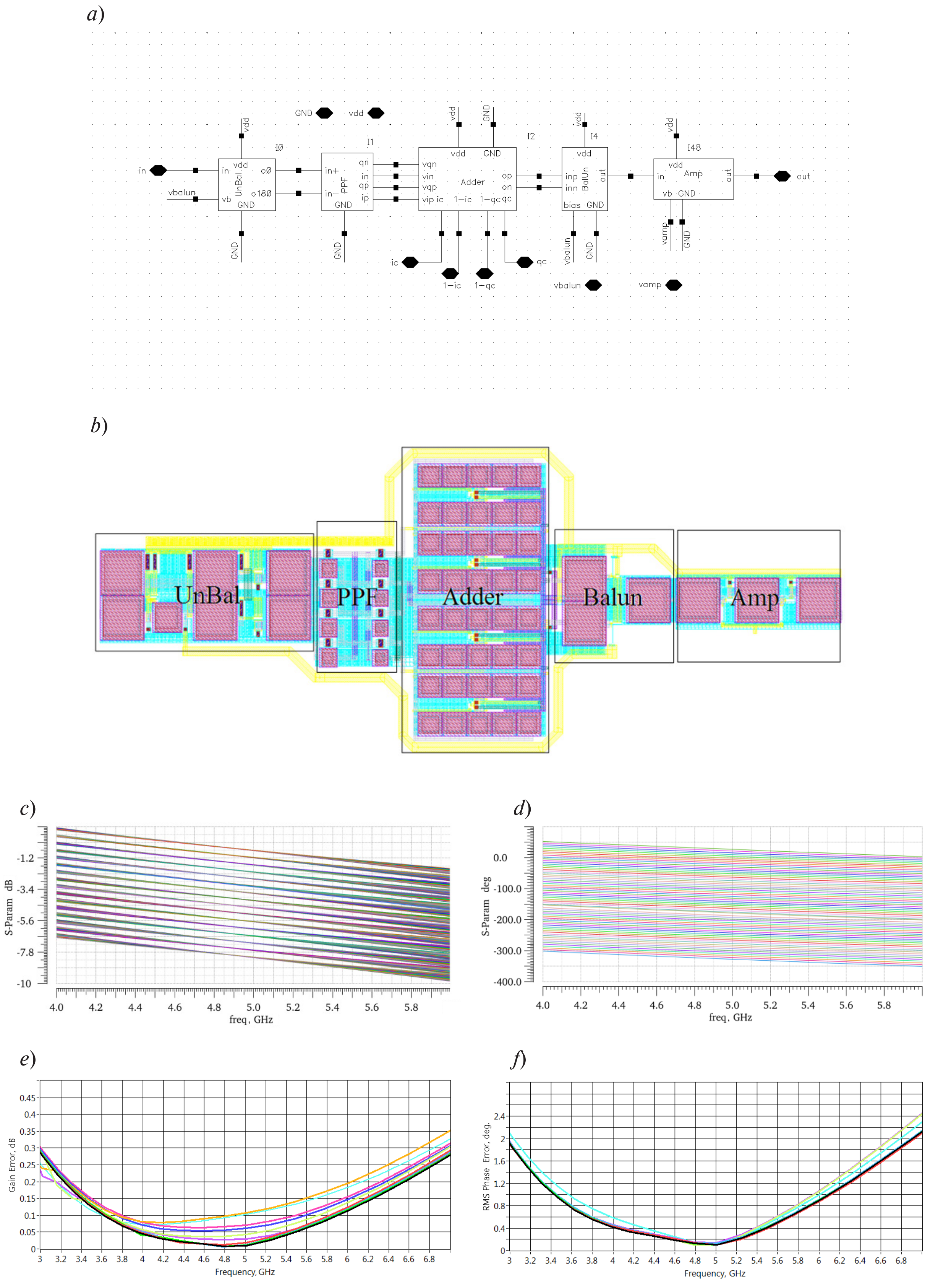

Fig. 3. Vector modulator block diagram (*a*), layout (*b*), simulated gain (*c*) and phase (*d*) versus frequency, calculated gain (*e*) and phase (*f*) errors versus frequency

Table 3

Performance Comparison of the PSs and VMs

	[25]	[26]	[27]	[28]	[29]	[30]	[31]	This work
Technology, nm	130	180	180	180	180	180	180	65
Frequency, GHz	0.5–6.0	1.0–2.1	2.3–4.8	0.8–2.7	2–3	2.2–3.2	2.8–3.2	3.2–5.0
Phase error, deg.	7.0	N/A	1.4	7.2	5.0	4.5	1.0	2.2
Gain error, dB	1.0	1.5	1.1	0.8	1.5	1.1	0.4	0.4
Gain, dB	8.0	4.8	–3.0	–17.4	0	–6	1.7	~ 0
Power consumption, mW	28	5	19	21	24	95	99	40
Input CP1dB, dBm	–22	–2	0.6	N/A	–14	4	4	–5.2
Area, sq. mm	1.3	0.3	0.9	0.9	0.4	6.0	5.3	0.4

results are presented in Fig. 3*e* and Fig. 3*f*. As can be seen from the data the designed circuit can be used in the whole sub-6 GHz band if it will be calibrated in the middle of this band. Table 3 summarizes the performance of the designed vector modulator and presents a comparison with similar solutions.

Conclusion

This paper presents a low noise amplifier, power amplifier and vector modulator for sub-6 GHz 5G systems in 65 nm CMOS technology. Due to inductorless structure, the designed blocks are broadband and occupy small silicon area (0.05–0.4 sq. mm) while providing competitive characteristics. Based on the proposed IP blocks, the universal transceiver module for sub-6 GHz 5G band (3–5 GHz) can be designed.

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THE AUTHOR / СВЕДЕНИЯ ОБ АВТОРЕ

Rumyancev Ivan A.
Румянцев Иван Александрович
E-mail: i.a.rumiantsev@spbstu.ru

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USING THE ANYLOGIC SOFTWARE PRODUCT IN MODELING THE PASSENGER TRAFFIC OF A RAILWAY STATION

A.S. Svistunova

St. Petersburg Federal Research Center of the Russian Academy of Sciences,
St. Petersburg, Russian Federation

The article is devoted to the search for optimal solutions for organizing passenger service at a railway station using simulation. The AnyLogic software system was used to build a discrete-event model and implement the procedure for modeling passenger traffic. To implement the task, a uniform distribution of passenger traffic was chosen. Many stages of passenger service have been implemented, such as entering the railway station, checking passengers through a metal detector, purchasing a ticket, using storage cells, as well as a café. As an additional service for passengers, a system of X-ray television introscopes has been used. All of these structures were used to distribute people around the railway station and to assess passenger traffic at the station. The study included tests to detect “bottlenecks” in the system of departure and arrival of passengers.

Keywords: logistics, railway station, passenger traffic, simulation, AnyLogic, service process, railway transportation.

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ИСПОЛЬЗОВАНИЕ ПРОГРАММНОГО ПРОДУКТА ANYLOGIC ПРИ МОДЕЛИРОВАНИИ ПАССАЖИРОПОТОКА ЖЕЛЕЗНОДОРОЖНОГО ВОКЗАЛА

А.С. Свистунова

Санкт-Петербургский федеральный исследовательский центр РАН,
Санкт-Петербург, Российская Федерация

Статья посвящена поиску оптимальных решений организации обслуживания пассажиров на железнодорожном вокзале с применением имитационного моделирования. Для построения дискретно-событийной модели и реализации процедуры моделирования пасссажиропотока использована программная система AnyLogic. Для реализации задачи выбрано равномерное распределение пассажиропотока. Реализованы многие этапы обслуживания пассажиров, такие как вход в железнодорожный вокзал, проверка пассажиров через металлоискатель, приобретение билета, использование камер хранения, а также кафе. В качестве дополнительного сервиса обслуживания и ожидания пассажиров использована система рентгенотелевизионных интроскопов. Все эти структуры использованы для распределения людей по железнодорожному вокзалу и возможности оценки пассажиропотока на вокзале. Проведено тестирование на наличие «узких мест» в системе отправки и прибытия пассажиров.

Ключевые слова: логистика, вокзал, пассажиропоток, имитационное моделирование, AnyLogic, процесс обслуживания, железнодорожные перевозки.

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Introduction

Railway and air transport are the main competitors in the market for services that provide mass passenger transportation over long distances. The duration and cost of the trip, as well as the quality of the range of services provided, determine the choice in favor of one or another type of transport. Taking into account these conditions, the level of service of railway transport as a whole does not fully meet the requirements of passengers. This is due to the fact that the quality of passenger service at railway stations was not given due attention. As you know, modern airports are trying to attract passengers with the best conditions of transportation and transit, a high level of various services, the presence of new amenities and infrastructure, while railway stations are developing in this area with a lower intensity. This article is devoted to the critical problem of finding optimal solutions for organizing passenger service at a railway station using simulation modeling [1, 2]. To achieve the goal, the following tasks have been set:

- Investigate the peculiarities of the functioning of a railway station when serving passengers.
- Determine the modeling method corresponding to the passenger service technology.

Methods

The key concept of the problem under consideration is passenger traffic. The management of passenger traffic is based on the following principle: it is necessary to organize the movement of a passenger in such a way that his path runs from point “A” to point “B”, taking into account the fact that while passing this route, the passenger will perform a number of related actions. With regard to the railway station, the passenger can carry out the following incidental actions: visiting shops, receiving information about the arrival of transport on the scoreboard, moving from one platform to another (when transferring), etc.

Such features that arise during the formation of passenger traffic at a railway station make it necessary to introduce a number of special commands. It should be noted that the modeling of the system reflecting the specified passenger traffic depends on the time of day due to the instability and dynamics of the ongoing processes. In this regard, the concept of “time” must be formalized.

The stages of the study of passenger traffic are:

- research of available passenger traffic on routes by time of day and days of the week;
- research of the route congestion factor by time of day and days of the week;
- analysis of research results;
- new proposals for optimizing the service system.

The construction of a relevant model makes it possible to assess the effectiveness of the management decisions made and promptly respond to changes of various kinds, as well as to determine the development strategy of the railway station, taking into account the expected passenger traffic.

To build the specified model and implement the modeling procedure, the well-known software system AnyLogic was used, which allows using various types of simulation modeling: discrete-event modeling, system dynamics, or agent-based modeling. AnyLogic uses the Java programming language and the graphical model building language, allowing the researcher to supplement and extend the constructed models [3].

Taking into account the above-described features, a discrete-event simulation model has been developed in the AnyLogic software environment, which will allow identifying bottlenecks in passenger service processes at a railway station.

Results

Since the goal is to identify problem areas in the services provided by railway stations, it is necessary to have knowledge of the calibration of the simulated system. For this it is necessary to choose the appropriate probability distribution.

To implement the model of a railway station in the case under consideration, a uniform distribution is chosen. The model has five entry points: three on the front and two on the opposite side. The choice of this value is due to the intention to create asymmetry in order to determine the difference in the behavior of passenger flows entering the station from different directions. The number of arched metal detectors for entrance control, used by the security service of the railway station, was calculated from the ratio: for each entrance, the number of frames is set equal to the number of entry points. This approach provides an opportunity to increase passenger traffic without creating crowds at the first stages of model operation. Ticket offices are considered in conjunction with ticket terminals. In the model under consideration, the number of checkouts is less than the number of terminals. This was done in order to analyze the efficiency of ticket vending machines and assess the degree of reduction in the load on the box office. Thus, the model presents two cash desks concentrated in one place and eleven terminals distributed across the territory of the railway station in groups. Since the waiting area in train stations has no specific boundaries, the model uses one abstract waiting area, which is a defined rectangular area. The number of escalator groups delivering passengers to trains corresponds to the number of railway tracks (platforms). The experience of the operation of the largest railway stations in the world, in which there were on average fourteen tracks, shows that two platforms correspond to one group of escalators. Consequently, the model has seven escalator groups. The group consists of two escalators going in opposite directions [4, 5, 7].

Consider the process of forming a model of a railway station. The incoming passenger traffic at the start of the simulation is 300 people per hour. The initial 2D model of the railway station in the AnyLogic GUI is shown in Fig. 1.

An hour of operation of the model under the specified conditions showed that there were no difficulties with servicing that would entail long queues, which makes it possible to expand the model by adding new

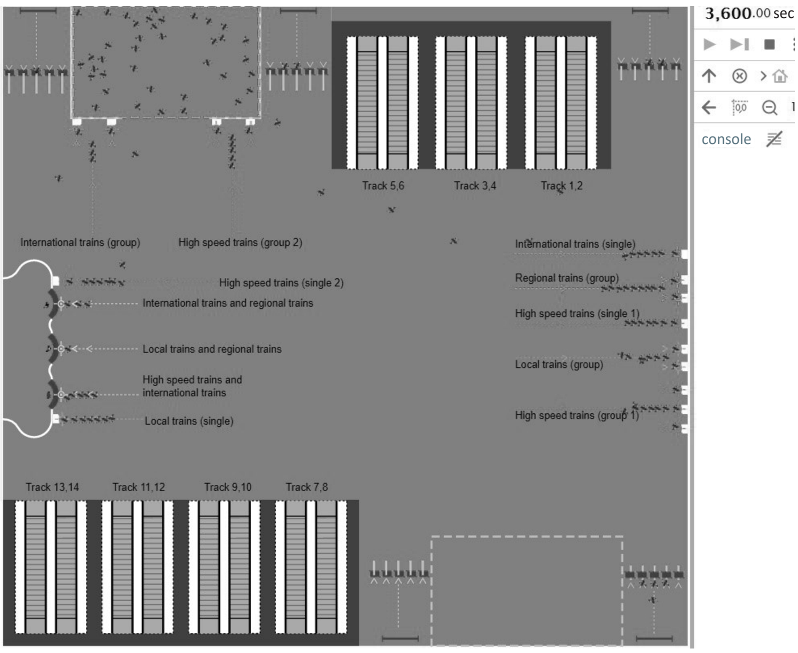

Fig. 1. Initial 2D model of a railway station in the AnyLogic GUI

elements to it. To remain competitive, a modern railway station must be able to provide various kinds of services, including such traditional ones as placing things in lockers.

There are two main types of storage rooms:

- Manual. The station employee accepts the baggage, determines the size of the baggage and allocates the appropriate cell for it, giving in return a receipt, with which the passenger later claims the baggage from the cell.
- Automatic. Mechanical: the cells are accessed using a lock. Electronic: a plastic smart card is used to open this type of cells.

There are two ways to use the service of automatic lockers:

- With the help of the station operator. The employee checks the passenger's passport, accepts payment and selects a cell, based on the size of the baggage, in return, issues a receipt.
- Independently. Terminals are used, with the help of which the passengers pay for the service themselves. Then a plastic smart card and receipt are issued. Using a smart card, the passenger opens the desired cell, independently choosing its size.

Practical experience shows that automatic lockers are actively spreading at large railway stations, which are used as an element of the process of self-service of passengers through the terminal. Based on this, it was decided to implement this service in the model in such a way that lockers are located in the current place of the waiting area, and the waiting area is located in the central part of the station [6].

The model with the specified advanced functionality is shown in Fig. 2.

Since, after the introduction of the new service, some of the passengers will use it, the load on the ticket offices will decrease, and, therefore, the model will need to be updated. It is necessary to increase the flow of passengers entering the model, assuming that in one hour of the model time, 1/6 of all passengers will use the storage services. Accordingly, given that initially the system includes a flow of 300 passengers per hour, it is necessary to increase it to 350 and distribute it among five PedSource blocks.

The territory of the station reserved for storage rooms is divided into 2 parts: a waiting line (Queue Baggage room) and a place for receiving services (Baggage room). To pay for the service, 2 terminals have been identified. If the terminals are occupied, the passengers wait, pay for the service and go to the lockers.

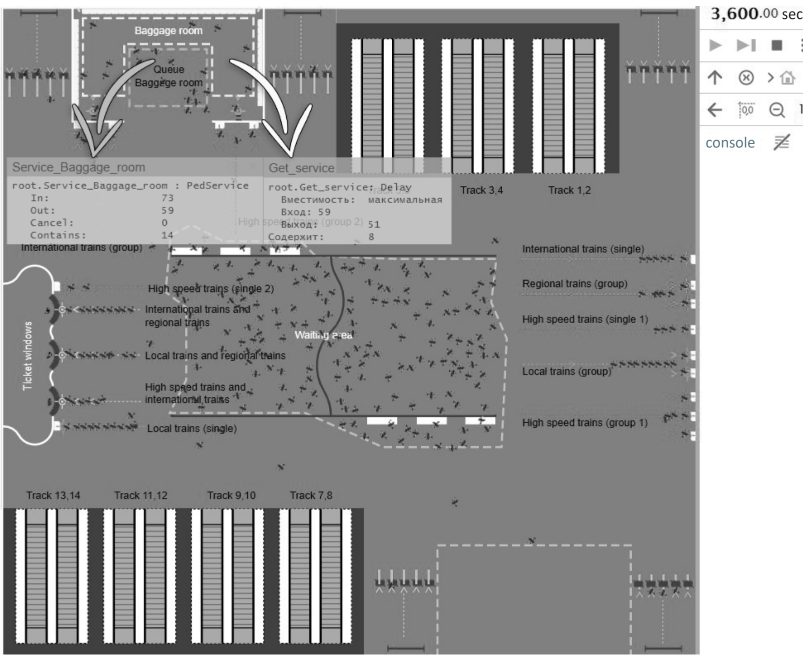

Fig. 2. 2D model of a train station enhanced by the introduction of automatic lockers

It is considered that passengers need 1 to 2 min. to receive a token. The terminal recovery delay time is 3-5 sec. The service itself takes 5-10 min.

Consider the new state of the model. For 1 hour of operation of the model, the queue was not formed, however, it should be noted that the risk of its occurrence appeared. Comparing the number of passengers waiting in line and the number of passengers using the baggage storage service, we can determine the following: with 51 people served, the queue is 14 people, and 8 people are currently in the process of receiving the service (see Fig. 2). The above estimate indicates that the model can cope with the current load, but it is recommended to improve it, otherwise, with an increase in passenger traffic, there is a risk of queues at this stage.

The analysis of the largest railway stations in the world also showed that in addition to the main activity related to passenger transportation, they have a number of additional services at their disposal, among them the main ones: shopping malls and various cafes [8, 9, 12]. Passengers should be able to wait for the train not only in a designated area, but also in other places, depending on their various interests. Let us add a service related to the provision of catering services to the model under consideration.

To implement a service providing catering services in AnyLogic, you need to use an element from the “Attractor” process modeling library. An attractor is a component that sets the exact position of an agent inside an area, as well as its orientation in space. There is an estimate that only 20 % of the total number of passengers visit cafes at railway stations. In this regard, it was decided to create 2 service points with one queue in the model. This addition paid off and did not lead to a large crowd of people.

It is known that at railway stations, special attention is paid to the safety of passengers, while taking into account the presence of people both on the territory of the station and outside, as well as on the platforms themselves. If arched metal detectors are installed at the entry points, which were mentioned earlier, then X-ray television introscopes are located at the exit points to the platforms. Such introscopes are of various types, the application of each of which depends on the specific field of activity. In the model under consideration, it is required to introduce introscopes that detect explosive, flammable substances and weapons in baggage [10, 11].

The implementation of baggage check using introscopes in the model is performed using services with queues. For paths with numbers 1–6, 4 services have been introduced, for each of which a queue is built. The same was done for paths numbered 7–14. To reduce the length of queues, security control is carried out selectively, following the instruction: “At least 50 % of the departing passengers must undergo the baggage screening process”.

The following factor is important for the model: the process of servicing passengers at a railway station is not one-way, i.e., the passengers not only depart using the services provided, but also arrive. Using the features of AnyLogic software, it is possible to combine different types of models, implementing more complex processes. The process of passenger arrival is organized with the simultaneous use of 3 libraries: railway, pedestrian and process modeling [13].

Let’s show how these libraries are used.

First of all, using the “Train_arrival_A” block from the railway library, a train is created on the railway at point “A”. Then, the train stops for 1 minute and waits for passengers to board (blocks “Stop_A” and “Boarding_Back”), after which it goes to point “B”, which is the simulated railway station. Passengers leave the cars by using the “Leave_train” block in the scheme, then the train waits at the station for another 1 minute and leaves. Within the developed model, this cycle is repeated every 8 min.

The second component of the scheme is the pedestrian library. The first block “Ped_from_A_to_B” creates pedestrians who move to the waiting area for the train. The “Retention” block is used to temporarily remove passengers from the system. Control is then passed to the process modeling library, which is the third major element in the arrival process and allows you to link different processes when developing the model.

Waiting for a train at point “A” is modeled by the “Stop_A” block, in the additional settings of which, in the “On entry” and “On exit” parameters, the freeAll () method of the “Waiting_for_train” and “Go_to_the_train” blocks of the pedestrian library is called. The ccl-port of the “Go_to_the_train” element must be bound to the input port “Waiting_for_train”. This algorithm allows, after one minute, to put all the passengers in the waiting area on the train. In this case, passengers who were heading to the car, but did not have time to board, will be returned back to the waiting area until the next arrival of the train. We should also highlight the “Queue_for_boarding” block, which simulates the buffer of agents waiting for processing by the next block, thus creating a “queue”. “Queue_for_boarding” connects to the inPickup port of the previously mentioned “Boarding_Back” block in order to “pick up” the agents (passengers) for their further movement to point “B” (to the train station). After the train reaches its destination, agents temporarily removed by the “Retention” element are restored by connecting the outDropoff port of the “Leave_train” block with the in-port of the “Recovery” block. Taken together, the presented elements simulate the process of passengers arriving at a railway station.

After arrival, each passenger with equal probability rises to the station building using one of the escalators. Then, 24 % of arriving passengers prefer to check in their baggage using the service of automatic electronic lockers, the rest leaves the railway station building [14, 15].

Fig. 3 shows a 2D model of a railway station with the adjustments outlined above.

In Fig. 3, one can observe the congestion of people in the area of lost baggage offices, since now not only departing passengers want to use the services of baggage offices, but also the arriving ones. Previously, it was noted that there is a risk of queuing at this stage of service. Consequently, the model needs to be adjusted again. Since with two terminals installed to pay for baggage lockers, there was already a possibility of large queues, doubling the terminals would lead to a similar result, since the number of people also doubled. Accordingly, in addition to two terminals that compensate the load, it is necessary to install an additional one that will reduce it. The result of the model adjustment is shown in Fig. 4.

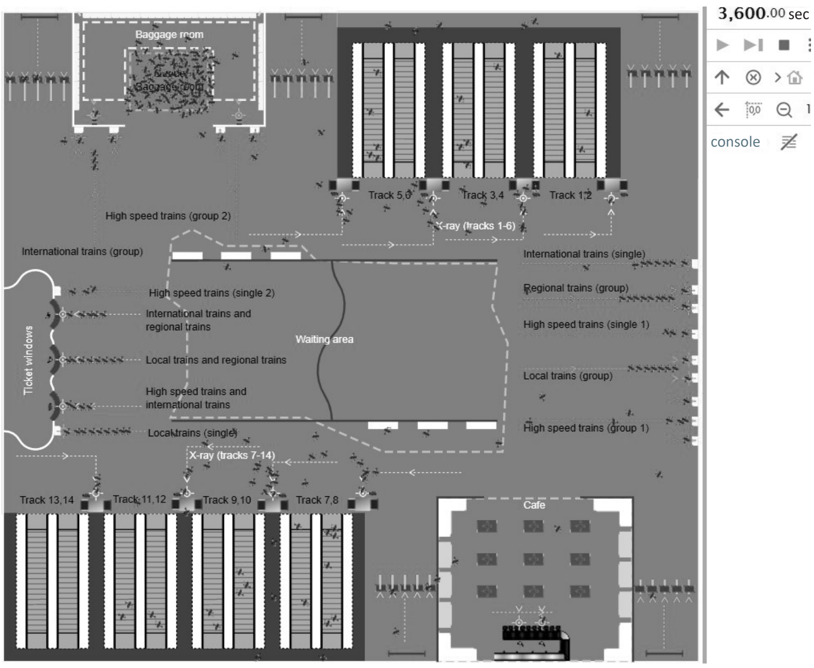

Fig. 3. 2D model of a train station with departing and arriving passengers, with introscopes and cafes introduced

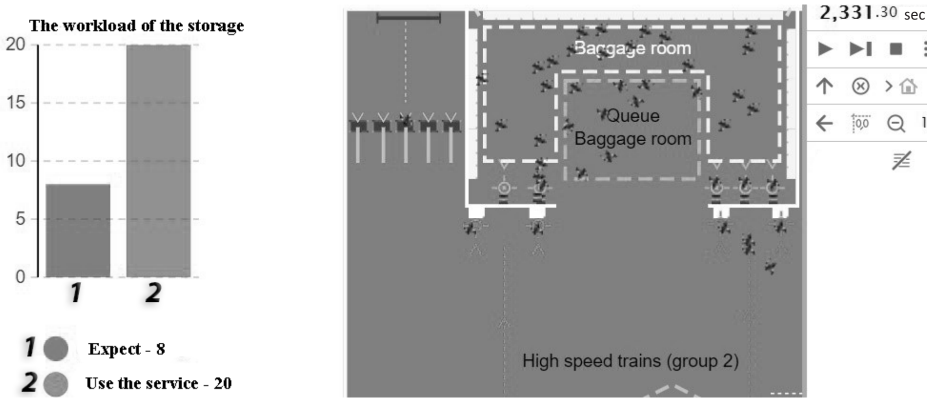

Fig. 4. 2D model of storage rooms with a graph of their load

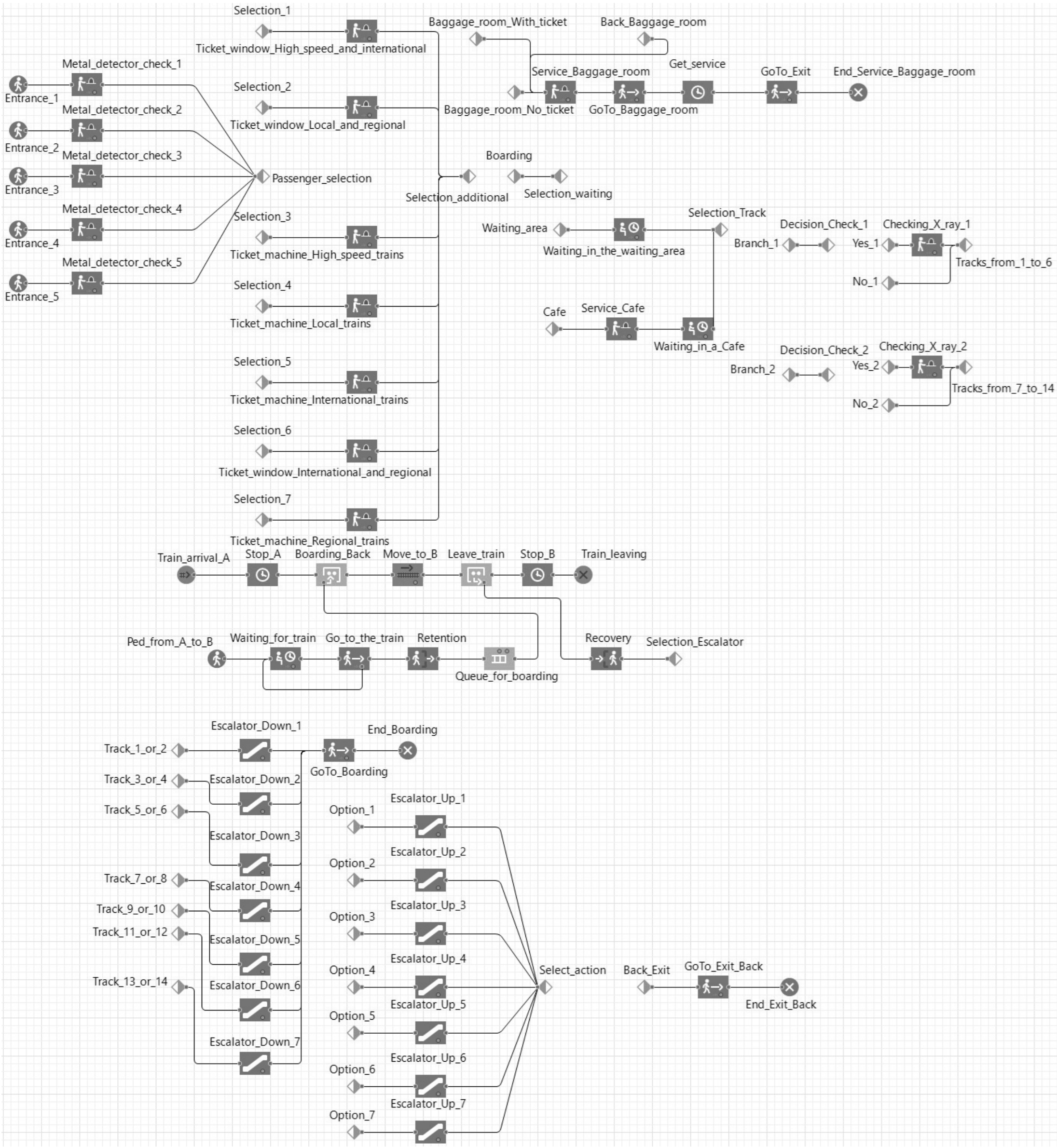

Fig. 5. Schematic of a model of a railway station

The time interval most at risk of queuing was selected for the assessment. In Fig. 4, the bar chart shows that out of 28 passengers present 20 are using the service and 8 are waiting for their turn, which indicates the correct decision [16, 17, 20].

Thus, a railway station was modeled, which includes the main modern services, the model diagram of which is shown in Fig. 5.

Discussions

After the formation of the model, it was tested with different amounts of passenger traffic, and the corresponding results were obtained based on the lengths of queues at each stage of service [18, 19, 29]. We also estimated the waiting time of passengers at each stage. It should be noted that in order to speed up the process of identifying bottlenecks, a passenger flow of 700 people per hour was set. The search results are shown in Table 1.

Table 1

Research results

	Queue length, person	Average waiting time in the queue, min
Incoming inspection	0	0
Ticket office (high-speed and international trains)	6	35.4
Ticket office (commuter and regional trains)	9	28.98
Ticket office (international and regional trains)	8	33.46
Ticket purchase Terminals (high-speed trains)	7	7.67
Ticket purchase Terminals (international trains)	20	44.34
Ticket purchase Terminals (suburban trains)	9	17.52
Ticket purchase Terminals (regional trains)	6	24.66
Cloakroom	4	7.43
Cafe	2	5.09
Inspection of baggage	19	2.35

The first thing you need to pay attention to is the workload of the baggage inspection service. In this case, the total queue for this service is 19 people, while the waiting time is less than three minutes, namely 2.35 min. The result is extremely optimal. Further, paying attention to the terminals selling tickets for international trains, you can see that the load was 20 people with a waiting time of 44.34 min. Considering the rather large workload of 700 people per hour, this figure is acceptable [21–23, 28]. If the load is reduced, the indicators will decrease proportionally, respectively, the model corresponds to an even distribution. With a given passenger traffic, the queue distribution schedule becomes uneven. This happens because all services, excluding the same type, have different specifics, differ in the principle of operation, and, as a result, the time spent by a passenger in each of the services also differs. Accordingly, in the aggregate visual presentation, the diagram reflects a system with a reduced level of abstraction, which has a positive effect on further decision making.

Conclusion

Thus, this article presents a workable model of a railway station, operating in a stable load of 700 passengers per hour, which is about 6,000,000 people annually. This simulated station, with a high probability, will be able to serve 3,000,000 arriving and 3,000,000 departing passengers without significant problems.

Simulation of passenger traffic in the AnyLogic environment allows solving several problems at once [24, 25]. In particular, it is possible to simulate the passenger traffic in the railway station as a whole, and to study the capacity in its individual parts.

It should be noted that those areas of the railway station territory where the service time was the highest or there was not a sufficient number of services were found to be the most exposed to the load [26, 27].

Further development of the model, in the interests of increasing the accuracy of the description of real processes, can be aimed at including knowledge about the train schedule.

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THE AUTHOR / СВЕДЕНИЯ ОБ АВТОРЕ

Svistunova Aliaksandra S.
Свистунова Александра Сергеевна
E-mail: svistunova_alexandra@bk.ru

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ANALYSIS OF THE STATE OF AUTOMATION OF MATERIAL FLOW CONTROL IN SILICON PRODUCTION

O.N. Masko, D.V. Gorlenkov

Saint-Petersburg Mining University,
St. Petersburg, Russian Federation

The problem of material flow control has a key significance in the silicon production since the proportional composition of furnace-charges (specific gravity, taking into account moisture) and current state of the furnace (slagging and etc.) essentially affect the yield and quality of the finished product, and the efficiency of the technological process as a whole. The relevance of the topic lies in the need to modernize and increase the level of transparency of production processes in the silicon industry. In this analytical review, the following tasks have been solved: the suitability of using automated material flow control systems in the silicon production has been proved; the bottlenecks of the process in terms of saving resources have been identified; the functionality of the automated material flows control system has been determined by means of examples of similar production; the method of control of emissions of valuable components has been put forward; the functional structure of the automated control system of the highest production level for the company "Silarus" has been proposed. This article examines the state of automated material control systems in the silicon production. The reasons for the introduction of such systems have been substantiated by the example of ferroalloy production. The general principles of the organization of automated systems of the factory operation of the largest foreign silicon enterprises, and their role in the accounting and management of material flows have been determined. A method for controlling the quality of microsilica capture has been proposed.

Keywords: metallurgical silicon, ore-smelting furnace, material flows control system, material balance, carbothermic reduction, MES system, microsilica.

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АНАЛИЗ СОСТОЯНИЯ АВТОМАТИЗАЦИИ УПРАВЛЕНИЯ МАТЕРИАЛЬНЫМИ ПОТОКАМИ В ПРОИЗВОДСТВЕ КРЕМНИЯ

О.Н. Масько, Д.В. Горленков

Санкт-Петербургский горный университет,
Санкт-Петербург, Российская Федерация

Проблема управления материальными потоками имеет центральное значение в производстве кремния, поскольку пропорциональный состав компонентов загрузочного материала (в удельном весе с учетом влажности), а также текущее состояние самой печи (зашлакование, закварцевание печи и т. п.), существенно влияют на выход, качество готового продукта и на эффективность технологического процесса в целом. Актуальность темы заключается в необходимости модернизации и повышения уровня прозрачности производственных процессов в кремниевой промышленности. В данном аналитическом обзоре решены следующие задачи: обоснована целесообразность применения автоматизированных систем управления материальными потоками в производстве кремния; выявлены узкие места процесса карботермического восстановления кремния с точки зрения сбережения материальных и энергетических ресурсов; определена функциональность АСУ материальными потоками на примерах производств, подобных кремниевому; обоснован метод контроля выбросов ценных компонентов в процессе выплавки металлургического кремния и предложена функциональная структура АСУ верхнего производственного уровня для предприятия ООО «Силарус». Представлено состояние автоматизированных систем управления материальными потоками в производстве кремния в России и в мире. Обоснованы предпосылки и возможность внедрения подобных систем на примере ферросплавных производств. Определены общие принципы организации систем автоматизации верхнего уровня производства крупнейших зарубежных кремниевых предприятий, их роль и функциональные особенности в учете и управлении материальными потоками. Предложен метод контроля качества улавливания печной пыли.

Ключевые слова: металлургический кремний, руднотермическая печь, система управления материальными потоками, материальный баланс, карботермическое восстановление, MES-система, микросилика.

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Introduction

Silicon is a key raw material for a number of strategically important industrial sectors. Polycrystalline silicon, which is a raw material for solar energy and the semiconductor industry, is produced from metallurgical-grade silicon with a purity of up to 98–99 %. With the development of the metallurgical industry, the use of silicon of metallurgical grades as an alloying additive to special steel and aluminum alloys is growing.

In industry, metallurgical (technical) silicon is produced by reducing the SiO_2 melt with carbon at a temperature of about 1800 °C between carbon-graphite electrodes in ore-thermal furnaces (OTF) of the mine type. The production of crystalline silicon is accompanied by the following set of technological operations: preparation of the charge, melting it in OTF, casting of silicon and its subsequent grinding to remove slag inclusions.

Loading the charge into the OTF is one of the most difficult stages of carbothermic silicon reduction. The exact compliance with the proportional composition of the charge materials directly affects the electric mode of the furnace and, subsequently, the quality of the finished product.

The complexity of the loading process consists in the need to load large volumes of charge on a relatively small area of the grate (more than 50 tons per 70–80 m^2). It is at the stage of loading the furnace that deviations in the material balance appear. Ensuring a smooth, continuous lowering of materials into the furnace without stopping or breaking is one of the main tasks of the OTF management. The disruption of the process of charge material run-off complicates the stability of OTF operation [1].

Violation of the proportional composition of the charge also leads to an increase in the volume of dust emissions containing a significant amount of valuable silica, which can be effectively sold on the market. Microsilica emissions in low-efficiency production, where there are no gas cleaning plants, can reach 50 %. This dust is blown out by reaction gases, when it enters the furnace or at the time of their formation, and is carried to the grate, where it is diluted with air. All this leads to the useless combustion of hydrocarbons. In the presence of a gas cleaning system, the gas-dust mixture is captured by a gas collecting probe. Furnace dust also pollutes the environment, negatively affecting the technical and economic performance of the plant [2].

It is possible to solve the problems mentioned above by increasing the level of the process automation, including through the introduction of material flow management systems.

Control of the material flow movement

Accounting for the movement of charge and other auxiliary materials is one of the main tools for financial and technical management of production based on the calculation of the material balances of raw materials processing into a finished product.

The material balance is the main indicator of the work of the workshop and the enterprise as a whole, reflecting the degree of efficiency of the technological process. On the basis of the material balance, both the extraction and the loss of valuable components are calculated, the technology is analyzed, etc. It is obvious that a more accurate balance gives a more correct idea of the process, allows revealing the reserves of production.

In the process of measuring the mass concentrations of components involved in the technological process, measurement errors are inevitable. The combination of them leads to an incorrect assessment of the company's resources and generates financial risks.

Accurate information about the composition of the raw materials and the final product is crucial to reduce the possible losses associated with incorrect estimates of material stocks, as well as to quickly identify them.

Automated control of the material balance allows you to:

- strategically plan enterprise resources;
- record any changes in the composition and quantity of raw materials;
- identify unknown material losses;
- calculate and account for measurement errors;
- compare input and output flows for the billing period [3, 4].

Domestic practices of application of material flow management systems

In Russia, technical refined silicon is produced at a single plant: "RUSAL" JSC. The volume of its finished products is about 1 % of the world production. An analysis of the production of domestic silicon shows that the degree of automation of the process has low indicators. Only the data of the first level is used as regulated parameters, but there is no automation of the upper (shop) level, which seriously affects the quality of the finished product.

It is necessary to modernize the production of silicon, to solve the tasks of effective management through multi-level automated process control systems along with the introduction of high-tech equipment and implement closed-cycle technologies.

The lack of timely and adequate data on the concentrations of charge components, material reserves, and carbon consumption leads to the irrational use of raw materials and energy resources, as well as to forced production downtime.

The uncorrected material balance of carbon in the charge, the inaccuracies in its calculation lead to an increase in silicon monoxide emissions, which negatively affects the state of the environment and reduces the degree of silicon recovery. When creating new modern technologies, the experience of advanced domestic enterprises for the production of metallurgical silicon should be taken into account. New technologies should solve the problems of resource and energy conservation, as well as to improve the environmental situation in the region by reducing the emissions of microsilica into the atmosphere [5].

As a typical example of a material flow management system, due to the lack of data on such systems in the production of silicon, consider the automated system for accounting for material flows and calculating the material balance of the metallurgical shop of the Copper Plant of "Norilsk Nickel" JSC, developed by "Summa Technologies". The metallurgical shop of the Copper Plant is one of the most significant subsidiaries of "Norilsk Nickel" JSC. The task of automating the accounting of material flows and calculating the balance of metals is particularly acute here. The products of the metallurgical shop account for about a quarter of the company's total marketable products. Within the workshop, 72 products are

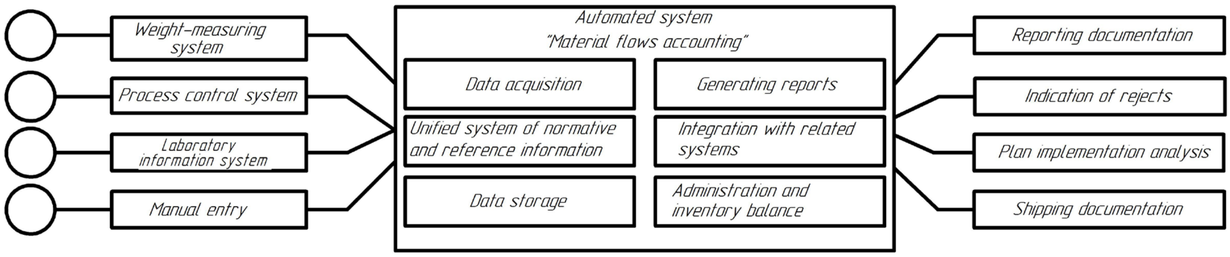

Fig. 1. Functional structure of the automated system "Accounting of material flows" of the metallurgical shopfloor of the Copper Plant

accounted for, each of which is analyzed for the amount and percentage of from 2 to 32 chemical elements, in total, more than 830 parameters are monitored.

The system allows you to track valuable components in the composition of materials for all stages of the workshop. The development of the system was accompanied by the introduction of automation of the products weighing operation.

The automated system for accounting for material flows and calculating the balance of metals provides more accurate control of the main technological parameters of the metallurgical shop of the Copper Plant, minimizes errors in the formation of documentation for products, provides timely reliable data for analyzing the quality of raw materials, optimizing the enrichment processes and increasing the recovery rate of precious metals [6].

"Norilsk Nickel" represents a multi-stage value chain of finished products from ore mining to metalworking. Continuous transformation of production, including digital, a huge number of interconnected objects makes it impossible to accurately quantify the effectiveness of a particular automated control system.

In the case of the balance of metals, it is possible to assess the efficiency of the integrated automated control system, covering all divisions of "Norilsk Nickel", including the system of the metallurgical shop of the Copper Plant under consideration:

- Data collection is 90 % automated, which minimizes the risks of misrepresentation of balance sheet data.
- Labor costs for collecting and forming balance sheets have been reduced by 70 %.

Material flows are not usually managed by a separate automated system. Automation of material flow management is carried out by implementing operational production management systems – systems of the MES class (manufacturing execution system), where accounting for material flows and reducing material balance are functions of only one of several system applications (modules).

To analyze the prospects of using MES systems to control the material flows of silicon production, we will consider ferroalloy production, which has a lot in common with enterprises that produce metallurgical silicon.

The main product of ferroalloy production is ferrosilicon. The process of smelting ferrosilicon is also based on the reduction of silicon from its dioxide in quartzite by carbon of coke and coal in an ore-thermal furnace and fusing it with iron of steel chips. In the production of ferrosilicon, the same problems occur as in the production of metallurgical silicon, namely, the influence of the charge composition on the electric mode of the furnace and the dust removal of valuable components, these disturbing factors can be eliminated by increasing the level of automation of production, including by implementing a MES solution.

The results of the implementation of the current MES class system, namely its module responsible for accounting for raw materials, are considered on the example of the "Aksu Ferroalloy Plant". The Enterprise Information System (EIS) is developed on the basis of the Wonderware software platform. It rep-

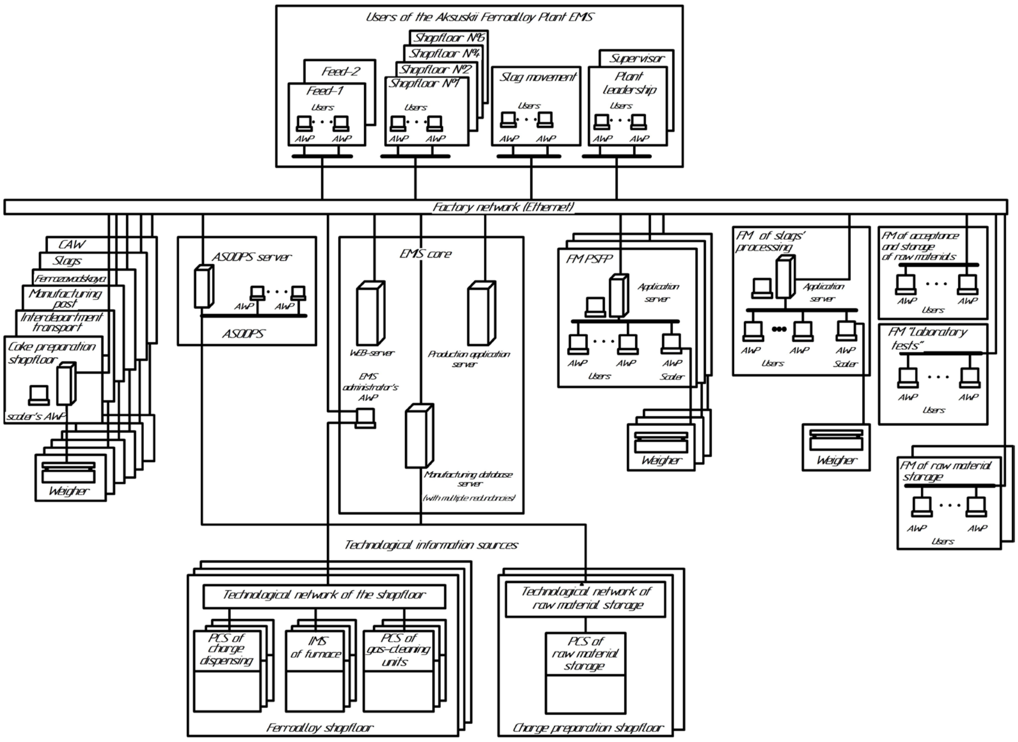

Fig. 2. Structure of EMIS of the Aksuskii Ferroalloy Plant:
CAW – central automobile weight room; FM PSFP – functional module of production, storage and shipment of finished products; IMS – information measurement system; awp – automation-equipped working place; ASODPS – automated system of operational dispatch control and power supply management

resents a single information space covering the main workshops and auxiliary divisions. This system was introduced in production in 2008 in order to reduce production costs by identifying the places and causes of production losses, inappropriate use of materials (including raw materials) and finished products.

The Automated System of Accounting and Control of material flows (ASCMF) is integrated into the plant's EIS and is a set of software and hardware tools for measuring, accounting for and controlling the movement of raw materials and finished products at the shop level and at the enterprise level.

Fig. 2 shows the detailed structure of the "Aksu Ferroalloy Plant" EIS, consisting of:

– core EIS;

– automated system of operational and dispatching control and management of power supply (ASODPS);

– functional modules;

– ASCMF.

The implementation of the system was carried out by stages in the form of functionally complete units of accounting for material flows (from the shipment of raw materials to the unloading of finished products).

As a result, the following qualitative improvements are identified:

• increased production efficiency by monitoring and analyzing the resources used and technological processes from the inside;

• an increase in the quality of the finished product (reduction of scrap, waste);

• compliance with the requirements of customers and supervisors by tracking the movement of the product from the raw material to the finished product.

With regard to the cost-effectiveness of the MES implementation, the following results were expected:

- reduced downtime of process equipment by 5 %;
- reduction of specific consumption of raw materials for the production of ferroalloys by 1 %;
- reduction of specific energy consumption for the production of ferroalloys by 2 % [7].

Main functions of MES systems for "Kuznetsk Ferroalloys" JSC:

- data collection and storage (DataCollection/Acquisition, DCA);

Collection of information from all automated process control systems and other related automated systems related to the course of the production process: the electric mode of operation of the furnace, the exact composition of the charge in specific gravity, the quality parameters of the finished product, etc.

- production process management (Process Management, PM);

Operational monitoring of the adjustment of the production process, either in automatic or automated (with the participation of the operator) mode. In any case, this function is based on an intelligent expert system that, based on the analysis of historical data on the parameters of the technological process and the resulting melt, selects the optimal composition of the charge, as well as the electric mode of the furnace.

- quality management (Quality Management, QM);

Manages laboratory studies of the parameters of the produced ferrosilicon, as well as provides analysis of the measured parameters in a close to real time mode.

- efficiency analysis (Performance Analysis, PA).

Generating reports on the actual results of production activities, comparing them with historical data and the expected commercial result. Formation and consolidation of the material balance for its transfer to the ERP system (enterprise resource planning).

In order to obtain reliable data, simultaneously with the introduction of MES at "Kuznetsk Ferroalloys" JSC, the existing automated process control system was upgraded. Measurement and control systems were put into operation to determine the humidity/icing of the charge components on the belt, as well as to measure the actual mass of the ferrosilicon melt. Control of the electric mode of the furnaces was also improved [8–10].

The successful implementation of the project significantly increased the profitability of the enterprise. Thus, from 2007 to 2012, the following positive results were achieved in the context of the global economic crisis:

– ferrosilicon smelting increased by 12 %;
– labor productivity increased by 42 %;
– number of highly qualified personnel increased by 10 %.

Foreign practices of application of material flow management systems in the silicon industry

The leader of silicon production today is China, with the production lines focused on silicon of the highest grades, including silicon for "solar energy". Approximately 40 % of the silicon market is occupied by Europe and the United States.

The major players in the silicon and polysilicon market are looking to expand the vertical integration of their businesses. Foreign enterprises are focused on the production of polycrystalline silicon used in the solar energy and semiconductor industries, which increases the value of the finished product and the profitability of production.

Due to the complexity of the production chain and the multi-stage process of raw material preparation, the level of automation, including top-level automation, is a single network covering all stages of production. Below are examples of the organization of operational management systems, including automated material flow management systems at enterprises that produce polysilicon.

For example, in 2004, in order to minimize production costs, the international company Wacker Polysilicon AG (Germany, USA) launched a group-wide program – Wacker Operating System (WOS) to increase productivity through the internal supply chain: from servicing and purchasing raw materials through production to packaging and shipping the finished product. Wacker has its own academy to train personnel for WOS maintenance [11–13].

In December 2006, TEC Silicon ASA (Norway/USA) installed an enterprise-wide MES system based on OSIsoft PI datahistorian. Its built-in intelligent forecast can increase the efficiency of the enterprise by 2 % or more [14].

The company SUPCON XinteEnergyCo. (China) won a contract to develop integrated solutions for a smart plant for the 36,000 tons per year polysilicon production base modernization project from XinteEnergyCompany in 2018. SUPCON will deliver a comprehensive intelligent solution for subsequent implementation, covering both the management of individual processes and the management of general enterprise information [15].

The analyzed foreign enterprises for the production of silicon followed the path of combining information systems that automate the activities of certain production units, without separating each division and technological process. These plants have fully integrated material flow control systems that process operational data in a single reporting format for the enterprise. This allows us to avoid disparate, poorly combined data and create an adequate analytical base for strategic resource planning [16, 17].

Based on the study of the possibilities of modernizing the process of material flow management in silicon production, using the example of the implemented automated system for accounting for material flows and calculating the material balance of the metallurgical shop of the Copper Plant, as well as the MES systems for ferroalloy production, it is possible to conclude that it is advisable to introduce an automated system for managing material flows at silicon production enterprises.

"Silarus" LLC

The platform for the implementation of this type of system is "Silarus" LLC, which is launching a new type of plant in the Sverdlovsk region. The main focus of the project is aimed at obtaining silicon of different grades with the associated recycling of related components, followed by their chemical transformation into high-quality commercial products.

To obtain high-purity silicon, it is necessary to pay special attention to improving the quality of the initial charge material, adjusting the technological parameters with high controllability and automation of the process, choosing the optimal type of carbon reducing agent, and improving the quality of graphite electrodes in ore-thermal furnaces.

It is also necessary to take into account the environmental safety of production and strive for effective capture of industrial emissions in the form of silicon dust and ash with their subsequent processing [19].

To address the above issues, "Silarus" SPA offers a number of new technical solutions for silicon production:

- It is planned to launch its own production of the main carbon reducing agent, charcoal, followed by the use of birch bark in the pharmaceutical industry. This solution will improve the quality of the reducing agent by controlling all stages of the technological process of coal production, as well as reduce the cost of the reducing agent.
- The use of chlorine-free technology for obtaining solar-quality silicon (high-temperature refining).
- Recycling of thermal energy generated in the process of carbothermic reduction of silicon.
- Implementation of an automated material flow management system.

Figure 3 shows a generalized structure of the planned material flow management system, including the servers and services required to integrate the system into a single enterprise information environment.

The main task on the way to increase production efficiency for "Silarus" SPA, as well as for all enterprises producing metallurgical silicon, is to reduce the emissions of microsilica.

During the production of one ton of metallurgical silicon, 400–450 kg of dispersed carbonaceous microsilica is formed at the enterprises. The composition of the dust may vary depending on the composition

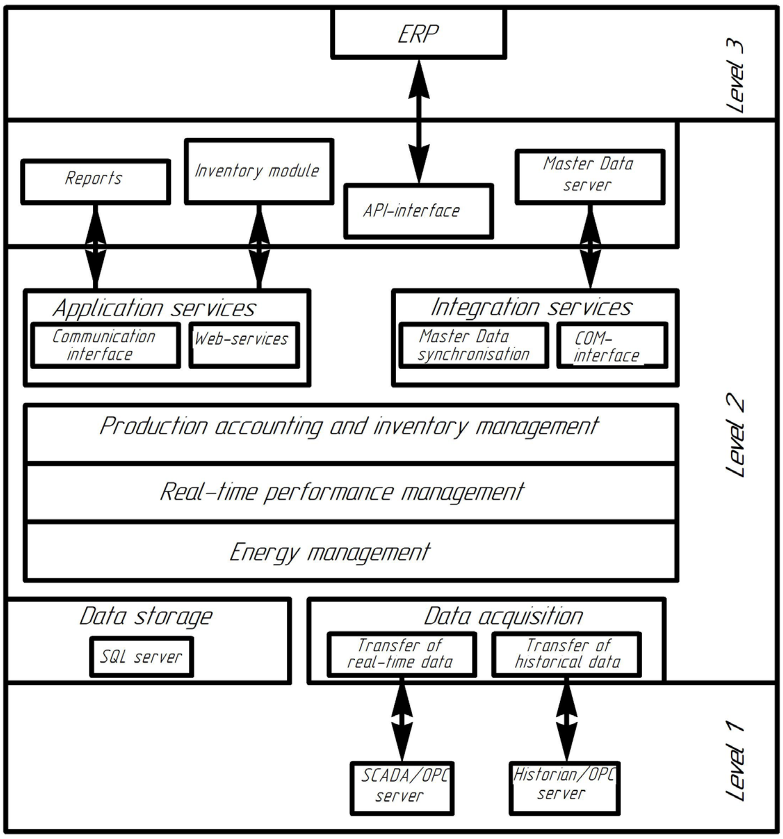

Fig. 3. The generalized structure of the project of the automated material flow management system, planned for further integration into the unified information system of the company "Silarus": level 1 – process control; level 2 – operational production management; level 3 – strategic enterprise management

of the charge and the electric mode of the furnace. The main components are SiO_2 (up to 85 %) and solid carbon (7–8 %), as well as silicon carbide (5 %).

Due to its high activity, this type of raw material, after separation into carbon and microsilica, can be used as a source of powders in 3D printers manufacturing complex building elements and blocks. In addition, carbon-free microsilica is widely used in the global construction industry as an additive to the main raw materials. Thus, the addition of microsilica allows producers to obtain concretes with special properties: increased durability (resistance to weak acids and seawater), increased compressive strength. The production of silicon carbide powder materials is rapidly developing and has a high cost of the final product: micronized carbide (particle size < 1 microns) for ceramics and nanocarbide (particle size < 1 nm) for high-quality structural ceramics and electroplating.

A variety of options for implementing microsilica puts the task of increasing the capture of dust emissions during silicon smelting in OTF in the first place in terms of production efficiency and resource saving.

The main mechanism for the formation of microsilica dust is active oxidation of liquid silicon melt, while a small fraction (< 1 %) of dust particles is formed when it is sprayed. In the absence of gas treatment system (hereinafter referred to as GTS), 30–40 % of microsilica is released through lantern emissions, the other part is deposited in production areas and collected manually in containers (such as FIBC).

In the presence of special-purpose GTS at the enterprise, and in the case of a comprehensive investment project, "Silarus" SPA plans to ensure 99 % capture of microsilica, and its storage in containers for sale and processing in various directions and commercial products.

However, even in the presence of GTS, silicon dust is extremely thin (about 80 % of the generated dust has a fraction of less than 1 mm) and is poorly captured; its size affects the efficiency of dust collection. The task must be solved comprehensively. Improving the quality of charge materials and strict compliance with the OTF process regime, the introduction of a material flow management system, and operational control of the amount of dust captured can significantly reduce the level of dust emissions in the production of technical silicon [18].

Microsilica dust emission control method

To estimate the amount of dust emissions in the production of metallurgical silicon, there are a number of devices and methods that can be divided into 2 groups according to the measurement method:

1. The measurement takes place directly in the dust and gas flow leaving the furnace. In this method of measurement, optical sensors requiring calibration for a specific production are usually used.
2. Extractive measurements related to sampling. A number of extractive methods for the quantification of solid particles have been tested in the silicon industry, such as

- Gravimetric filters offer a reliable, cheap and simple, but unsuitable for continuous monitoring method for estimating the mass concentration of microsilica emissions;
- Standard Optical Particle Counter (OPC) and Condensation Particle Counter (CPC) are not suitable for silicon enterprises because they detect too low concentrations of solid particles.

Monitoring of waste gases in the production of silicon and its alloys is associated with a number of industry-specific problems:

- The gas temperature in the immediate vicinity of the OTF is very high (about 600 °C), which leads to the need for diluting the gas-dust flow before the contact with the sensitive device in the case of extractive measurements;
- High concentration of solid particles in front of the filter causes rapid wear of measuring instruments installed in gas streams with particles, as well as of the measured data [19].

The described difficulties make it relevant to search for new solutions. Based on the basic physical properties of gas-dispersed media, a method was developed for determining the mass concentration of microsilica dust in OTF exhaust gases by temperature control.

The presence of particles in the gas stream changes the velocity and temperature profiles of the gas and, consequently, the heat transfer that is attributed to the gas. The change in heat transfer in gas-dust flows is primarily a consequence of a change in the heat capacity of the mixture, along with a change in the characteristics of the gas phase flow.

The main mechanisms of increasing heat transfer in the presence of solid particles in the gas stream are due to:

1. transfer of thermal energy by bouncing particles;
2. increasing the heat capacity of the medium;
3. changes in the flow structure due to a higher effective Reynolds number of the suspension.

The heat capacity has the strongest influence on the heat transfer. The dispersed system, represented by gases leaving from OTF (90 % CO, 5 % CO_2, etc.), depending on the concentration of microsilica particles, has a different heat capacity.

Since a dispersed system consists of particles and a medium, the total amount of heat transferred to the system is equal to the sum of the heat transferred to the particles and the dispersion medium. The heat capacity of the dispersed system will be equal to:

$$c_{ds} = \frac{c_p \cdot m_p \cdot \Delta T + c_{dm} \cdot m_{dm} \cdot \Delta T}{m_{ds} \cdot \Delta T},$$

where c_p – particle heat capacity, J/kg * K; m_p – particle mass, kg; ΔT – temperature change, K; c_{dm} – heat capacity of the dispersion medium, J/kg * K; m_{dm} – mass of the dispersion medium, kg; m_{ds} – system weight, kg.

By determining the heat loss in the section of the exhaust gas pipeline, it is possible to indirectly determine the mass concentration of microsilica in the exhaust gases.

Conclusion

The analysis of the existing level of automation of the movement of material flows of silicon production in Russia showed the absence of this important link between the automated process control system and ERP. Automation of individual units and the presence of a lower level of process control cannot completely eliminate the problem of divergence of material balances and the irrational use of energy and material resources. The most effective ways to solve these problems are:

1. expanding the functions of existing control systems;
2. end-to-end enterprise automation;
3. using closed-loop technology.

In the global silicon market, the state of automation today is several steps higher than in Russia.

In most foreign silicon production facilities, the production of metallurgical silicon is an intermediate step in the chain of production of polycrystalline silicon. Due to the multi-stage technology for obtaining the finished product, the complexity of the production chain, the requirements for the level of automation are significantly increasing. At the largest enterprises producing polysilicon (Wacker Polysilicon, REC Silicon, Xinte Energy Co.), the methods described above for solving the problems of controlling the movement of materials and energy resources are implemented, which brings the companies to the leading position in this industry.

In order to keep up with the leaders of foreign production, "Silarus" SPA is developing a qualitatively new project for the production of silicon of different grades in accordance with the concept of closed-cycle production. The project, which aims to combine successful experience of foreign companies, as well as new technologies (high-temperature refining), will become a launching pad for the development and implementation of a specialized automated system for operational management of enterprise resources and waste.

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THE AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Masko Olga N.
Масько Ольга Николаевна
E-mail: olgamasko.17@gmail.com

Gorlenkov Denis V.
Горленков Денис Викторович
E-mail: denis.gorlenkov@gmail.com

ИНФОРМАТИКА, ТЕЛЕКОММУНИКАЦИИ И УПРАВЛЕНИЕ

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Телефон редакции (812)552-62-16

E-mail: infocom@spbstu.ru

Компьютерная верстка *А.А. Кононова*

Перевод на английский язык *Д.Ю. Алексеева*

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