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REVIEW ARTICLE

Comparative analysis of compression algorithms for four-dimensional light fields

RETRACTED

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Abstract

Objectives. The widespread use of systems for capturing light fields is due to the high quality of the reproduced image. This type of capture, although qualitatively superior to traditional methods to capturing volumetric images, generates a huge amount of data needed to reconstruct the original captured 4D light field. The purpose of the work is to consider traditional and extended four-dimensional image compression algorithms, to perform a comparative analysis and determine the most suitable.

Methods. Mathematical methods of signal processing and methods of statistical analysis are used.

Results. Algorithms are considered and analyzed in relation to the compression of four-dimensional light fields using the PSNR metric. The selected evaluation criterion is affected not only by the dimension of the compression algorithm, but also by the distance of the baseline of the capture setting, since the difference between images increases with the distance between the optical centers of each camera matrix. Thus, for installations consisting of an array of machine vision cameras located on racks and placed in a room, the obvious choice would be to use conventional image compression methods. Furthermore, based on the assessment of the arbitrariness of video compression methods, it should be noted that the XVC algorithm remains undervalued, although its results are higher. Algorithm AV1 can be considered the next in order of importance. It has been established that the latest compression algorithms show higher performance if compared to their predecessors. It has also been shown that with a small distance between the optical centers of the captured images, the use of video compression algorithms is preferable to the use of image compression algorithms, since they show better results in both three-dimensional and four-dimensional versions.

Conclusions. A comparison of the results obtained shows the need to use algorithms from the video compression family (XVC, AV1) on installations with a long baseline (mounted on camera stands). When working with integrated light field cameras (Lytro) and setting the capture with a short baseline, it is recommended to use image compression algorithms (JPEG). In general, video compression algorithms are recommended, in particular XVC, since on average it shows an acceptable level of PSNR in both the case of a short and long installation baseline.

Keywords: 3D visualization, 4D light field, light field compression

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ОБЗОР

Сравнительный анализ алгоритмов сжатия четырехмерных световых полей

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Резюме

Цели. Широкое распространение систем захвата световых полей обусловлено высоким качеством воспроизводимого изображения. Этот вид захвата, хотя и качественно превосходит традиционные подходы к захвату объемных изображений, генерирует огромное количество данных, необходимых для восстановления исходного заснятого четырехмерного светового поля. Цель работы – рассмотреть традиционные и расширенные до четырехмерности алгоритмы сжатия изображений, провести их сравнительный анализ и определить наиболее подходящие из них.

Методы. Использованы математические методы обработки сигналов и методы статистического анализа.

Результаты. Проведены сравнение и анализ алгоритмов применительно к сжатию четырехмерных световых полей с использованием метрики PSNR. Установлено, что на выбранный критерий оценивания влияет не только размерность алгоритма сжатия, но также и расстояние базовой линии установки захвата, так как разница между изображениями увеличивается в зависимости от расстояния между оптическими центрами каждой матрицы камеры. Так для установок, состоящих из массива камер машинного зрения, находящихся на стойках, расставленных в помещении, очевидным выбором будет применение обычных методов сжатия изображений. Также, исходя из оценки произвольностей методов сжатия видео, замечено, что алгоритм XVC остается недооцененным, хотя его результаты оказываются выше остальных. Следующим по значимости можно считать алгоритм AV1. Установлено, что новейшие алгоритмы сжатия показывают более высокую производительность по отношению к своим предшественникам. Продемонстрировано, что при небольшом расстоянии между оптическими центрами запечатленных изображений применение алгоритмов сжатия видео более предпочтительно, чем применение алгоритмов сжатия изображений, так как они показывают более высокие результаты как в трехмерном, так и в четырехмерном варианте.

Выводы. Сравнение полученных результатов показывает необходимость применения на установках с длинной базовой линией (установленных на стойках камеры) алгоритмов из семейства сжатия видеозаписей (XVC, AV1). При работе с интегрированными камерами светового поля (Lytro) и установкой захвата с короткой базовой линией рекомендуется использовать алгоритмы сжатия изображений (JPEG). В общем случае рекомендуется использовать алгоритмы сжатия видео, в частности XVC, поскольку в среднем он показывает приемлемый уровень PSNR как в случае с короткой, так и с длинной базовой линией установки.

Ключевые слова: 3D-визуализации, 4D-световое поле, сжатие световых полей

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INTRODUCTION

By its nature, light field information describes the parameters of light emitted from a point in space captured, for example, by a large number of cameras [1] or a light-field imaging camera [2] based on the light field principle [3]. Requirements for the storage and transmission of such data often come down to increasing the volume of their storage and improving the performance of transmission channels. Therefore, the development and research of compression methods for light fields has become increasingly important in recent years. Although there are many effective compression formats for still and moving images, little research has been reported in the literature on the influence of these methods on the properties of light field images [4]. In this work, we assessed the impact of modern methods of image and video compression on the quality of images obtained based on light field data. These methods include the latest video compression standards, especially AV1 [5] and XVC[2] [6]. In order to take full advantage of the potential of common image compression algorithms on 4D light field images, we extend these techniques to 3D and 4D measurements. The paper demonstrates that 4D light field data can be compressed much higher than independent still images while maintaining the same visual quality of the perceived image.

In order to describe a three-dimensional scene from any possible position of the observer, we define the function $P(x, y, z, \varphi, \psi)$ [2], where (φ, ψ) is the viewing angle of the camera (in spherical coordinates); (x, y, z) is the absolute position of the viewpoint (Fig. 1). The result of the execution of the P function is a color that describes the visual representation of the observed point in space. The parameter t (time) can be added to the definition of the function P in order to describe a dynamic scene.

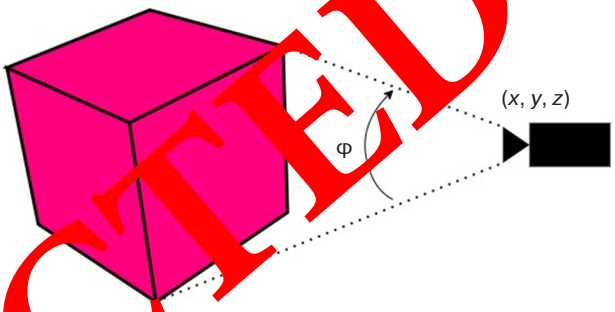

Fig. 1. Capturing a scene from one viewing position. For simplicity, the viewing angle is specified for one spherical coordinate

Our objective is to describe the scene by shooting either with multiple cameras (camera array) or with a single compact array with microlenses in front of it, such as in Lytro. In this case, the aperture can be depicted as a grid of views (cameras) located on a two-dimensional plane. This case is illustrated in Fig. 2, where the distance on the line passing through the base points between the individual views is described by the parameter d. This representation is often referred to as a 4D light field (LF) since we are dealing with a light field function L sampled in four dimensions (k, l, m, n), where (m, n) are pixel coordinates; (k, l) are subaperture image indexes.

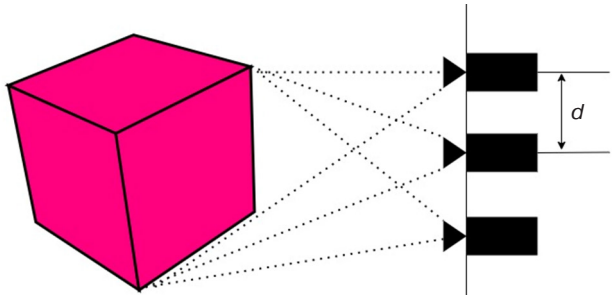

Fig. 2. Capturing a 4D light field with a camera array

The light fields received by one compact single device have limitations on the viewing angle. Light fields based on multiple cameras provide large viewing

[1] AOMedia Video 1 (AV1) is an open video compression standard for encoding video transmitted over the Internet. It replaces the VP9 video encoding format developed by Google. According to [5], AV1 outperforms H.265/HEVC by 17% and VP9 by 13% over a wide range of bitrates/resolutions. Developed by the Alliance for Open Media (AOMedia), created in 2015 and comprised of electronics, video-on-demand, and web browser companies (AMD, Apple, Arm, Broadcom, Intel, Nvidia, Amazon, Facebook, Google, Hulu, Netflix, Mozilla, Microsoft). Timothy B. Terriberry. Progress in the Alliance for Open Media (slides). URL: https://people.xiph.org/~tterribe/pubs/lca2017/aom.pdf (18 January 2017). Accessed June 22, 2017.

[2] XVC is a video encoding format with a strong focus on low bitrate streaming applications. The official website (URL: https://xvc.io/. Accessed December 04, 2021) claims that the codec is superior to AV1, H.265/HEVC, and VP9.

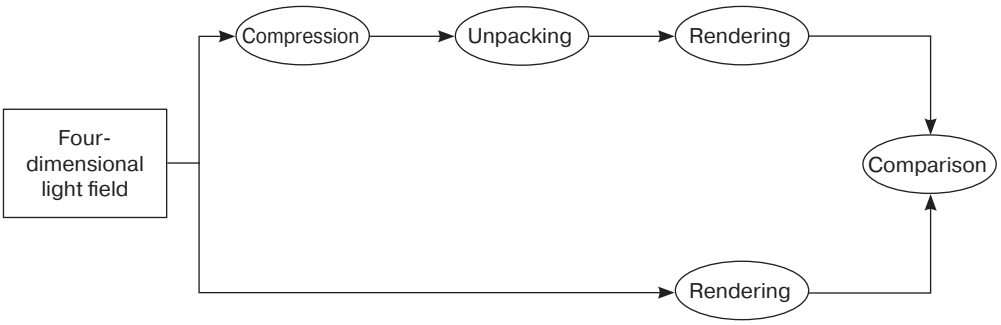

Fig. 3. Data flow diagram of the technique for comparing compression algorithms

angles by distributing camera arrays in the space around the object. In practice, the number of views located on a two-dimensional plane varies from a couple units. Given the high resolution of the sensors, it is not surprising that the volume of light field data is enormous. As an example, consider the "Treasure Chest" light field[3] (Fig. 3) taken from the Stanford Light Field Archive. This field is captured using a 17 × 17 grid of cameras with an image resolution of 1536 × 1280 pixels. The size of uncompressed data exceeds 1 Gb. When using photo sequences to organize footage, storage and transmission requirements will increase proportionately.

METHODS FOR COMPRESSING 4D LIGHT FIELDS

Recently, several methods for compressing light fields have been proposed in the literature [5, 7–19]. Using some of these methods, researchers are trying to directly compress data received from sensors that are preceded by microlenses (lens images). Others compress the resulting 4D light field instead of processing the original "raw" data. In this article, we will focus only on the latter.

Let us compare various present-day compression methods applicable to 4D light field data. These methods include the latest video compression standards, especially AV1 (approved in June, 2018) and XVC (version released in July, 2018). In order to make a comparison, we refocus the original and decompressed light field. The evaluation is then carried out using the PSNR (peak signal-to-noise ratio) metric as a full-scale quality benchmark.

Separate displays from the original light field are usually not rendered. Therefore, it makes no sense to directly compare the original and decompressed light fields, although such methodology is usually used to evaluate the performance of one kind of compression. For this reason, the compression performance estimation methodology for multi-focus rendering from [4] will be used. This methodology consists basically of evaluating the rendering quality of views for multiple breakpoints. Rendered displays are obtained by combining pixels from different 4D light field views for different focal planes. The average distortion is calculated as the average of the PSNR for several rendered views in the focal plane. The comparison technique is illustrated in Fig. 3. Note that PSNR is calculated from the mean square of the error over all three color components.

A 4D light field contains a 2D grid of 2D views captured from cameras. The baseline length between individual views varies from a few millimeters (microlenses) to a few centimeters (camera array). Therefore, it is natural to expect a high level of similarity between views adjacent in either of the two grid directions. This similarity opens the way to understanding 4D light field data as a video sequence moving between viewpoints. Alternatively, we can consider a 4D light field as 3D or directly as a 4D body. The approaches described above can also be found in light field compression using an image, video, 3D or 4D image coding system (although other approaches are possible, for example, using 3D video).

In recent years, the compression performance of various approaches to light field imaging have been compared and evaluated.

In [4], the authors evaluated the performance of the main image coding standards with independent views and H.265/HEVC[4] with independent views. The label "with independent views" indicates that the individual views have been compressed independently of each other. Approaches to video encoding were not evaluated in the work. As expected, the H.265/HEVC internal profile proved to be the most efficient compression method.

In [7], the authors compared the compression performance of three strategies using the H.265/HEVC codec. The first strategy performs compression directly

[3] Standford light-field dataset. URL: http://lightfield.stanford.edu/?gclid=Cj0KCQiA47GNBhDrARIsAKfZ2rD2CB3lMtzHJXPr0uXM_KJm_tEllZIZLviFERCFsasV9JygG55uBIaAtRTEALwwcB. Accessed December 04, 2021.

[4] H.265/HEVC is a high efficiency video coding; MPEG-H is a video compression standard developed as a successor to the widely used H.264/AVC (MPEG-4).

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on the original light-field image. The following strategy organizes the views of the 4D light field into a pseudo-temporal sequence in a spiral order and subsequently compresses them. In the latter strategy, compression occurs on a subset of images extracted from the light-filed image by transforming into a four-dimensional light field. The results of the work carried out by the authors show that the encoding of a four-dimensional light field leads to better performance when compared to direct encoding of images received from cameras.

The authors of [8] compared the performance of JPEG[5], JPEG 2000, and SPIHT[6] directly on images obtained from camera matrices. The comparison was carried out using the same methodology as in this article. As you might expect, JPEG 2000 shows the best compression performance.

In [9], the authors proposed to rearrange the 4D light field as a tiled representation of a large rectangular image. This image was then compressed using a JPEG 2000 encoder. The proposed scheme was compared with standard image encoding algorithms, namely JPEG 2000 and JPEG XR. However, it is not clear how accurately these standard encoding algorithms were applied to 4D light field data.

In [10], the author reconstructs a four-dimensional light field into a three-dimensional body. The volume is then encoded using a 3D DCT scheme for 8 × 8 × 8 blocks similar to the JPEG coding system.

Besides conventional coding methods, there is also an alternative approach [11] which uses deep learning to estimate a 2D representation from sparse sets of 4D representations. Another approach [12] proposes its own sparse coding scheme for the entire four-dimensional light field, based on several optimized key representations.

The method described in [13] is based on the construction of superbeams which limit the superpixels that form a given superbeam. This constraint is necessary in order that superbeams can be used to support angular dimensionality reduction based on low-rank matrix approximation. Then, an approximation of the low-rank matrix for the superbeams is calculated with inconsistency compensation using singular value decomposition (SVD). The base vectors are then encoded using HEVC or JPEG-Pleno VM 1.1 for each individual representation.

In [14, 15], the authors propose a hierarchical coding structure for four-dimensional light fields. The 4D light field is broken down into several views and then organized into an encoding structure according to spatial coordinates. All representations are coded hierarchically. The scheme is implemented in the H.265/HEVC reference software.

In [16], the authors propose an encoding scheme which divides a four-dimensional light field into several central views and other adjacent views. The adjacent views are subtracted from the center views, and then both groups are encoded using the H.265/HEVC codec. The authors of [17, 18] transfer the four-dimensional light field to the H.265/HEVC codec using the inter-prediction mode for individual LF views. Finally, great attention has been paid to compression approaches based on convolutional neural networks [19, 20]. It can be seen from the above that JPEG 2000 and especially H.265/HEVC coding schemes are quite popular when compressing 4D light fields.

In this article we compare the performance of the main presently available methods for compression with losses. These methods can be divided into four groups depending on how the 4D LF data is processed. The first group covers the following image encoding methods: JPEG and JPEG 2000. In [21] they are called methods based on 2D-similarity. The second group includes video encoding methods: H.265/HEVC, AV1, VP9, and XVC. They are generally referred to as pseudo-sequence-based methods. The third group extends methods for encoding images in three dimensions. This group consists of JPEG 3D and JPEG 2000 3D. Note that JPEG 3D refers to a 3D image and not to a pair of stereoscopic images. The fourth group extends image encoding methods in four dimensions. However, there is only one method in this group—JPEG 4D.

The following codecs are used to assess the above methods: OpenJPEG, x265, libaom (AV1 codec library), libvpx (VP8/VP9 codec SDK), and XVC codec.

INITIAL DATA

This section presents the data set, the multifocal imaging method, the experiments performed with this data set, and the results obtained.

The data set consists of four 4D light fields based on two types of capture devices. Two light fields were taken with a Lytro Illum B01 light-field camera (manufactured by Lytro, USA), and the other two were taken with conventional DSLR cameras.

The first conventional camera light field was captured with a multi-camera array, and the second with a simple motorized setup equipped with a Canon Rebel XTi digital camera (manufactured by Canon, Japan). The corresponding resolutions and corresponding image divergence ranges are listed in Table. The values in the last column—image divergence—describe the difference in pixels in the location of the same 3D object projected onto images taken by the camera or calculated from the light-field camera image, in the case of Lytro.

[5] JPEG—Joint Photographic Experts Group, titled after the name of the developer.

[6] SPIHT is a set partitioning in hierarchical trees.

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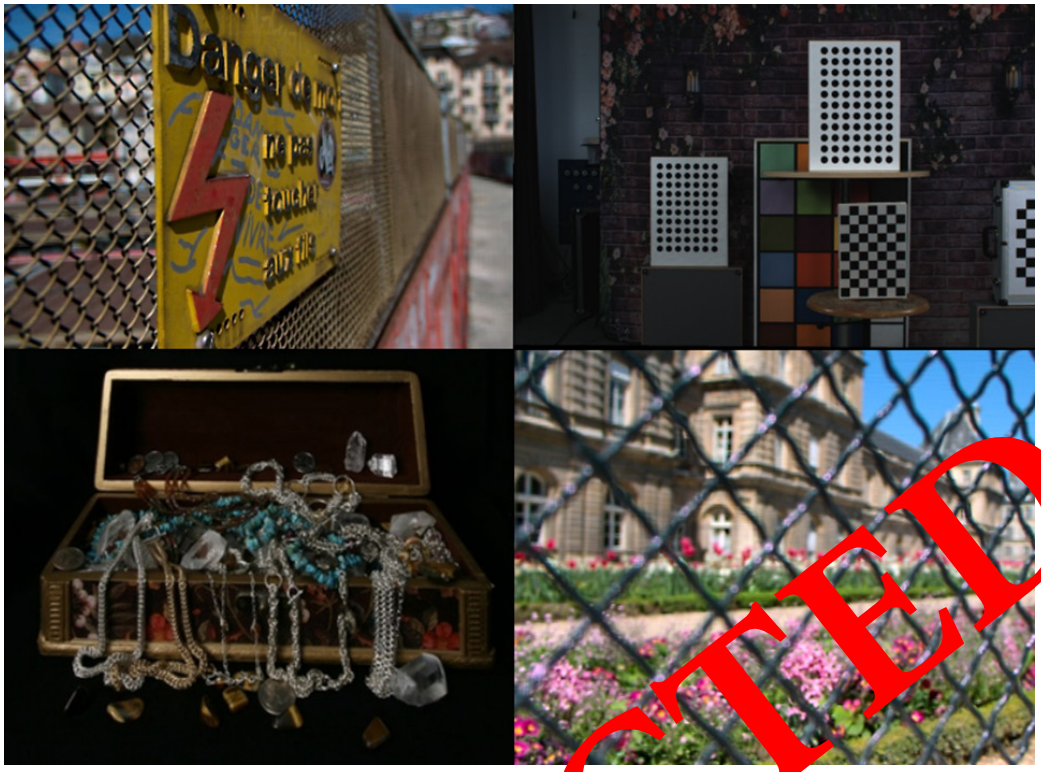

Fig. 4. Data set used f comparison
Left to right: Danger de mort, Chessboard, T sure Ches , Palais du Luxemburg

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As can be seen, the range of discrepancies will be of the pixel value at point (*m, n*) of the refocused image narrow (from −1 to +1 pixels) for a light field with a den sample (short baseline) in the case of a Lytro mera an wide (from 40 to 90 pixels) for image btained by a array of cameras. These values obviously rrela ith the focal length of the came d the dista e between the centers of the cameras r ligh ield lense in the case of Lytro. For conven ence, the cent view for each light field is shown in 4.

The first and l ight fields shown in Fig. 4 are taken wi ht-fie amera; Chessboard is captured using arra of came s; Treasure Chest is captured using a with a camera affixed to it.

Digita focusing of images in the virtual focal plane is achieved ing the shift-sum algorithm [22]. This algorithm shifts subaperture images (views) according to the optical center of the camera relative to the camera baseline relative to the reference frame and accumulates the corresponding pixel values. The refocused image will be the average of the converted images. The calculation

is given by the equation:

$$E_{\mathrm{d}}(m,n)=\frac{1}{N}\sum_{k,l}L(k,l,m+\alpha k,n+\alpha l), \qquad (1)$$

where N is the number of summed images; α is the distance of the synthetic plane from the main lens; k and l are indices of the subaperture image of the light field representation; αk and αl are the shift parameters with respect to the reference system. Linear interpolation was also performed in the last two 4D measurements, in order to convert the sampled light field function to a continuous one.

EXPERIMENT 0

It is worth clarifying in advance whether it is really necessary to evaluate the quality of images displayed for several focal points, rather than on the original data (that is, directly compare the original and decompressed

Table. Dataset used for comparison

Description	Source	Resolution	Discrepancy in pixels
Danger de mort	EPLF dataset	15 × 15 × 625 × 434	From −1 to 1
Chessboard	Saarland University	8 × 8 × 1920 × 1080	From 40 to 90
Treasure Chest	Stanford Computer Graphics Lab	17 × 17 × 1536 × 1280	From −1 to 7
Palais du Luxemburg	EPLF dataset	15 × 15 × 625 × 434	From −1 to 1

set of images). A quick experiment shows that there is a big difference between these approaches (Fig. 5). It is about 10 decibels in PSNR depending on the bit rate and compression method. This can be explained by the fact that any pixel in the displayed form is the sum of the pixels from the 4D light field, so this sum together reduces compression artifacts. In other words, we can afford to compress 4D light fields much more than independent images while maintaining the same visual quality of the displayed image.

Figure 5 shows the difference in quality evaluation using a 4D light field directly compared to using images rendered at virtual focal planes. The illustration is shown on the Danger de mort light field.

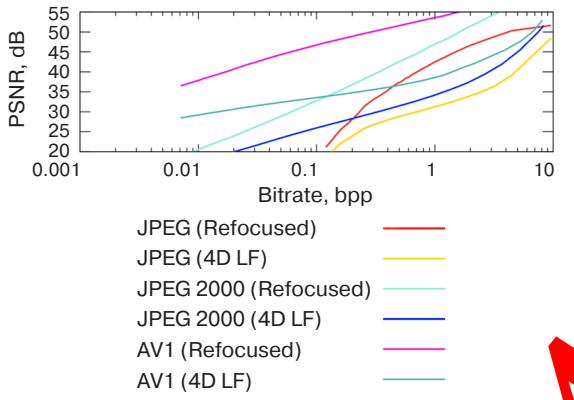

Fig. 5. Experiment 0: difference in quality evaluation

EXPERIMENT 1

As can be seen from the literature review, most present-day approaches to light field compression process either 2D data or its sequence (video compression). The compression of 4D light field images is still a relatively unexplored area. Since the 4D light field is sequences of 2D images (viewpoints), 2D compression techniques can be used to independently encode the viewpoints. However, such methods do not allow the use of pixel correlations in all four dimensions. A similar reasoning can be applied to 3D methods. In our Experiment 0, we were interested in studying the effects of contraction of light fields in three and four dimensions. In order to fairly evaluate compression performance, the same compression method must be used for the 2D, 3D and 4D cases. Thus, in the work we used a custom implementation of the JPEG compression method with the ability to process 2D, 3D or 4D data. In addition, there exists the JPEG 2000 standard with the ability to compress 2D and 3D data in the same way. Unfortunately, JPEG 2000 does not work with 4D images. Since the similarity of neighbouring pixels in 3D and 4D is highly dependent on the camera baseline, different results can be expected. The result of this experiment is shown in Fig. 6. In each graph, the horizontal axis shows the bitrate (bits per pixel) and the vertical axis shows the average PSNR for multiple rendered focal plane viewpoints.

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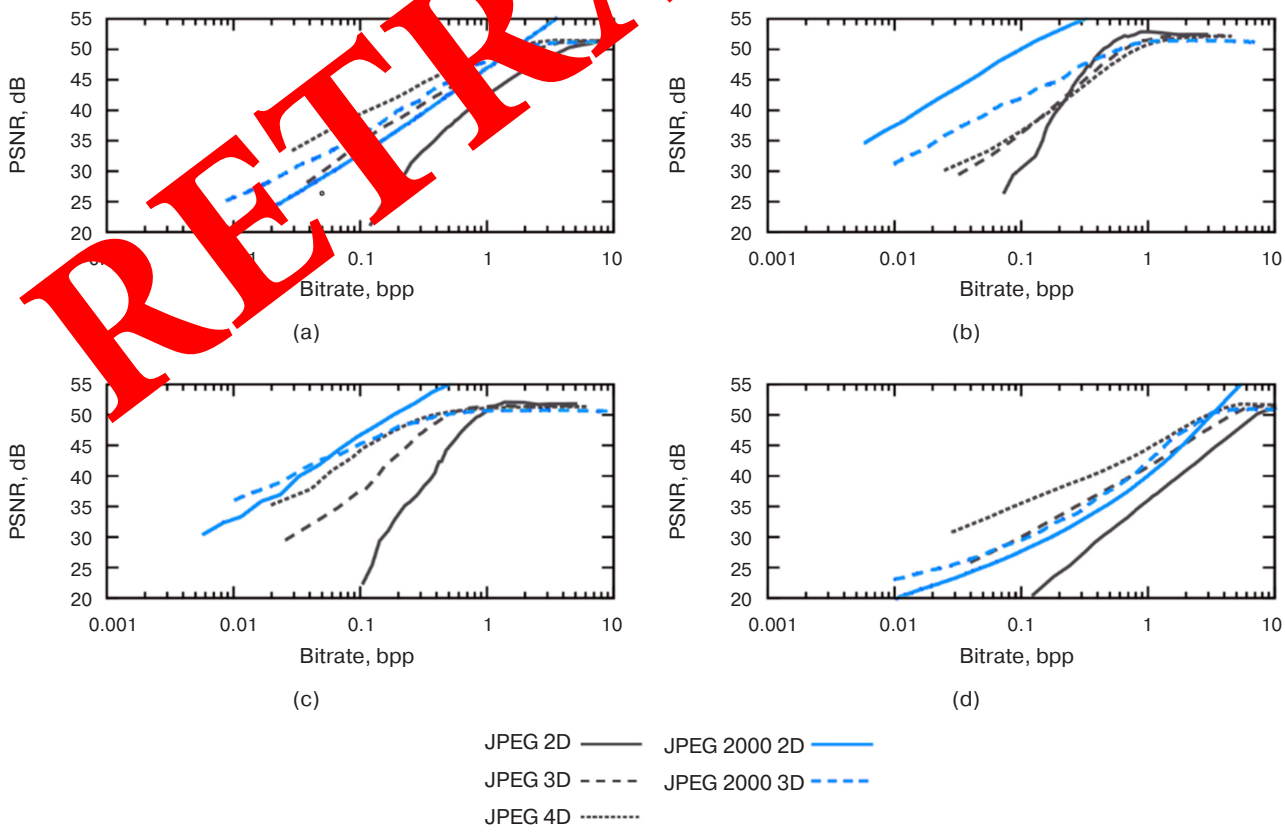

Fig. 6. Experiment 1: performance comparison of image compression methods:
(a) Danger de mort, (b) Chessboard, (c) Treasure Chest, (d) Palais du Luxemburg

For light fields with a small baseline (Danger de mort and Palais du Luxemburg), both 3D compression methods clearly outperform their 2D counterparts over the entire bitrate range. Likewise, the 4D JPEG method is clearly superior to its 3D counterpart.

This is not surprising since pixels in the same spatial position in neighboring views are highly correlated. However, the situation changes as the baseline increases. In doing so (Treasure Chest and Chessboard), adjacent views become less and less similar, resulting in higher amplitudes of base transform coefficients. Consequently, the situation is changing in favor of compression methods with smaller sizes.

Considering the JPEG method, Treasure Chest is a special case since it contains a large number of black pixels. It turns out that it is more efficient to compress these solid areas at once with a single 4D block rather than with multiple 3D blocks. Likewise, it is more efficient to use one 3D block than multiple 2D blocks.

EXPERIMENT 2

The second thing to note in the previous section is the use of video compression standards. The question arises whether it is better to compress 4D light fields as a sequence of 2D frames or as a multidimensional body? Therefore, we measured the performance of all the above video compression standards. The results can be seen in Fig. 7. This time the results for only two light fields are shown for brevity.

Interestingly, the XAVC codec actually showed better compression performance than HEVC and AV1.

In order to answer the question, "What is the best compression method for these light fields?", an additional comparison of the results with the most efficient methods from Experiment 1 was carried out. The overall comparison is shown in Fig. 8. Interestingly, video compression methods perform better than all image compression methods, even better than their 3D and 4D extensions.

CONCLUSIONS

The objective of this work was to evaluate existing methods suitable for compressing 4D light fields with losses. Since the light field in the original version is a set of images captured by an array of cameras, image compression methods will be the first thing to choose from in compression problems. The experiment shows that methods which process 4D light fields directly in

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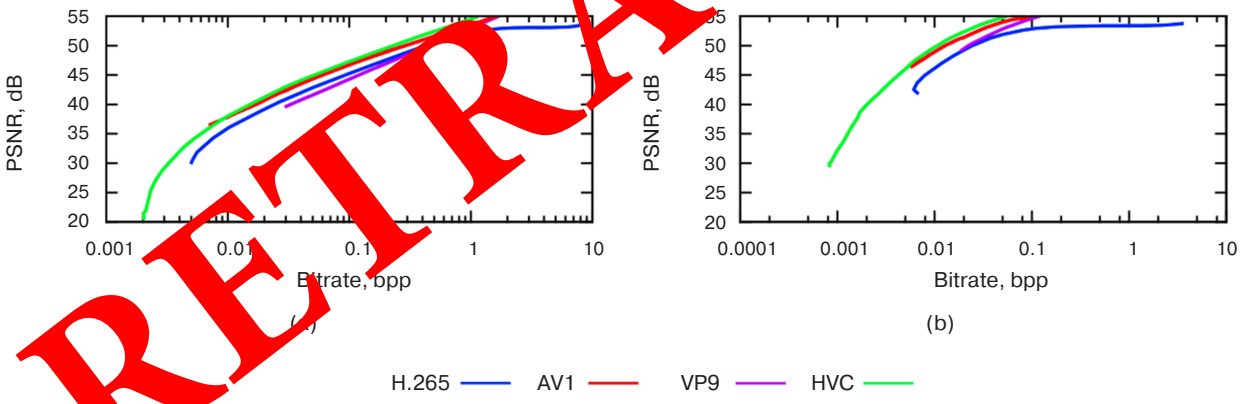

Fig. 7. Experiment 2: performance comparison of video compression methods. Fields used: (a) Danger de mort, (b) Chessboard

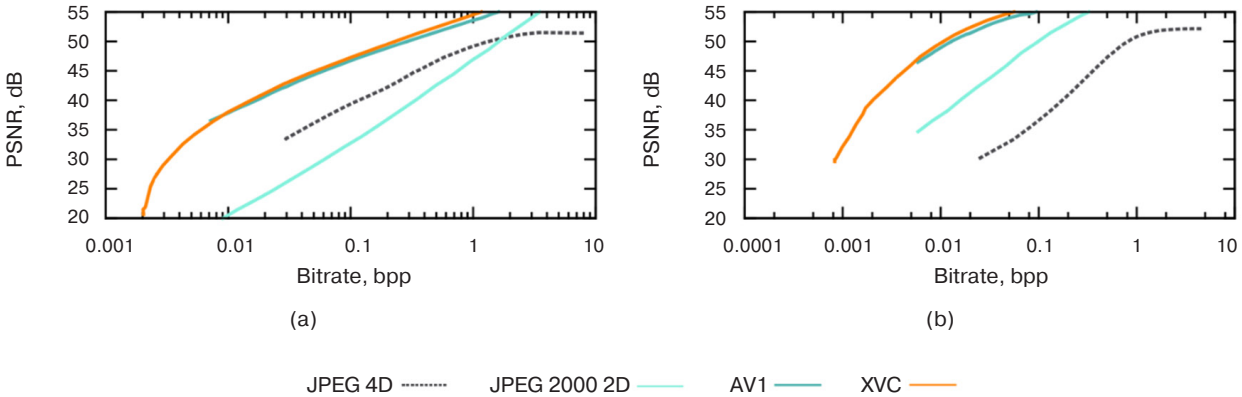

Fig. 8. Performance comparison of video compression methods in relation to image compression algorithms. Fields used: (a) Danger de mort, (b) Chessboard

four or three dimensions can achieve better compression results than classical implementations of 2D image compression.

However, it should be noted that the chosen evaluation criterion, namely PSNR, is affected not only by the dimension of the compression algorithm, but also by the baseline distance, since the difference between images increases with the distance between the optical centers of each camera matrix. Thus, for installations consisting of an array of machine vision cameras located on racks and placed in a room, the obvious choice would be to use conventional image compression methods.

In addition, based on the evaluation of the arbitrariness of video compression methods, we can see that the XVC algorithm remains underestimated, although its results are higher. Algorithm AV1 can be considered the next in order of importance. This confirms the fact that the latest compression algorithms show a higher performance in relation to their predecessors.

Also, when the distance between the optical centers of the captured images is small, the use of video compression algorithms is preferable to the use of image compression algorithms, since they show better results in both three-dimensional and four-dimensional versions.

Authors' contributions

R.G. Bolbakov—idea, development of research design, consultation on the problems of carrying out all the stages of the study.

V.A. Mordvinov—analysis of scientific work, revision with the contribution of valuable intellectual content.

A.D. Makarevich—literature analysis, article writing, research planning; carrying out all stages of the study, formalization of the list of references.

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RESEARCH ARTICLE

Designing modules of system dynamics in decision support systems

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Abstract

Objectives. When creating models of system dynamics, the basic construct at the design stage is the representation of the process under study in terms of a causal relationship consisting of a positive feedback loop and a negative feedback loop. The construction of a model of a dynamic environment can experience a number of difficulties in using feedback. This work shows the possibility of designing modules of system dynamics for decision-making systems based on the situational-activity approach. The study proposes the gap in knowledge about models of system dynamics to be filled with a conceptual model of an act of activity, by means of which an expert system can be implemented based on production rules. In this context, conceptual models are applied to human reasoning with reference to certain types of activity. The objective of the study was to investigate the possibility of applying the situational-active approach to designing models of system dynamics of infectious diseases based on particular representations of the conceptual structure of the act of activity.

Methods. By synthesizing Bolotova's situational algorithm and Shchedrovitskiy's system-activity approach, the conceptual structure of the act of activity is presented as a methodology of the situational-activity approach. The analysis of this structure leads to the construction of a plan of processual structure and a plan of analytical relationships. The article proposed a hypothesis that the process representations describe the notation of flows and levels, and the analytical relationships implement differential equations. In order to prove this hypothesis, the subject area of infectious diseases was investigated.

Results. Based on the set of these plans, a graphic image was synthesized for constructing models of system dynamics, which is identical to the diagram of flows and levels of development of the SIR process. However, the problem of constructing conceptual structures is nontrivial, complex, and laborious. Therefore, the Designer–Solver–Interpreter software suite was implemented. The software tools enable a visualization of the conceptual structures and implementation of the knowledge bases for expert models of system dynamics. It also tests the completeness and viability of the model.

Conclusions. To date, there is no single conceptual structure for designing expert systems and situational and simulation dynamic models. The proposed method and software tools allow these problems to be resolved using the situational-activity method. Various types of dynamics in expert systems interact, thus confirming the reliability of knowledge in the models of system dynamics. The conceptual structures of the act of activity are the core part of designing expert systems, while he derivative process and analytical representations of the act of activity are the core part of developing modules of system dynamics.

Keywords: situational-activity approach, conceptual structure of an act of activity, process representations, analytical representations, models of system dynamics

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НАУЧНАЯ СТАТЬЯ

Проектирование модулей системной динамики в системах поддержки принятия решений

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Резюме

Цели. При проектировании моделей системной динамики базовым конструктом стадии проектирования является представление исследуемого процесса в терминах причинно-следственной связи, состоящей из петель положительной и отрицательной обратной связи. При построении модели динамической среды возникает ряд трудностей использования обратной связи. Настоящее исследование показывает возможность проектирования модулей системной динамики для систем поддержки принятия решений на основе ситуационно-деятельностного подхода. Предполагается восполнить нехватку знаний о моделях системной динамики концептуальной моделью акта деятельности, с помощью которой может реализоваться экспертная система на основе продукционных правил. Концептуальные модели при таком аспекте применяются к человеческим рассуждениям с привязкой к определенным видам деятельности. Целью работы является исследование возможности применения ситуационно-деятельностного подхода для проектирования моделей системной динамики инфекционных заболеваний на основе частных представлений разработанной концептуальной структуры акта деятельности.

Методы. На основе синтеза двух подходов – ситуационного, предложенного Л.С. Болотовой, и системно-деятельностного, предложенного Г.П. Щедровицким, представлена концептуальная структура акта деятельности как методика ситуационно-деятельностного подхода. Анализ данной структуры приводит к построению процессуального плана и плана аналитических закономерностей. Была проверена следующая гипотеза: процессные представления описывают нотацию потоков и уровней, а аналитические закономерности реализуют дифференциальные уравнения. Для доказательства гипотезы исследовалась предметная область инфекционных заболеваний.

Результаты. На совокупности данных планов синтезирован графический образ для построения моделей системной динамики, который идентичен диаграмме потоков и уровней развития SIR-процесса. Однако задачу построения концептуальных структур следует признать нетривиальной, сложной и трудоемкой. Поэтому реализован программный комплекс следующего состава: «Оформитель», «Решатель» и «Интерпретатор». Программный инструментарий позволил визуализировать концептуальные структуры и реализовать базы знаний для экспертных моделей системной динамики, а также провести исследования на полноту и адекватность модели.

Выводы. На сегодняшний день не существует единой концептуальной структуры для проектирования экспертных систем, ситуационных и имитационных динамических моделей. Предложенный в работе метод и программный инструментарий позволяет решить данные задачи на основе ситуационно-деятельностного метода. Таким образом, осуществляется взаимодействие различных видов деятельности в экспертных системах, тем самым подтверждается достоверность знаний в моделях системной динамики. Концептуальные структуры акта деятельности являются ядерной частью при проектировании экспертных систем, а производные процессные и аналитические представления акта деятельности являются ядерной частью при разработке модулей системной динамики.

Ключевые слова: ситуационно-деятельностный подход, концептуальная структура акта деятельности, процессные представления, аналитические представления, модели системной динамики

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PROBLEM STATEMENT

The value of the decisions made depends on the reliability and completeness of the data used. At the same time, the activity in a highly dynamic environment is intense and tends to independently choose its own state. Acts of activity also impose requirements on the decision-making system. The objects of acts of activity in situations of a dynamically changing environment and the need to make a managerial decision are controlled by their states. These states, in turn, are determined by the definition of objectives by the controlling object. If there are sufficient controlling actions in the system, then there is uncertainty in the dynamics of processes, favoring a simplified perception of reality and an emotional solution to a complex control problem [1]. A situation arises in which the sequence and relationships of actions in the decisions being made are impossible to identify. Therefore, the hypothesis of the behavior of a complex object controlled by several controlling actions needs to be defined, on this basis, the process of change in the object with various variants of solutions to be simulated [2].

A simulation model is defined by a logical-algorithmic description of the behavior of a complex object and includes continuous and discrete states. The discrete model consisting of conventional functional blocks, can be characterized by an average level of abstraction, and is implemented using the structured analysis and design technique (SADT) or function modeling (IDEF0) methodology. The continuous modeling supports all levels of abstraction and is written in the unified modeling language (UML), mainly, state and activity diagrams.

In the simulation model, there is a high level of abstraction, referred to as system dynamics. Real-world processes in the system dynamics are represented in terms of information and flows between levels and storages, while their formal basis is represented as flow rate equations using dynamic processes in the state space. The idea of changes by feedback loops is one of the most important in determining the structure of the system dynamics. This led to the creation of tools for constructing causal (feedback) loop diagrams (CLDs). The graphical model obtained by the modeling process is, in fact, a diagram of links, reflecting the relations between elements of the system modeled as a CLD. If a change in the cause entails a similar change in the effect, then such a relationship is called positive. However, if the change in the cause causes the opposite change in the effect, then the relationship is called negative, so the correctness of the model mainly depends on the correct definition of the role of the CLD. This process without a conceptual study is laborious [3].

Knowledge representation models are similar in expert and situational systems. A frequent tool for situational modeling is the use of simulation models. This means that the language of situational design must include certain tools of modeling languages.

INVESTIGATION OF THE STAGE OF DESIGNING MODELS OF SYSTEM DYNAMICS

Models of system dynamics comprise two main stages. The first of them is called “qualitative,” the implementation of which takes into account the relationships of elements of the system and also the structure of the problem itself. Here, the basic construct of the system is the process diagram, consisting of a positive feedback (“+”) and a negative feedback (“–”) with the corresponding notation of their polarities (Fig. 1).

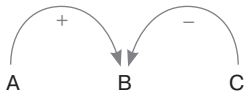

Fig. 1. Polarities of relationships

The second stage is called "quantitative." When it is implemented, the correctness and reliability of the model are checked, as are the scenarios of the behavior of the system under various conditions [4].

If two negative relationships are connected in series, they form a positive relationship. In turn, causal relationships (CRs) can form a loop that is unidirectional and closed. It can be either positive feedback (PF) or negative feedback (NF).

The rules for determining the polarity of a feedback loop in a generalized form state that the absence or an even number of CRs therein makes it a PF loop, while an odd number of negative CRs makes it an NF loop.

The dynamic nature of the modeled environment can give rise to difficulties. For example, if the system is sufficiently complex, then there may simultaneously be both several PFs and several NFs, while the causes of dynamic changes in the environment can be difficult to achieve in the model. Note also that only the CRs that are understandable without any additional actions need to be determined. An important role is also played by the objectification of the feedbacks that incorrectly reflect the objective reality of the problem [5].

The CRs of the model enable the quantitative stage of modeling the dynamic system to be determined, thus making them the main tool for designing flows and levels of systems. The elementary units of the system are levels, decisions (of a functional type), information flows, and material flows (Fig. 2).

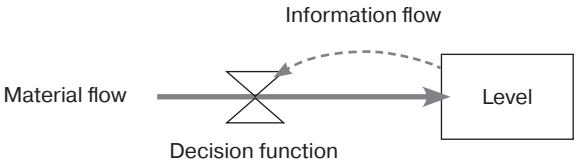

Fig. 2. Structure of the quantitative stage

Levels have a clear time dependence and denote a certain variable (at a particular point of time), while their content can be completely heterogeneous. Mathematically, the level value at a certain point of time is equal to the sum of the level value at the previous point of time, while the product of the rate of change in the level value and the increment of time. The rate of change in the level value is the difference between the rates of the incoming and outgoing flows. Figure 3 presents a model of the levels.

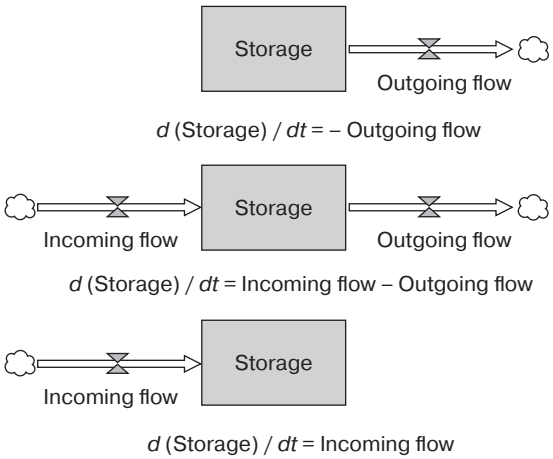

Fig. 3. Simulation dynamic model of the levels

If the equations of the levels allow the value of a certain level to be determined at the current point of time from its value at the previous point of time, then the rate equations are predictive, i.e., can predict the values at the next point of time [6].

In the problem of predicting the rates, it is important to take into account not only the direct, but also the indirect factors of influence, e.g., time, as well as the information flow.

A single experiment may be sufficient to obtain results from the decision space. However, a comprehensive study of the environment requires a certain set of experiments, which may ensure the variability of decisions for the decision maker.

DESIGNING MODELS OF SYSTEM DYNAMICS BASED ON THE SITUATION-ACTIVITY APPROACH

According to the methodology of the situational-activity approach, the types of activities that exist in the complex dynamic environment need to be determined, thereby defining the boundary of the validity of the selected subject area. Imagine, e.g., a dynamically complex environment "Combating infectious diseases," in which there are many activities (Fig. 4) [7].

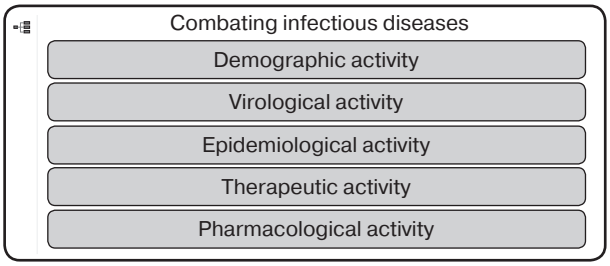

Fig. 4. Numerous activities in a dynamic environment

The structuring of an activity enables certain types of the activity to be identified. This in turn, makes it possible to transition to another activity within the selected type by a logical (formal) analysis. In the structure created,

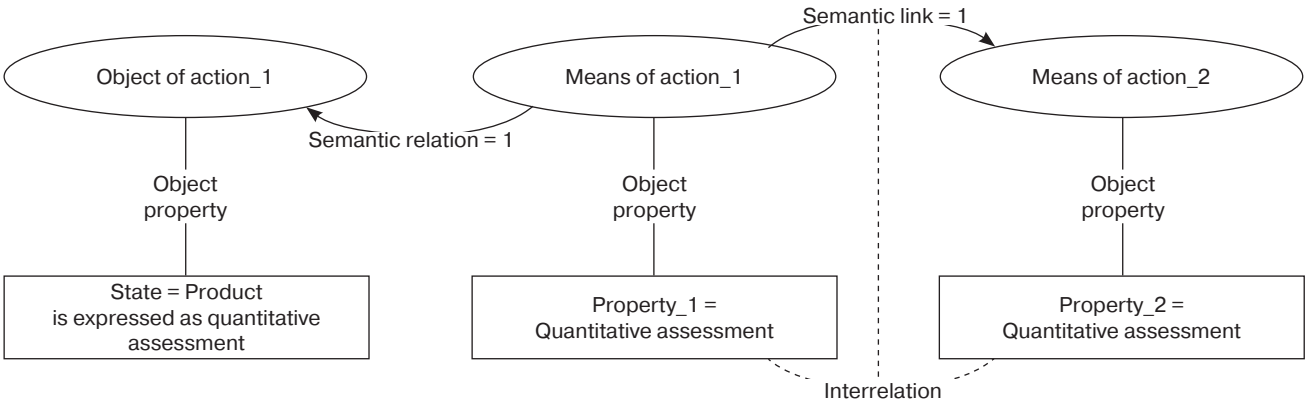

Fig. 5. Structure of the plan of relationships

the fundamental unit is an act of activity, which does not limit the researcher in identifying any other units that depend on the setting of objectives and problems [8, 9].

From the conceptual structures of acts of activity, four different contents of the act of activity can be defined: a plan of functional structure, a plan of processual structure, a plan of context, and a plan of analytical relationships [10]. These plans are expressed in a single structure which combines them into a single whole. Not only does not this create contradictions, but also it allows them to be applied both in parallel and in series [11, 12]. In view of the above, the main subject of this work is the plan of processes and relationships of the dynamic simulation model.

The planning of processes is determined by the processes themselves, the objects involved in them, the states of these objects, and the means by which the system reaches its objective state [13].

The planning of relationships is determined by the set of objects and the set of relations between them, and also by the properties of the objects and the relationships between them (Fig. 5).

The plan of relationships is implemented in accordance with the following rules:

- the state of the object of action is equal to the product (production element) expressed by the quantitative assessment and is associated with the decision;
- the properties of the means of action are equal to the quantitative assessment and are associated with the parameters defined in the structure of the equations;
- the relations must be unidirectional, and the relations of the type of "$a > b$ by x," "$a < b$ by x," "$a > b$ by a factor of x," and "$a < b$ by a factor of x" (where x is a real number greater than one, and a and b are some signs of comparison of objects or relations of objects of the subject area) should be indicated using the corresponding arithmetic operations;
- objects of relationships of the "increase" type should be denoted by the plus sign; of the "decrease" type, by the minus sign; and "define," by the equals sign.

A variety of representations of the sequence of arithmetic operations in the models of system dynamics is formed due to the plan for defining relationships for its further application in the differential equations of the corresponding models.

SOFTWARE SUITE FOR THE IMPLEMENTATION OF DYNAMIC MODELS OF DECISION SUPPORT SYSTEMS

The conceptual modeling of a subject area (SA) requires the specialist to understand the methods of analyzing situations, activities, and processes occurring in a given SA [14]. In particular, there is a range of assignments that can only be performed using software that can:

1) represent concepts (as elements of sign systems);
2) check the completeness and consistency of systems;
3) generate databases.

As part of the first assignment, we developed the Designer application, which performs the following tasks [15]:

- creates objects based on standard geometric shapes (primitives);
- implements links between objects;
- edits text of elements of the model;
- scales the model.

Tasks 2 and 3 are solved using the Small Problem Solver (SPS) application designed especially for situational analysis. SPS supports the following functions [15]:

- creation, storage, modification and testing of the model, and also verification of the correctness of production knowledge bases (KB) consisting of a working database (WDB) and a rule base (RB);
- logical conclusion;
- creation of reports on the analysis of problem situations and on the achievement of objective situations.

The functionality of the SPS is determined by its architecture (Fig. 6).

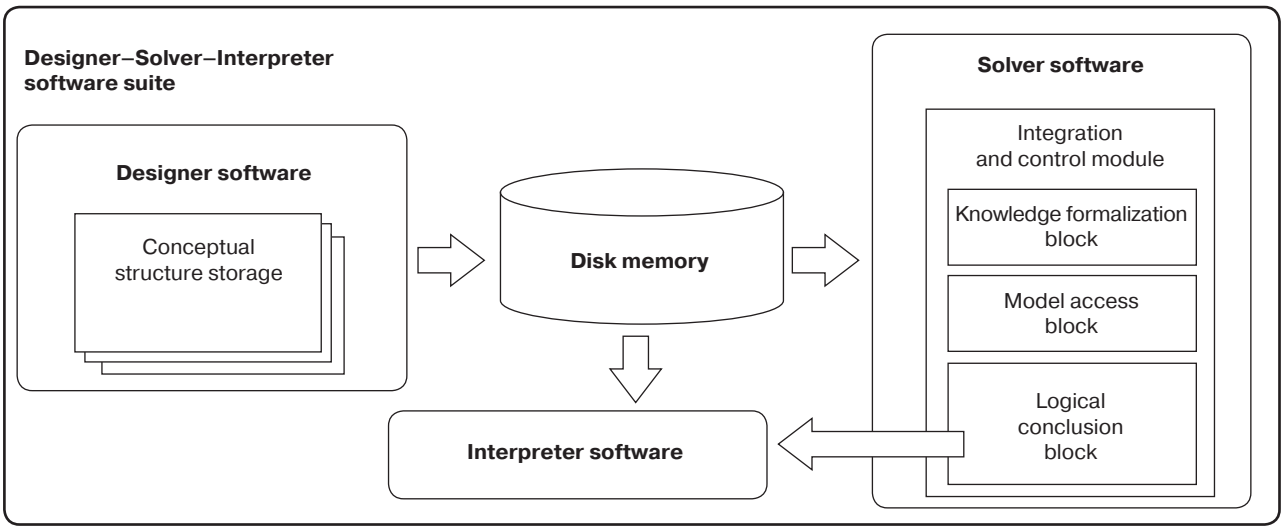

Fig. 6. Designer–Solver–Interpreter software suite and the SPS architecture

Thus, the following sequence in the operation of the Designer–Solver–Interpreter (DSI) software suite can be defined. When a file is saved in the Designer program, an XML file is created with the markup of a graphical model. Then this file is opened by the SPS, and the program using its own application programming interface (API) reads information from a file. It writes it to its knowledge base, checks the model for syntax errors, and informs the user about the loading result. The next step is to check the knowledge base for completeness and consistency. Initial values are set in the editors of objects, relationships, conflict resolutions, and objective situation, after which the situation is checked in the Description/Analysis section.

The knowledge base consists of WDB and RB, which contain the model elements and the names of rules and products.

Products have a left side (precondition), which is a set of the values of properties and relations that are required to activate the rule, and a right side (postcondition), which is a set of the values of properties and relations that that these properties and relations take after the rule is executed.

In essence, the Interpreter is an API receptor for the perception and translation of XML files of a graphical model of the concept of the subject area. Its structure includes:

- a parser which searches for data in the XML markup using certain pointers (tags);
- a lexer which translates the data located in the places labeled by the tags into a form understandable by the SPS.

Upon completion of the transformation and transmission of data by the lexer, the main stage of the operation of the SPS begins. After setting the initial conditions for the properties of objects and relations, the initial situation, and the conflict resolution strategies, a logical conclusion is attained from the RB in accordance with the production rules. The report obtained as a result of the operation of the SPS allows the researcher to understand the degree of correctness of the conceptual model of the subject area which he or she constructed. This is because the SPS not only can create a basic initial situation but it also allows the researcher to modify it by changing the initial objects, properties, relations, and rules and adding additional ones.

In the act of conflict situations in the modeled system, or if these conflicts were intentionally created by the researcher, there are two main ways of resolving them [16]:

- prioritization of production rules in the rule editor with subsequent assignment of top priority to a conflict resolution strategy;
- definition of conflict resolution strategies other than prioritization, e.g., “getting closer to the objective,” “not creating cycles,” etc.

The optimal solution for the conflicts created intentionally when designing the conceptual model is to set priorities. The highest priority should be defined by the rule which is related to the most important factor, e.g., human life. If the conflicts are related to errors made at the design stage, then the SPS user can manually change the products in the rule editor. This provides for the possible branching when the model is implemented under changed initial conditions.

In general, it is recommended that at least three problem situations be checked for:

(1) all the conditions of the problem situation should correspond to the initial logic of the graphical model (no changes are made to the initial conditions);
(2) for one (or several) key properties, the value of which changes during the actions of the model, the values to be reached in the course of the

operation (state changes in accordance with the knowledge base) of the model need to be set. Thus, the result of the operation of the SPS needs to be checked, in order to verify that it converges with the logic (which the researcher assumed) of the model;

(3) one (or several) properties need to be set to such values that the logic of the model is broken or does not work at all. This makes it possible for the correctness of the model to be verified under impracticable and contradictory conditions.

Thus, the main purposes of the DSI software suite are [16]:

- to construct a conceptual model of the subject area of the problem considered by the researcher;
- to convert the model from the graphical model to a software one, common for most actual applications;
- to analyze the program model for possible problem situations using a formal theory.

Summarizing all of the above, it can be stated that the DSI allows the researcher to create a conceptual model of the subject area under investigation and to understand how true and complete this model is, i.e., whether the logic embedded in the model works from the point of view of program logic (and from the point of view of formal theory), and whether the model provides for all kinds of situations and their consequences.

CONCLUSIONS

The experience and practice of creating decision support systems (DSSs) show that, to date, there is no single conceptual structure of a knowledge base for the implementation of intelligent modules, and also the software that supports the situational-activity approach. The absence of such a single structure indicates that, at present, there is at least one problem in decision support. The situational-activity approach allows systems that are complex in terms of dynamics to be studied efficiently, in order to create simulation models, models of expert systems, as well as other intelligent DSSs.[1]

A set of conceptual structures are defined as a certain elemental composition, which when synthesized enable the construction of intelligent DSSs. Given that the knowledge of a complex dynamic environment based on the conceptual structures of the situational-activity approach is the key to designing intelligent modules, there are several potential directions for development: as a language for understanding and modeling, as well as a tool for identifying a knowledge base.

Authors' contribution. All authors equally contributed to the research work.

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RESEARCH ARTICLE

Photonics-based modular multistate digital coherent system

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Abstract

Objectives. The study aimed to develop interspecies and interclass methods for constructing coherent radio engineering systems based on a modular complementary structure.

Methods. A set of modules and submodules having no narrow specialization and together constituting a flexible broadband hardware-reconfigurable software-defined radio engineering structure is considered as the basic set for constructing a digital radio photonic system path. Due to their broadbandness and complementary structure, modules and submodules have many applications both as self-sustained devices and as part of more complex systems.

Results. Functional diagrams of modern digital receiver-shapers, as well as modules for amplifying radio frequency signals and converting radio frequency signals into an optical signal are presented along with a radio photonic synchronization network for generating clock signals. Calculations of the introduced phase error of a quartz single-mode fiber and graphs of the dependence of the change in the signal phase on external influencing factors are given. A concept for integrating the presented modules into the construction of a modular transceiver multiposition wideband coherent digital radio photonic system is proposed. The results of calculating radiation patterns and mathematical modeling the beam deflection of a broadband antenna array are presented along with antenna systems based thereon.

Conclusions. The proposed circuit design solutions allow the time required for developing new types of systems to be significantly reduced due to the range of ready-made technical solutions. Not only are the parameters of the developed devices comparable to the best world analogues, but they also surpass existing solutions in terms of system integration. The developments have been tested under R&D project at the Kaluga Scientific Research Institute of Radio Technology and Hardware Solution Technologies (TAR). The proposed solutions are integrated at the subsystem level into advanced developments of products for civil and special purpose. Further development of the concept of building ultra-wideband devices allows reaching a new level in the technology of constructing modular multiposition coherent digital radio photonic systems.

Keywords: digital antenna arrays, radar, active phased antenna array, laser, photodiode, digital-to-analog converter, analog-to-digital converter, digital beamforming

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НАУЧНАЯ СТАТЬЯ

Модульная многопозиционная когерентная цифровая радиофотонная система

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Резюме

Цели. Разработка межвидовых и межклассовых способов построения радиотехнических когерентных систем на основе модульной дополняемой структуры.

Методы. В качестве базового набора для построения тракта цифровой радиофотонной системы предлагается рассмотреть комплекс модулей и субмодулей, не имеющих узкой специализации и в совокупности составляющих широкополосную гибкую аппаратно-реконфигурируемую программно-определяемую радиотехническую структуру. Благодаря широкополосности и дополняемой структуре модули и субмодули имеют множество применений, как в качестве самостоятельных устройств, так и в составе более сложных систем.

Результаты. Представлены функциональные схемы современных цифровых приемников-формирователей, модулей усиления радиочастотных сигналов, модулей преобразования радиочастотных сигналов в оптический сигнал, радиофотонной синхросети формирования тактовых сигналов. Приведены расчеты вносимой фазовой ошибки кварцевого одномодового волокна и графики зависимости изменения фазы сигнала от внешних воздействующих факторов. Предложена концепция интеграции представленных модулей и построения модульной приемо-передающей многопозиционной широкополосной когерентной цифровой радиофотонной системы. Приведены расчеты диаграмм направленности и результаты математического моделирования отклонения луча широкополосной антенной линейки. Показаны антенные системы на ее основе.

Выводы. Предложенные методы позволят существенно сократить сроки разработки новых типов систем за счет линейки готовых технических решений. Разработанные устройства обладают параметрами, не уступающими лучшим мировым аналогам, а в рамках интеграции в систему позволяют превзойти существующие решения. Апробирование разработок проведено в рамках НИОКР на базе АО «Калужский научно-исследовательский радиотехнический институт» и ООО «Технологии аппаратных решений». Предложенные решения интегрированы на уровне подсистем в перспективные разработки продукции гражданского и специального назначения. Дальнейшее развитие концепции построения сверхширокополосных устройств позволит достигнуть нового уровня в технологии построения модульных многопозиционных когерентных цифровых радиофотонных систем.

Ключевые слова: цифровые антенные решетки, радар, активная фазированная антенная решетка, лазер, фотодиод, цифроаналоговый преобразователь, аналогово-цифровой преобразователь, цифровое диаграммообразование

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INTRODUCTION

Digital antenna arrays (DAAs) in communication systems are increasingly used in radar systems (RSs), as well as for various civil and special purpose systems. Along with general development trends in electronics and the component base, the constant increase in operating frequencies and bandwidth of modern communication systems including RSs results in the displacement of traditional active-phased antenna arrays (APAs). As well as fiber optic networks for frequency transfer allowing synthesized signals to be converted to any spectral range, analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) support direct digital beamforming (DBF) across a wide frequency band [1, 2]. Works [3–9] further develop the idea of constructing ultra-wideband (UWB) devices.

The paper aims to develop interspecies and interclass methods for constructing radio engineering coherent systems based on a modular supplemented structure to achieve a new level in the technology of constructing modular multiposition coherent digital photonic systems.

FUNCTIONAL STRUCTURE OF THE DIGITAL RADIO PHOTONIC SYSTEM PATH

A set of modules and submodules having no narrow specialization and together constituting a broadband flexible hardware-reconfigurable software-defined radio structure is considered. Due to their broadbandness and complementary structure, the modules and submodules have many applications both as self-sustained devices and as part of more complex systems.

This system may include the following components: basic digital module (BDM), submodule for direct radio frequency (RF) signal amplification (SRFA), submodule for optoelectronic frequency conversion (SOFC), auxiliary module for controlling and powering submodules, photonic synchro network (PSN), and wideband phased antenna arrays.

The basic digital module, which comprises a self-sustained receiving and transmitting device, is designed for the digital processing and synthesis of RF signals across a wide frequency range. The functionality of the basic digital module can be extended by installing additional submodules. Generally, it is proposed to include the following: two-channel ADC and DAC, programmable logic device (PLD), digital signal processor (DSP), low-noise amplifiers (LNA), controlled attenuators (At), set of switches (S), bandpass filters (BPF), and input signal quadrature processing circuit via a dual ADC containing switches and directional dividers (D). The block diagram of such a basic digital module is shown in Fig. 1.

The SRFA is designed for amplifying the received and transmitted signals as well as switching antenna inputs for receiving and transmitting. The block diagram of the submodule is shown in Fig. 2.

The SRFA consists of receiving and transmitting paths. A switched control signal path and transmitter channels with integrated directional dividers were used for self-monitoring. In functional terms, the SRFA comprises directional dividers, directional couplers, controlled attenuators, low-noise amplifiers, power amplifier stages, switches, and limiters (LIM). The submodule was installed on a printed circuit board (PCB) of the basic digital module in which the standardized circuit of submodule power supply and information exchange channel with end-to-end control protocol and initialization of submodules were organized.

The SOFC comprises a four-channel bi-directional (2 × 2) submodule for optoelectronic and electrooptical frequency conversion of broadband signals synthesized and digitized by transceiver channels of the basic digital module. The SOFC spaced-apart modules were coupled. The SOFC receiving channel consists of a photonic LNA, an optical modulator performing additional modulation by local heterodyne signal, and an output photodetector for converting the optical signal into RF signal. The transmission channel was intended for converting RF signal to the optical band and transmitting the signal to the receiver of the spaced-apart coupled SOFC through fiber-optic communication lines. The scientific, technological, and practical groundwork for implementing SOFC is based on research and development activities carried out by the company Hardware Solution Technologies (TAR) under the project Development, Manufacture

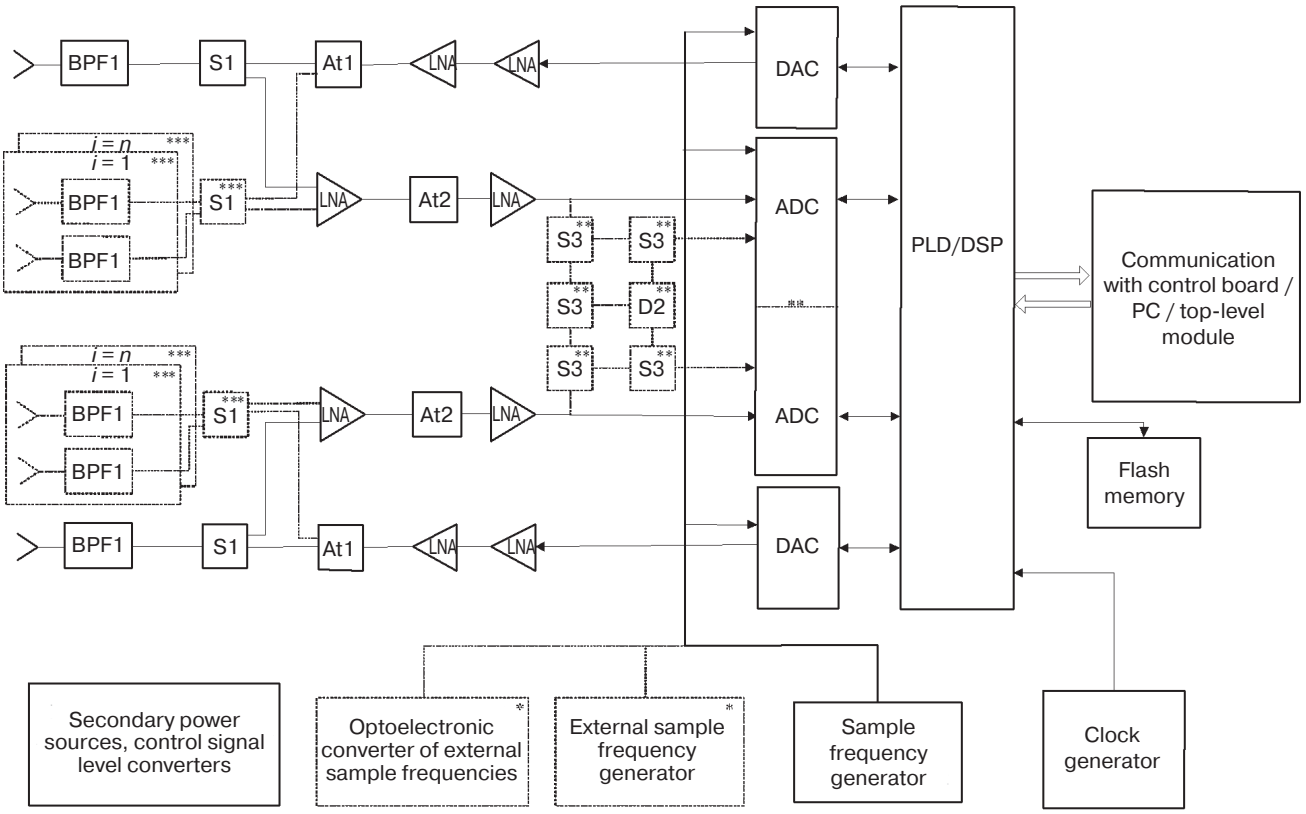

Fig. 1. BDM block diagram

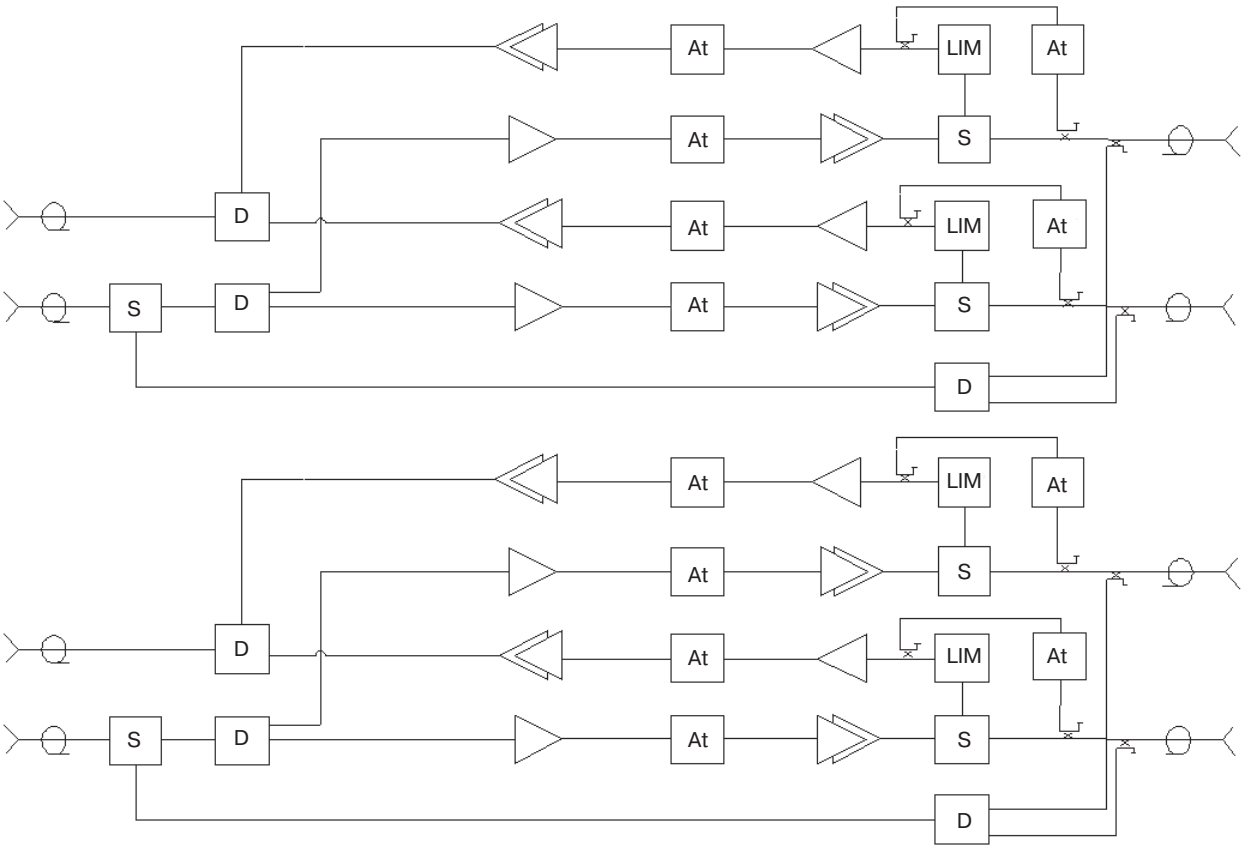

Fig. 2. SRFA block diagram

and Testing of a Prototype Photonic Transceiver[1, 2, 3] supported by the Foundation for Assistance to Small Innovative Enterprises in Science and Technology[4].

The SOFC block diagram is shown in Fig. 3.

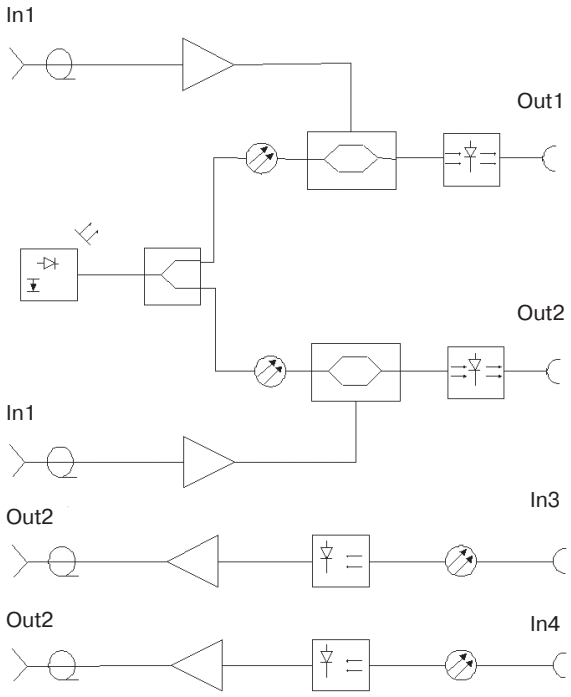

Fig. 3. SOFC block diagram

PHOTONIC SYNCHRO NETWORK

The photonic synchro network is intended for clocking a basic digital module using an optical sync signal. The characteristic feature of the proposed phase synchronization system for all ADCs, DACs and PLDs comprises using the use of a unified highly stable clock signal source distributed through single-mode fiber optic cables of equal electric length to reduce the impact of inherent noise in the clock source and common clock distribution circuits (up to the optical divider) on measuring errors in the received signal phase difference. The use of single-mode fiber can reduce losses in the transmission channel, as well as eliminating the influence of intermodal dispersion, resulting in signal distortion and fiber optic bandwidth reduction on the signal[5]. The PSN structure including a master oscillator and two spaced-apart ADC radioelectronic modules is shown in Fig. 4.

The clock signal generator produces ADC clock frequency f_1 (S-band), signal processor clock frequency f_2 (for fast-acting ADC, usually, $f_1 = 2if_2$, where $i = 1, 2, 4$), and ADC synchronization and reset pulse signals. To exclude the time divergence of these four signals, they are all transmitted through a single optical fiber several tens of meters long, while four frequency spaced lasers, optical spectral multiplexers, and demultiplexers are used for independent transmission and reception. Bandpass filters are installed after photodiodes in clock circuits, with no filtering required for the PLD (DRR) and ADC (ASYNC) reset signals.

In addition to phase noise, other sources of phase distortion in optical fibers include: temperature, vibration and acoustics, chromatic dispersion, polarization mode dispersion, and transient interferences [10]. Based on the data presented in [10], the introduced phase error was calculated. The calculation results are set out in the Table.

In the table, the following notation is used: n is the effective group refractive index of quartz fiber (typical value $n = 1.468$ for standard single-mode fiber SMF-28[6]); L is a fiber length (20 m for the considered system); c is the speed of light; ω_r is an angular frequency of S-band synchronous signal; T is temperature, °C; $(1/L)dL/dT$ is the coefficient of thermal expansion (typical value $5.6 \cdot 10^{-7}$/°C, 1/°C); dn/dT is the temperature coefficient of refractive index (typical value $1.2 \cdot 10^{-5}$, 1/°C; $[(1/L)dL/d\sigma]^{-1}$); $dn/d\sigma$ are Young's moduli (typical values by length and refractive index of fiber are $7.2 \cdot 10^{10}$ Pa and $-3.4 \cdot 10^{-12}$/Pa, 1/Pa, respectively); D is a chromatic dispersion coefficient (typical value 18 ps/nm·km); $\Delta\lambda$ is the wavelength difference between the optical carrier and components of the first order sidebands in the spectrum of the intensity-modulated optical signal propagating along the fiber, determined for C-optical range (1551–1563 nm) by the clock radio signal frequency in gigahertz from proportion 10 GHz ≈ 80 pm; D_{pmd} is the coefficient of polarization mode dispersion (typical value $0.1\ \text{ps}/\sqrt{\text{km}}$;) A_c is the relative level of transient interference appearing during multiplexing (value is ≈30 dB).

Thus, the phase synchronization system proposed in the paper is capable of distributing a single clock signal from one source to all ADCs at distance up

[1] *Development, manufacture and testing of a prototype photonic transceiver*: R&D report (interim), TAR, LLC. Director Unchenko I.V., executives: Emelyanov A.A., Unchenko I.V., et al. Maloyaroslavets, 2021. 48 p. Grant No. 121031900169-9. https://www.rosrid.ru/ikrbs/detail/MYS684SV1OP68CW4NR4SZHWO. Accessed June 01, 2022 (in Russ.).

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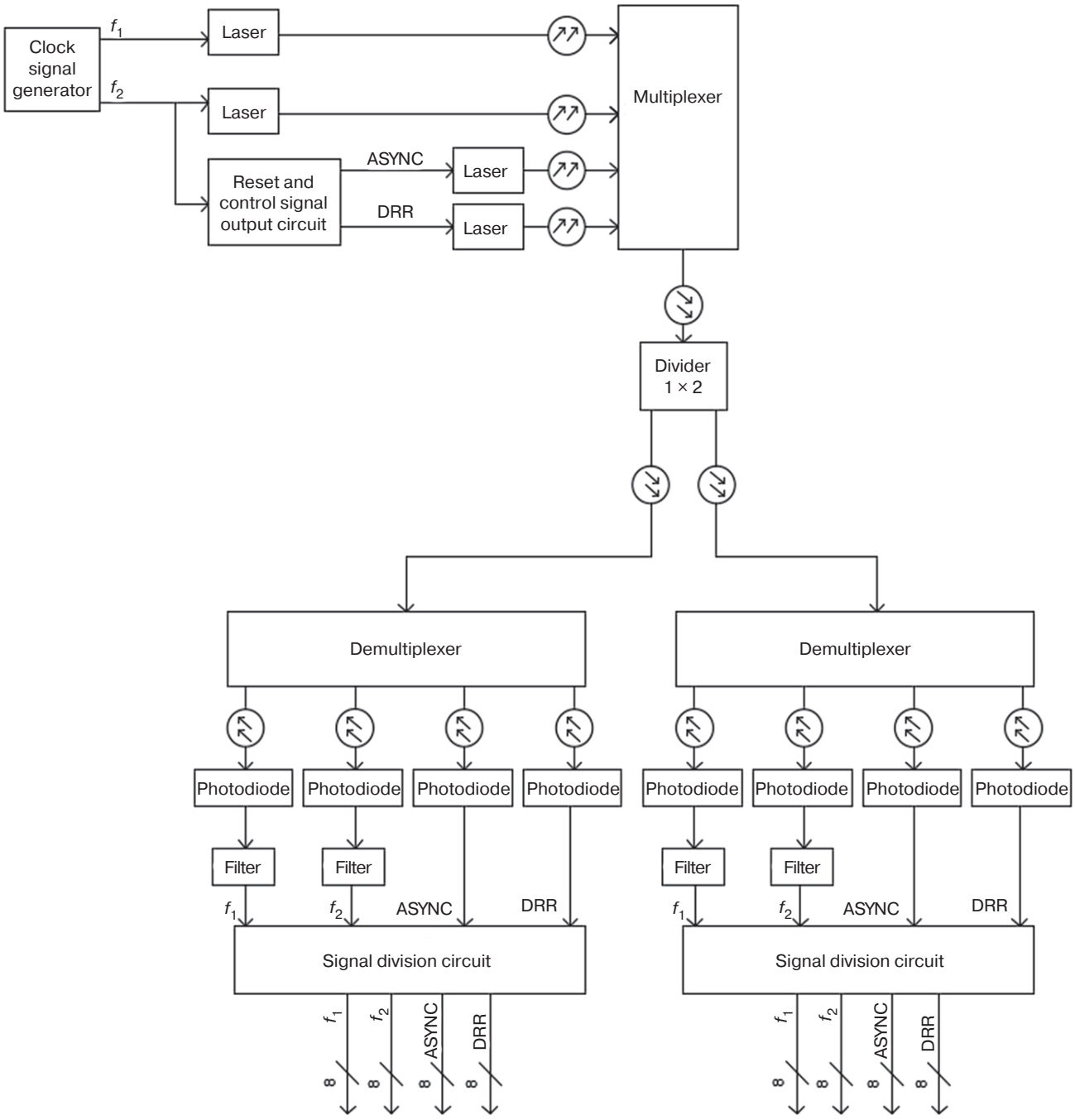

Fig. 4. PSN structure

Table. Calculation results for the introduced phase error

No.	Effect	Calculating formula	Calculated value
1	Temperature	$\frac{d\varphi}{dT} = \frac{\omega_r L}{c}\left(\frac{n}{L}\frac{dL}{dT} + \frac{dn}{dT}\right)$	Fig. 5
2	Vibrations and acoustics	$\frac{d\varphi}{d\sigma} = \frac{\omega_r L}{c}\left(\frac{n}{L}\frac{dL}{d\sigma} + \frac{dn}{d\sigma}\right)$	Fig. 6
3	Chromatic dispersion	$\Delta\varphi = \omega_r D L \Delta\lambda$	$1.1 \cdot 10^{-4}$ deg
4	Polarization mode dispersion	$\Delta\varphi = \omega_r D_{pmd} L^{1/2}$	$2.2 \cdot 10^{-4}$ deg
5	Transient interferences	$\Delta\varphi = \text{arctg}(10^{-A_c/20})$	1.8 deg

to tens meters, as well as transferring the reset and synchronization signals to processing devices. Here, the theoretical phase error of the processed signals, which would be no more than 1.8 deg, is primarily introduced by the signal multiplexing unit.

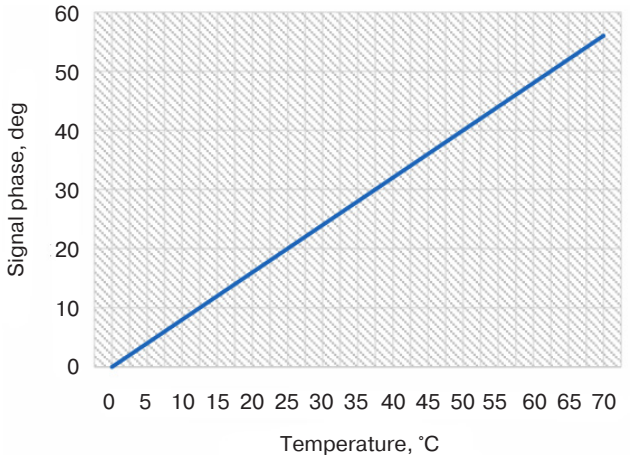

Fig. 5. Dependence of the signal phase change on temperature

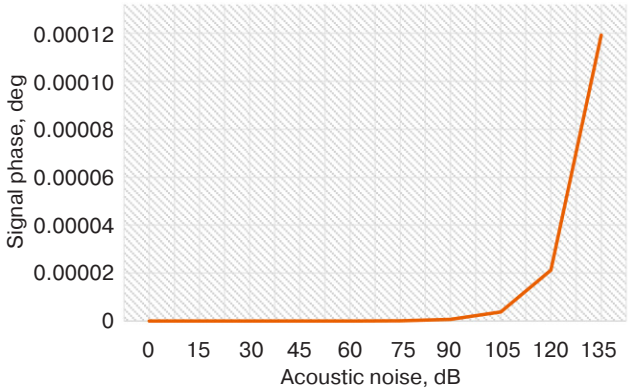

Fig. 6. Dependence of the signal phase change on the level of acoustic noise

DAA MODULAR ARCHITECTURE

The proposed solutions for constructing the synchronization system and integral path when using directional antennas with optimal step already comprise both self-sustained devices and the DAA element. The basic digital module and submodule for direct RF signal amplification may be integrated into DAA via the external interfaces of the basic digital module using solutions in the field of on-board computers and data processing centers. The main limitation for DAA extension is the bandwidth of the information exchange channel interfaces. In addition, maximum synchronization accuracy between the ADC and DAC is required for plotting the directional pattern and providing DAA electronic scanning. The DAA block diagram based on the modular architecture is shown in Fig. 7, where CLOCK1–CLOCK*n* comprise the PLD, while the ADC synchronizes and resets signals generated by the photonic synchro network.

The required values for phase distribution between channels are calculated depending on the antenna array (AA) design determining the directional pattern, the viewing angle, and the required number of beam positions. The eight-element antenna array based on the Vivaldi aerial shown in general in Fig. 8 is considered to plot the directional pattern for such system.

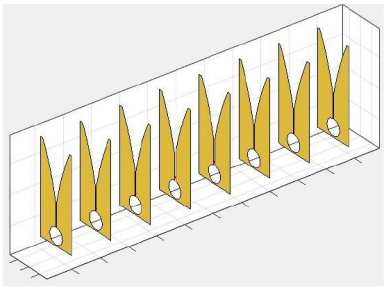

Fig. 8. General view of the antenna array

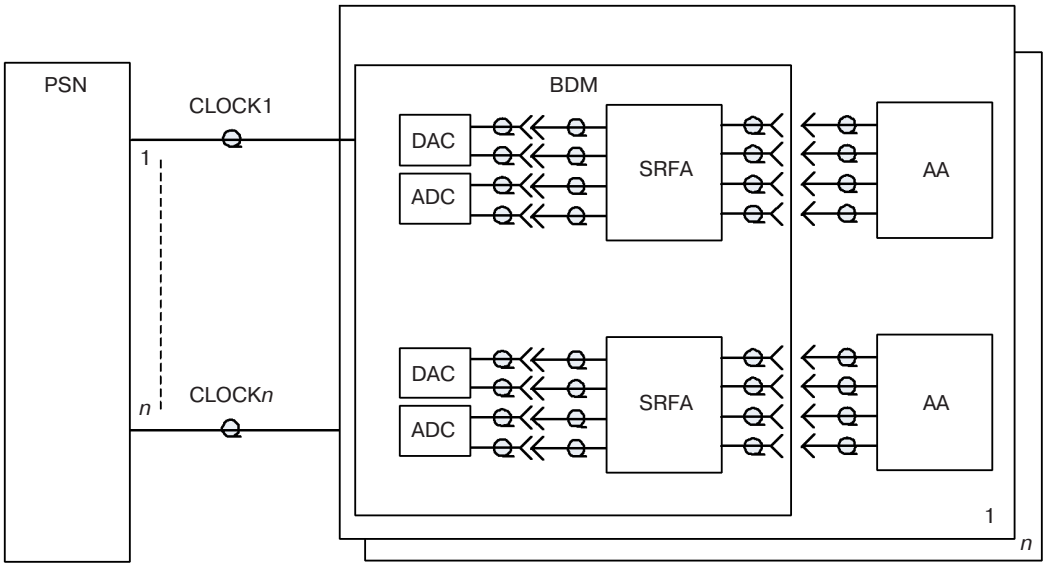

Fig. 7. DAA block diagram

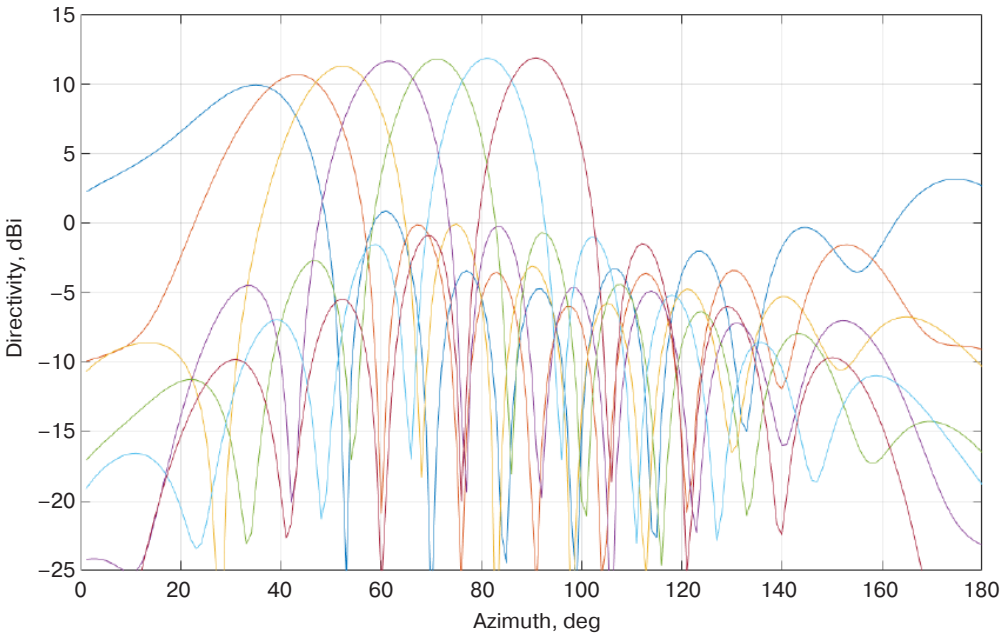

Fig. 9. Calculation results for AA directional patterns

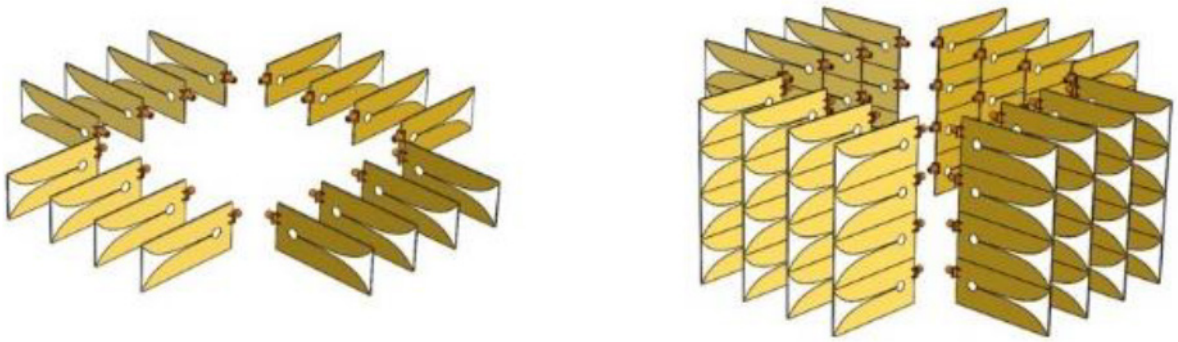

Fig. 10. DAA antenna systems

The modifications of wideband radiators based on symmetric slot lines (Vivaldi aerial) are widely presented in [11, 12]. DBF methods are described in [13–15], while beamforming options, APA scanning methods, as well as phase distribution calculations for such array, are given in [12, 13].

The calculated directional pattern and beam deflection of the eight-element AA are shown in Fig. 9.

The antenna systems constructed according to the DAA integration and scaling principle based on modular architecture, providing reception and transmission of signals in the range of angles 360° in azimuth and angular planes, are shown in Fig. 10. Each module is based on the Vivaldi type radiator having exponential aperture, one of whose advantages is broadbandness [16, 17].

CONCLUSIONS

The proposed circuit design solutions allow the time required for developing new system types to be significantly reduced due to the range of ready-made technical solutions. Not only are the parameters of developed devices equivalent to state-of-the-art analogues, but they also improve on existing solutions in terms of integration into the system. The developments were tested as part of an R&D project carried out at the Kaluga Scientific Research Institute of Radio Technology in partnership with TAR. The proposed solutions are integrated at the subsystem level into advanced developments of products for civil and special purpose.

Authors' contribution. All authors equally contributed to the research work.

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RESEARCH ARTICLE

Parameterization of user functions in digital signal processing for obtaining angular superresolution

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Abstract

Objectives. One of the most important tasks in the development of goniometric systems is improving resolution in terms of angular coordinates. This can be achieved in two ways: firstly, by increasing the aperture, which is very expensive and often technically challenging to implement; secondly, with the help of digital signal processing methods. If the recorded signal sources are located close to each other and not resolved by the Rayleigh criterion, it can be impossible to determine their number, location and reflection characteristics. The aim of the present work is to develop a digital signal processing algorithm for obtaining angular superresolution.

Methods. Mathematical methods for solving inverse problems are used to overcome the Rayleigh criterion, i.e., obtain angular superresolution. These problems are unstable, since there is an infinite number of approximate solutions and false targets may occur. The search for the optimal solution is carried out by minimizing the standard deviation.

Results. A description of a mathematical model for a goniometric system is presented. A signal processing algorithm is developed based on existing methods according to the principle of parameterization of user functions. Results of numerical experiments for achieving superresolution by algebraic methods are given along with an estimation of solution stability. The accuracy and correspondence of the amplitude of the obtained objects to the initial parameters are measured. The degree of excess of the Rayleigh criterion by the obtained solution is estimated.

Conclusions. Algebraic methods can be used to obtain stable solutions with angular superresolution. The results obtained correctly reflect the location of objects with a minor error. Errors in the distribution of the signal amplitude are small, appearing false targets have negligible amplitude.

Keywords: computer simulation, super resolution, object search, simulation model

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НАУЧНАЯ СТАТЬЯ

Параметризация пользовательских функций в цифровой обработке сигналов для получения углового сверхразрешения

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Резюме

Цели. Одна из важнейших задач развития угломерных систем – улучшение разрешающей способности по угловым координатам. Этого можно добиться двумя способами: во-первых, увеличением апертуры такой системы, что весьма дорого и часто технически трудновыполнимо; во-вторых, с помощью методов цифровой обработки сигналов. Если регистрируемые источники сигнала расположены близко друг к другу и не разрешаются по критерию Рэлея, то невозможно определить их количество, расположение и характеристики отражения. Цель работы – разработка алгоритма цифровой обработки сигналов для получения углового сверхразрешения.

Методы. Использованы математические методы решения обратных задач. Эти методы позволяют преодолеть критерий Рэлея, т.е. дают возможность получить угловое сверхразрешение. Данные задачи обладают неустойчивостью. Существует бесконечное количество приближенных решений, возможно возникновение ложных целей. Поиск оптимального решения проводится путем минимизации среднеквадратического отклонения.

Результаты. В статье приведено описание математической модели работы угломерной системы. На основе существующих методов разработан алгоритм обработки сигнала, использующий принцип параметризации пользовательских функций. Представлены результаты численных экспериментов по достижению сверхразрешения алгебраическими методами. Проведена оценка устойчивости решения. Измерены точность и соответствие амплитуды полученных объектов начальным параметрам. Проведена оценка степени превышения критерия Рэлея полученным решением.

Выводы. Показано, что алгебраические методы позволяют получать устойчивые решения с угловым сверхразрешением. Получаемые результаты правильно отражают расположение объектов с незначительной ошибкой. Ошибки в распределении амплитуды сигнала невелики, появляющиеся ложные цели имеют пренебрежимо малую амплитуду.

Ключевые слова: компьютерное моделирование, сверхразрешение, поиск объектов, имитационная модель

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Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Goniometer systems have many applications. The determining criteria for the implementation of such a system are accuracy and speed. There are various ways to obtain angular superresolution—the Capon method, the thermal noise method, MUSIC (MUltiple SIgnal Classification), ESPRIT (Estimation of Signal Parameters via Rotational Invariant Techniques), etc. Methods such as MUSIC and ESPRIT use narrowband signals and are inefficient when applied to broadband and ultra-wideband signals (UWB). Many of these methods are not sufficiently effective and universal, because at a signal-to-noise ratio of less than 20 dB, errors occur in the solution [1–8]. In addition, not all of the listed methods allow one to solve two-dimensional problems [9–11].

In this study, an algorithm for the approximate determination of the angular location of closely spaced targets has been developed. The algebraic methods considered in the article make it possible to obtain a solution with low computational costs. The presented algorithm has a high speed, which allows it to be used in real time. To assess the quality of the method, the degree of excess of the Rayleigh criterion by the obtained solution is measured.

PROBLEM STATEMENT

The model of the signal received by the surveillance system is a two-dimensional integral (1):

$$U(x,y) \coloneqq \int_{\Omega} F(x-q,y-r)I(q,r)drdq, \qquad (1)$$

where $F(x,y)$ is the radiation pattern (RP) of the observation system; Ω is the two-dimensional region of the source location; $I(q, r)$ is the angular distribution of the amplitude of the signal source, which is to be determined [12, 13].

The purpose of the study is to develop a digital signal processing algorithm for obtaining angular superresolution. To accomplish this, it is necessary to restore the angular distributions of the reflected signal amplitude from the measured signal $U(x, y)$ and the known characteristics of the goniometric system. This can be achieved through obtaining an approximate solution of the linear Fredholm integral equation of the first kind of the convolution type (1).

Obtaining angular superresolution using digital signal processing $U(x, y)$ is a solution to the inverse problem.

SOLUTION METHOD

The search for a solution to the inverse problem is carried out based on the parametrization [14, 15], when instead of the unknown function $I(q, r)$, the expansion of the desired distribution of amplitudes with respect to a given system of orthogonal functions is used. Then the solution can be represented in the form:

$$I(q,r) = \sum_{i=1}^{\infty} a_i g_i(q,r) \approx \sum_{i=1}^{N} a_i g_i(q,r), \qquad (2)$$

where a_i are unknown coefficients; $g_i(q, r)$ are functions specified by the user. The coefficients a_i can be found by minimizing the standard deviation of the solution in the region $\theta > \Omega$ from the original signal:

$$\delta^2 = \int_{\theta}\left[U(x,y) - \sum_{i=1}^{\infty} a_i \int_{\Omega} F(x-q,y-r)g_i(q,r)drdq\right]^2 dydx, \qquad (3)$$

where θ is the two-dimensional region of scanning.

To do this, the partial derivatives of δ^2 with respect to a_i are equated to zero. The result is a system of linear algebraic equations (SLAE) of N equations:

$$a = GV, \qquad (4)$$

where

$$G_{j,i} \coloneqq \int_{\theta} \psi_j(x,y)\psi_i(x,y)dydx,$$

$$\psi_i = \int_{\Omega} F(x-q,y-r)g_i(q,r)drdq, \qquad (5)$$

$$V_j \coloneqq \int_{\theta} U(x,y)\psi_j(x,y)dydx. \qquad (6)$$

Although the angular superresolution increases when using a larger number of functions $g_i(q, r)$, the dimension of the SLAE also increases along with the consequent instability of the solution, which manifests itself in the form of false signal sources and distortions in the resulting solution. This is due to the characteristic problem of inverse problems that minor changes in the initial data—for example, random variables (noise)—can lead to significant errors, i.e., instability. While low levels of noise in well-posed problems can lead to small errors in the solution, the resulting solution in inverse problems may differ from the true one by several orders of magnitude.

RESULTS OF NUMERICAL EXPERIMENTS

The resulting solutions of inverse problems were studied in the course of numerical experiments on mathematical models. The source objects and the received signal are shown in Fig. 1, where $\theta_{0.5}$ is the RP half-width. Three-point objects were specified. All objects are located sufficiently close to each other and are not resolved by the Rayleigh criterion.

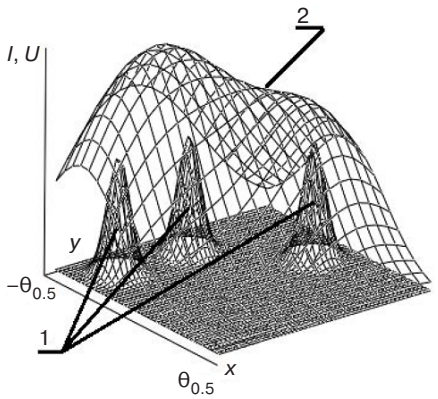

Fig. 1. Model of the received signal and the source objects:
1 – original objects; 2 – received signal

The form of the signal $U(x, y)$ does not allow objects to be observed separately, in particular, three original objects merge into one (mesh surface 2).

In order to search for a solution, nine functions $g_i(q, r)$ are specified to cover the entire region Ω under study, three of which are shown in Fig. 2.

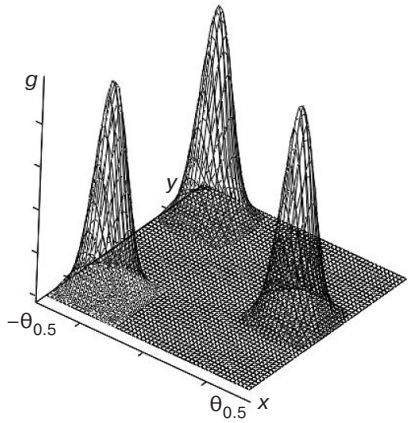

Fig. 2. View of three user-defined functions

The original objects and results of solving the SLAE system (4)–(6) are shown in Figs. 3a and 3b, respectively.

As a result of the experiment, a stable solution with angular superresolution was obtained. The angular coordinates of all three objects are determined with good accuracy, with the found amplitudes of the central and right object appearing close to the original (≈ 80%), while the amplitude of the left object is slightly lower than the original (≈ 60%). The resulting angular superresolution significantly exceeds the Rayleigh criterion (the angular distance between objects is 0.3θ).

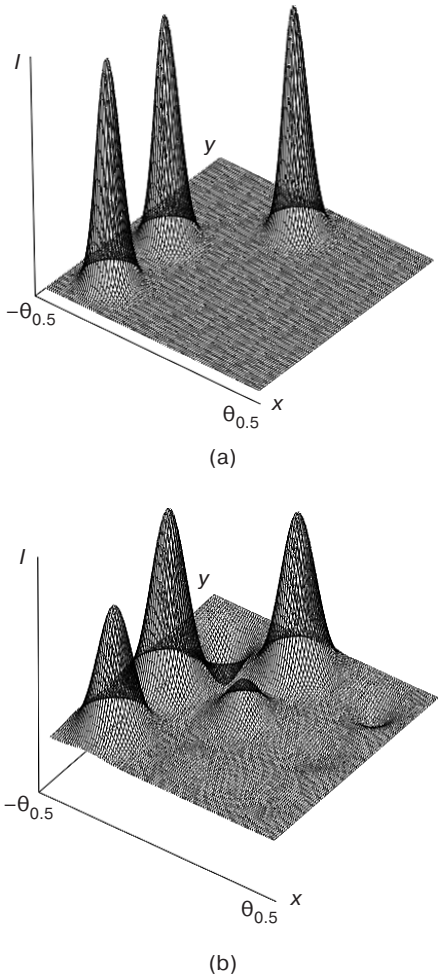

Fig. 3. Original objects (a) and result (b)

CONCLUSIONS

The possibility of using algebraic methods to obtain stable solutions of inverse problems with angular superresolution, which reflect the location of the original objects with a slight error (the coordinates of the original objects and the resulting solution coincide), has been demonstrated. The errors in the distribution of the signal amplitude are small (the amplitude of the obtained solution is 60% to 80% of the amplitude of the original objects). A false target appears between the central and right objects, but with negligibly small amplitude <10% of the amplitude of the true objects (Fig. 3b, in the center of the region).

Authors' contributions

A.A. Shchukin—preparing algorithms and graphic materials, writing the text of the article.

A.E. Pavlov—preparing algorithms and graphic materials, writing the text of the article.

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RESEARCH ARTICLE

Collective dynamics of domain structures in liquid crystalline lipid bilayers

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Abstract

Objectives. Numerous studies of biosystems indicate the distinct role of quasi-one-dimensional molecular structures in the transport of energy, charges, and information. Of particular interest are the studies on the collective dynamics of quasi-one-dimensional lateral structures in liquid crystalline membranes and the possibility of local excitation transfer through such structures. In this paper, we developed a model for the collective dynamics of quasi-one-dimensional domain structures in lipid bilayers interacting with the environment. The objective is to study the mechanisms of the directed energy transport in liquid crystalline lipid membranes.

Methods. In this paper, the percolation domain structures formed as a result of phase separation in multicomponent lipid membranes are considered to be quasi-one-dimensional domain structures. The model distinguishes two subsystems interacting with each other and differing in their structural and dynamic properties, i.e., the membrane surface formed by polar groups of lipid molecules and the internal hydrophilic region of the membrane formed by acyl chains of lipids. The acyl chain subsystem is simulated using the Ginzburg–Landau Hamiltonian which considers the dependence of its dynamics on temperature close to the lipid melting phase transition temperature T_c.

Results. Analysis of dynamic states has shown that elastic excitations moving at constant rate in the form of solitons may exist near temperatures T_c in the considered quasi-one-dimensional domain structures. In addition, motion of the elastic excitation region (kink) along domain structures in the acyl chain region causes the formation of acoustic soliton, i.e., the compression region in the polar group subsystem moving in concert with the kink displacement. The soliton localization region covers about 10 molecules and depends significantly on the interaction parameter of the polar group and acyl chain subsystems. Soliton moves at a subsonic speed determined, in particular, by the magnitude of an external force.

Conclusions. The model developed in this paper shows that liquid crystalline domain structures in lipid membranes exhibit properties of active media, wherein the formation and displacement of localized elastic excitations on macroscopic spatial and temporal scales may occur. The proposed molecular mechanism of the soliton transport along quasi-one-dimensional domain structures may be used for describing the directed energy transfer along lateral domain channels in biomembranes and the cooperative functioning of the membrane bioenergetic and receptor complexes.

Keywords: collective dynamics, liquid crystalline domain structures, multicomponent lipid membranes, soliton, directed energy transport

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The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Коллективная динамика доменных структур в жидкокристаллических липидных бислоях

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Резюме

Цели. Многочисленные исследования биосистем указывают на особую роль квазиодномерных (квази-1D) молекулярных структур в процессах транспорта энергии, зарядов и информации. В этой связи особый интерес представляют исследования коллективной динамики квази-1D латеральных структур в жидкокристаллических (ЖК) мембранах и возможности передачи по таким структурам локальных возбуждений. С целью исследования молекулярных механизмов направленного транспорта энергии в ЖК липидных мембранах в настоящей работе разработана модель коллективной динамики квази-1D доменных структур (ДС) в ЖК бислоях, взаимодействующих с окружающей средой.

Методы. В качестве квази-1D ДС рассмотрены перколяционные ДС, формирующиеся при фазовом разделении липидных молекул в многокомпонентных мембранах. В модели выделены две взаимодействующие между собой подсистемы, различающиеся по своим структурным и динамическим свойствам: поверхность мембраны, образованная полярными группами (ПГ) липидных молекул и внутренняя гидрофильная область мембраны, сформированная ацильными цепями (АЦ) липидов. При моделировании подсистемы АЦ использован гамильтониан Гинзбурга – Ландау, учитывающий зависимость ее динамики от температуры вблизи температуры фазового перехода плавления липидов T_c.

Результаты. Анализ динамических состояний модели показал, что вблизи температур T_c в рассматриваемых квази-1D ДС могут существовать перемещающиеся с постоянной скоростью возбуждения в виде солитонов. При этом движение упругого возбуждения (кинка) вдоль ДС в области АЦ вызывает образование акустического солитона – области сжатия в подсистеме ПГ, перемещающейся согласованно с движением кинка. Область локализации солитона охватывает примерно 10 молекул и существенно зависит от параметра взаимодействия подсистем ПГ и АЦ. Движение солитона происходит с дозвуковой скоростью, которая определяется, в частности, величиной внешнего воздействия.

Выводы. В рамках разработанной модели показано, что ЖК ДС в липидных мембранах проявляют свойства активных сред, в которых может происходить формирование и перемещение локализованных упругих возбуждений в виде солитонов на макроскопических пространственных и временных масштабах. Предложенная модель молекулярного транспорта энергии вдоль квази-1D ДС может быть применена к описанию направленной передачи энергии по латеральным доменным каналам в биомембранах и кооперативного функционирования мембранных биоэнергетических и рецепторных комплексов.

Ключевые слова: коллективная динамика, жидкокристаллические доменные структуры, многокомпонентные липидные мембраны, солитоны, направленный транспорт энергии

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INTRODUCTION

The electro-optical and morphological properties of liquid crystal (LC) planar systems determine their high sensitivity to external influences resulting in a fast change in their macroscopic characteristics. The occurrence of a threshold collective response in nematic liquid crystal (NLC) films to external factors is the basis of their high structural mobility. This determines their wide application in various fields of engineering as materials with easily controllable properties. The unique properties of LC are also responsible for the wide distribution of LC structures in living systems and their important biological role [1]. The application of LC physics and condensed matter physics approaches to studying LC states in living cells has led to the development of physics of active LC structures in living systems functioning far from equilibrium states in the presence of pumping and energy dissipation [2].

Active LC structures in cells include lyotropic LC cell membranes as one of their main structural and functional elements. In addition to the functions of cellular compartment formation, they play an active role in the spatial organization of the matrix for embedding signal membrane receptors and bioenergetic protein complexes on the membrane surface, providing optimal conditions for their functioning [1]. Due to the high structural mobility of LC states, membranes may perform a variety of communication functions, providing the transmembrane transport of substances and signal molecules between the cell and the external environment. Furthermore, LC membranes provide the lateral transport of biologically active molecules along the membrane surface. Mitochondrial membranes also play a complex spatial-organizing role in cell bioenergetics, providing cluster organization of nanoscale molecular machines of the respiratory system [3]. It is assumed that the functioning of active LC membranes is realized by the excitation of cooperative molecular processes in complex LC bilayers.

The complex structure of LC lipid membranes is related to their heterogeneous structure resulting from the diverse composition of lipid molecules which differ both in their molecular structure and phase state. The heterogeneous structure of membranes manifests itself in their domain organization by determining many physiological properties of biomembranes [1]. First, the role of membrane domain organization in the formation of specific lipid microenvironment for membrane proteins ensuring their optimal functioning is noted. The destruction of domain structures (DSs) has been shown to result in membrane protein system failure [4]. Secondly, the role of DS in transport and communication processes on the membrane surface is noted [5]. In particular, this study considers the formation of quasi-one-dimensional (quasi-1D) percolation cluster networks formed in the phase separation area of lipid molecules which differ in their structure and phase state [6]. It is assumed that quasi-1D DSs and their networks can act as lateral channels for the directed energy and charge transport along the membrane surface, as well as provide interaction between membrane bioenergetic and receptor complexes [5]. The directed transport and channelling of energy and charges along quasi-1D DSs may surpass the passive transport realized through the two-dimensional diffusion of molecules along the membrane surface in its efficiency.

In the paper, we developed the model for collective dynamics of quasi-1D DSs in lipid bilayers interacting with the environment, in order to study mechanisms of the directed energy transport along LC DSs. It was shown that nonlinear excitations capable of maintaining the interaction and energy transfer between membrane proteins and receptors over considerable distances possibly occur in the DS system. The analytical study has revealed that when considering the interaction of lipid molecules with each other and the environment, excitations like acoustic solitons representing compression (extension) regions moving at constant rate may exist in the considered quasi-1D lateral DSs in lipid bilayers.

1. A DYNAMIC MODEL OF LIPID DOMAIN STRUCTURES

Let us consider the one-dimensional chain of lipid molecules which forms a quasi-1D domain in a flat membrane. The following two subsystems may be distinguished in the lipid membrane structure: the membrane surface formed by the polar groups (PG) of lipid molecules; and the inner hydrophobic region of the membrane formed by the acyl chains (AC) of lipids.

Since the PG and AC regions have different properties and participate in different molecular excitations, the Hamiltonians of non-interacting PG and AC subsystems may be written separately, and then the interaction energy between them may be introduced. The Hamiltonian of interacting PGs of lipid molecules in the harmonic approximation may be written as follows:

$$H_1 = \sum_n \frac{1}{2} m \left[\dot{p}_n^2 + \Omega_0^2 p_n^2 + \Omega_1^2 \left(p_{n+1} - p_n \right)^2 \right], \quad (1)$$

where p_n is the displacements of the nth PG relative to the equilibrium position of the PGs spaced a distance a apart; m is PG mass; Ω_0 and Ω_1 are the characteristic frequencies of vibrations in the PG system. The last term in Eq. (1) takes into account the dispersion of elastic waves in the PG chain. The point stands for differentiation by time t.

The dynamics of the AC subsystem significantly depends on the membrane temperature T. The phase transition, i.e., lipid melting occurring through AC rotational isomerization of lipid molecules (conformational melting) thus resulting in their increased mobility, can be observed in membranes near the phase transition temperature T_c [1]. Therefore, the Ginzburg–Landau Hamiltonian widely used for studying critical phenomena in various structures, including the description of the collective dynamics of lipid membranes, may be most suitable for describing the AC chain dynamics [7, 8]. It is written as follows:

$$H_2 = \sum_n \frac{1}{2} M \left[\dot{u}_n^2 + \omega^2 \left(u_{n+1} - u_n \right)^2 \right] + U_T(u_n) \quad (2)$$

with double-well potential

$$U_T(u_n) = \frac{1}{2} G u_n^2 + \frac{1}{4} B u_n^4, \quad (3)$$

where $G < 0$ and $B > 0$ at $T < T_c$; $G > 0$ and $B > 0$ at $T > T_c$. M is AC mass; $\omega^2 = K/M$, where K is the membrane elastic modulus. The variable u_n characterizes the instantaneous position of the nth AC relative to the equilibrium position corresponding to the top of the potential barrier.

In Eq. (3), the dependence of parameter G on temperature may be written as follows:

$$G(T) = E_0(T/T_c - 1), \quad (4)$$

where E_0 is the height of the potential barrier [9]. The temperature range near T_c spans a few degrees [1]. The symmetric double-well potential (3) has two minima located at a distance from the barrier top:

$$u_0 = \pm \sqrt{\frac{|G|}{B}}. \quad (5)$$

Within the high-temperature range, the following harmonic representation of the AC subsystem Hamiltonian is valid at $T >> T_c$:

$$H_2' = \sum_n \frac{1}{2} M \left[\dot{u}_n^2 + \omega^2 (u_{n+1} - u_n)^2 \right]. \quad (6)$$

The Hamiltonian of the interaction between PG and AC considering the change in the conformation of the closest ACs, when PGs are displaced from the stable equilibrium position may be written as [8]:

$$H_3 = \sum_n \chi p_n (u_n^2 - u_0^2), \quad (7)$$

where χ is the interaction constant generally depending on the lipid molecule structures and the membrane environment.

Turning from the discrete to the continuum approximation in describing the dynamics of the quasi-1D lateral structure in the membrane, the following expression for the system Hamiltonian may be written:

$$H_M = \frac{1}{a} \int \frac{M}{2} (u_t^2 + c_0^2 u_x^2) + U_T(u) + \\ + \frac{m}{2} (p_t^2 + \Omega_0^2 p^2 + V_0^2 p_x^2) + \chi p (u^2 - u_0^2) dx, \quad (8)$$

where $c_0 = a\omega_1$ is the velocity of sound in the AC subsystem and $V_0 = a\Omega_1$.

At temperatures $T < T_c$, potential function $U_T(u)$ (3) may be written as follows:

$$U_T(u) = \frac{1}{2} |G(T)| u^2 + \frac{1}{4} B u^4. \quad (9)$$

The system of motion equations for the coupled PG and AC system with Hamiltonian H_M (8) may be written as follows:

$$M u_{tt} - M c_0^2 u_{xx} - |G| u + B u^3 + 2\chi p u = f_u, \quad (10)$$

$$M p_{tt} + \Omega_0^2 p - V_0^2 p_{xx} + \chi (u^2 - u_0^2) = 0. \quad (11)$$

When considering the interaction of the two basic PG and AC subsystems with physical fields of the environment, the following terms accounting for viscous friction and external influences should be added to Eqs. (10) and (11):

$$Mu_{tt} - Mc_0^2 u_{xx} - M\Gamma_u u_t - |G|u + Bu^3 + 2\chi pu = f_u, \quad (12)$$

$$Mp_{tt} + \Omega_0^2 p - M\Gamma_p p_t - V_0^2 p_{xx} + \chi(u^2 - u_0^2) = f_p. \quad (13)$$

where $\Gamma_u > 0$ and $\Gamma_p > 0$ are viscous friction coefficients the PG and AC subsystems, while $f_u > 0$ and $f_p > 0$ are are right-hand sides of the equations considering external and internal forces acting upon each subsystem. The elastic stress forces acting at phase interfaces (domains) may act as internal forces. The structures in the quasi-1D DS model under consideration resulting from phase separation are either influenced by compression forces or experience tension depending on the membrane lipid composition and the interface type.

2. DYNAMICS OF QUASI-ONE-DIMENSIONAL DOMAIN STRUCTURES OF LIPID MOLECULES

Let us consider the equations of motion (11) and (12) without taking into account the interaction between PG and AC subsystems and the environment. Then Eq. (11) for the AC dynamics may be transformed into the well-known Ginzburg–Landau equation, as follows:

$$Mu_{tt} - Mc_0^2 u_{xx} - |G|u + Bu^3 = 0. \quad (14)$$

In the low-amplitude limit, $u(x, t)$ describes small displacements $\delta u(x, t)$ of AC near one of the equilibrium positions $u(x, t) = \pm u_0 + \delta u(x, t)$. In a first approximation in $\delta u(x, t)$, these displacements are described by the following equation:

$$M\delta u_{tt} - Mc_0^2 \delta u_{xx} - |G|\delta u = 0, \quad (15)$$

which has the following fundamental solution:

$$\delta u(x,t) \sim e^{i(\omega t - kx)}. \quad (16)$$

The dispersion of elastic waves is defined by the following expression:

$$\omega^2 = \frac{|G|}{M} + c_0^2 k^2 = \omega_0^2 + c_0^2 k^2, \quad (17)$$

where k is a wave vector.

In addition, Eq. (15) has a solution in the form of a soliton wave of non-small finite amplitude:

$$u(x,t) = \mp u_0 \tanh\left(\frac{\omega_0}{\sqrt{c_0^2 - V^2}}(x - Vt)\right). \quad (18)$$

Here, the upper sign corresponds to the soliton (kink) moving with velocity $V < c_0$, while the lower sign corresponds to the antikink. The width of the soliton (kink or antikink) is determined by the following formula:

$$\Delta_0 = \frac{\sqrt{c_0^2 - V^2}}{\omega_0} = \sqrt{\frac{M(c_0^2 - V^2)}{|G|}},$$

where $\omega_0 = (|G|/M)^{1/2}$.

In the absence of interaction between the PG and AC subsystems with each other and with the environment, Eqs. (12) and (13) describe longitudinal (sound) waves with dispersion, as follows:

$$\Omega^2(q) = \Omega_0^2 + V_0^2 q^2, \quad (19)$$

where q is a wave vector.

Let us consider the dynamics of the quasi-1D lateral structure of lipids when taking into account the interaction between the PG and AC subsystems, which is described by Eqs. (12) and (13). In this case, the viscous friction coefficient Γ_u in the PG subsystem is ignored and the external influence on the PG subsystem is assumed to be small, so the PG displacements caused by the external forces may be neglected. Turning to a new spatial variable $\xi = x - Vt$ in Eqs. (12) and (13), the following system of two ordinary differential equations may be written:

$$M(V^2 - c_0^2)u_{\xi\xi} - M\Gamma_u u_\xi - |G|u + Bu^3 + 2\chi pu = f_u, \quad (20)$$

$$M(V^2 - V_0^2)p_{\xi\xi} + m\Omega_0^2 p + \chi(u^2 - u_0^2) = 0. \quad (21)$$

Of particular interest is the excitation moving along the considered structure at constant velocity $V = V_0$. Then Eq. (21) implies the following:

$$p = -\frac{\chi}{m\Omega_0^2}(u^2 - u_0^2). \quad (22)$$

Substituting this relationship into Eq. (20) with the consideration of the expression for u_0 (5), the equation describing the excitation dynamics in the AC subsystem may be written in the following form:

$$M(V^2 - c_0^2)u_{\xi\xi} - M\Gamma_u u_\xi - G_1 u + B_1 u^3 = f_u, \quad (23)$$

where

$$G_1 = \theta|G|, \; B_1 = \theta|B|, \; \theta = 1 - \frac{\chi^2}{m\Omega_0^2 B}, \; 0 < \theta < 1.$$

We shall turn to the new variables in Eq. (23)

$$z = \frac{\xi}{L} = \frac{\sqrt{2}\xi}{\Delta} \text{ and } \eta = \frac{u}{u_0},$$

where Δ is the width of the excitation localization region. Then the equation describing the excitation state in AC subsystem of lipid molecules is written in the following form:

$$\eta_{zz} + \mu\eta_z - \eta + \eta^3 - \lambda = 0, \quad (24)$$

where

$$\mu = V\Gamma_u\sqrt{\frac{M}{(c_0^2 - V^2)G_1}}, \quad (25)$$

$$\lambda = f_u\sqrt{\frac{B_1}{G^3}}. \quad (26)$$

The solution of Eq. (24) may be written using the roots of a polynomial [9]:

$$\Phi(\eta) = -\eta + \eta^3 - \lambda = (\eta - \eta_1)(\eta - \eta_2)(\eta - \eta_3). \quad (27)$$

Here, values $\eta_1 < \eta_2 < \eta_3$ satisfy the following relations:

$$\eta_1 + \eta_2 + \eta_3 = 0,\ \eta_1\eta_2 + \eta_2\eta_3 + \eta_1\eta_3 = -1,\ \eta_1\eta_2\eta_3 = \lambda$$

and define the stationary states of the system:

$$u_1(x,t) = \eta_1 u_0,\ \ u_2(x,t) = \eta_2 u_0,\ u_3(x,t) = \eta_3 u_0. \quad (28)$$

In addition, Eq. (24) has a solution describing excitation moving at constant velocity in the form of a soliton wave (of non-small finite amplitude), provided that

$$\mu = \pm\frac{3\eta_3}{\sqrt{2}}. \quad (29)$$

The specified solution in variables u, x, and t may be written in the following form [9]:

$$u(x,t) = \pm u_0\left(\eta_1 + \frac{\eta_2 - \eta_1}{1 + \exp\dfrac{x - Vt}{\Delta}}\right), \quad (30)$$

where

$$\Delta = \frac{\sqrt{2M(c_0^2 - V^2)}}{\sqrt{G_1(\eta_3 - \eta_1)}}. \quad (31)$$

The minus sign in Eq. (30) corresponds to the kink ($\eta < 0$), while the plus sign stands for the anti-kink. Eqs. (25) and (26) define the relation between the soliton velocity and the external field in the following form:

$$V^2 = \frac{9c_0^2 G_1\eta_3^2}{2M\Gamma_1^2 + 9G_1\eta_3^2} = V_0 < c_0^2. \quad (32)$$

The soliton velocity V is always less than c_0 because the soliton radiates waves when accelerating under external influence. This results in the additional energy loss (dissipation) not considered in Eqs. (23) and (32), according to which $V \to c_0$ with decreasing f_u (at $f_u \to 0$). The propagation direction of excitation (soliton) is determined by the f_u sign.

The excitation (kink) motion in the AC subsystem causes the formation of the compression (extension) region in the PG subsystem moving in concert with the kink motion in the AC subsystem. The spatiotemporal structure of the deformation region in the PG system is determined by the equation following from relations (22) and (30):

$$p(x,t) = \frac{\chi u_0^2}{m\Omega_0^2}\left[\left(\frac{\eta_1\exp\dfrac{x - Vt}{\Delta} + \eta_2}{1 + \exp\dfrac{x - Vt}{\Delta}}\right)^2 - 1\right]. \quad (33)$$

At the fixed value of parameter $V = V_0$, the solutions for Eqs. (10) and (11) have the following forms:

$$u(x,t) = \mp u_0\tanh\frac{x - Vt}{\Delta}, \quad (34)$$

$$p(x,t) = \frac{\chi u_0^2}{m\Omega_0^2}\operatorname{sech}^2\frac{x - Vt}{\Delta}. \quad (35)$$

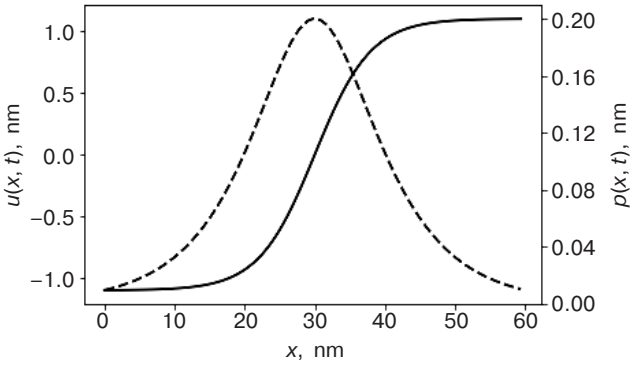

Figure. Displacements of AC $u(x, t)$ (34) (solid curve) and PG $p(x, t)$ (35) (dashed curve) of lipid molecules in quasi-1D DS of the membranes

Figure shows calculation results of the displacement of AC $u(x, t)$ (34) and PG $p(x, t)$ (35) of lipid molecules

in a quasi-1D DS of the membrane. Calculations have been performed with the parameters derived from the following experimental data. The characteristic frequency $\Omega_0 = 10^{11}$ Hz is estimated on the basis of experimental data for PG dipole oscillations [8]. The value $c_0 = 200$ m/s as an estimate of sound velocity was taken from the interval of values obtained in experiments on measuring of the sound velocity in lipid monolayers [7]. The value $u_0 = 1.1$ nm is estimated on the basis of experimental data for the AC average angle of inclination (34°–41°) in $L_{\beta'}$ phase in lecithin liposomes [10]. The kink width value $\Delta = 8.0$ nm is estimated from the data on the size of defect area formed in the AC subsystem of the lipid membranes at temperatures close to the main phase transition temperature (pre-transition temperature range) [10]. At the calculated value of width Δ, the soliton region covers approximately 10 lipid molecules. The kink solution for the AC displacement $u(x, t)$ describes a dislocation-type defect forming in AC subsystem. Negative and positive values $u(x, t)$ correspond to deviations of AC of lipid molecules in opposite directions. The soliton solution for the PG displacement $p(x, t)$ describes the compression deformation in PG subsystem caused by the defect in AC.

Comparing the equations for the soliton width Δ (18) and (31) derived without considering the PG and AC interaction, it may be seen that the interaction of the PG and AC subsystems results in increasing excitation region (kink or antikink width) by $\sqrt{\theta}$ times. Thus, with increasing interaction parameter χ, the potential barrier height $E = \theta E_0$ decreases and the excitation autolocalization region increases.

With increasing temperature in the temperature range below T_c, the value of parameter $G(T)$ (4), determining the barrier height of the potential $U_T(u_n)$ (3), decreases that leads to a single minimum potential $T > T_c$ and disappearing of bistability in the system. A decrease in $G(T)$ results in the soliton spatial size reduction.

Thus, the degree of excitation localization in the one-dimensional membrane lipid structure increases as the temperature approaches T_c. This is due to the increase in the effective force λ (26) in Eq. (24), which increases with increasing temperature as $|T - T_c|^{-1.5}$ up to the maximum value determined by Eq. (26). At the same time, as noted above, the sign of the external force determines the propagation direction of excitation along quasi-linear DCs in the membrane. In addition, the soliton becomes asymmetric under the impact of the external field.

With increasing temperature T and, consequently, effective force λ (26), the soliton velocity along the lipid chain also increases. At temperatures close to $\lambda = \lambda_{max}$, the localized state begins to collapse, and a periodic spatiotemporal structure of cnoidal wave type is formed.

3. DISCUSSION

Numerous theoretical studies in biophysics indicate the distinct role of quasi-1D regular molecular structures in biosystems including the transport of energy, matter, and information over considerable molecular distances [11–13]. This research area covers mainly the transport of energy and charges along linear molecules such as DNA, polypeptides, and linear polymers [14–16]. Of particular interest in this regard are studies of the collective dynamics of quasi-1D lateral structures in multicomponent biological membranes and the possibility of transferring local excitations through such structures, which are caused by physical and chemical influences on selected membrane components. This interest is determined by the crucial role of biological membranes in living cells. It is assumed that the nature of the cooperative properties of biological membranes is determined by the interaction of its subunits (receptors and ion channels) carried out through such quasi-1D structures in lipid bilayers [5].

This paper undertakes a theoretical study on the collective dynamics of quasi-1D domain structures in liquid crystalline lipid membranes. Here, quasi-1D structures of lipid molecules formed as a result of lateral domain organization of the bilayer are considered as quasi-1D DS in the membranes. The existence of these structures in cellular membranes is confirmed by various experimental methods: X-ray diffraction, neutron scattering, electron paramagnetic resonance (EPR), and electron microscopy in multicomponent lipid bilayers [6, 17, and 18], as well as by numerical simulation of DSs in lipid membranes. Computer simulations showed that the self-organization of percolation DSs may result from phase separation in two-component membranes formed by lipid molecules differing in their structural and physical properties [19, 20].

In the developed model of quasi-1D DS dynamics, we considered two interacting subsystems in lipid bilayers: the membrane surface formed by PG of lipid molecules; and the inner hydrophobic region of the membrane consisting of lipid ACs. The model took into account the significant dependence of the AC subsystem dynamics on temperature T in temperature range T_c of the lipid melting phase transition [1]. Therefore, the Ginzburg–Landau Hamiltonian, widely used in the study of critical phenomena, is chosen for describing the hydrophobic region dynamics of lipid ACs. The results of an analytical study in the paper showed that elastic excitations moving at constant velocity in the form of soliton waves (of non-small finite amplitude) may exist in the quasi-1D lateral structures of lipids when taking into account the interaction of two subsystems with each other and the environment. The formation and displacement of a defect (dislocation) in the AC

subsystem causes the formation of the acoustic soliton as the compression region in the lipid PG subsystem moving in concert with the displacement of the defect (kink) in the AC subsystem. Thus, the soliton-type excitations formed in quasi-1D DS are local regions of of lipid PG displacements and structural defects in the AC subsystem moving along the molecular structure. When increasing temperature T (with the external influence unchanged), the soliton velocity along the chain of lipid molecules and its localization degree increase. However, at a certain temperature value close to melting temperature T_c, the localized state begins to collapse, and the periodic spatial structure of cnoidal wave type is formed. We suggested that this periodic structure may be correlated with the $P_{\beta'}$ phase observed in lipid bilayers in the temperature range below the main phase transition temperature [10]. It should also be noted that disturbances in the form of small amplitude waves (small-amplitude phonons) whose frequency decreases with increasing temperature up to zero at $T = T_c$ ("soft mode") may exist in the considered quasi-1D DS at $T < T_c$ [21].

Experimental data on the observation of soliton-type excitations in lipid bilayers have been obtained in a number of experiments using different methods for excitation and registration of elastic pulses. In the experiment with optical generation of elastic waves in lipid monolayers, excitation of acoustic soliton-like pulses forming and propagating with shape preservation has been observed at surface pressure above a certain threshold value [22]. Elastic excitations of the soliton type have been also observed in lipid liposomes in the lipid melting temperature range [23]. Soliton formation and motion have been also detected and studied in nematic and cholesteric LC planar structures using methods of nonlinear optics under various experimental conditions [24, 25]. It has been shown experimentally that formation of solitons (small-width domain walls) occurs in the magnetic field or under the action of shear stresses within a certain range of values. Soliton formation and motion in nematic LC planar structures have been described theoretically within the framework of the Ericksen–Leslie theory for the nematic state [24]. It was shown in our paper that similar soliton-type excitations may occur in lyotropic LC DSs in lipid membranes.

The described mechanism of local region formation of elastic deformation and its motion in the form of a soliton is considered to be a possible molecular mechanism of directed transport of elastic energy along the LC membrane surfaces. The soliton capture by membrane protein complexes (receptors, ion channels) results in the elastic energy transfer to the protein molecule, which may be a trigger for their conformational transitions and their activation [26]. It is also assumed that excitation and propagation of the elastic deformation pulse in the form of a soliton may accompany the nerve impulse propagation in the axon [23].

The formation and displacement of the local deformation region in the membrane may also result in the charge capture by the soliton and the charge motion together with it. The capture mechanism and the resulting charge transport process by the acoustic soliton along one-dimensional molecular structures are discussed in [13, 27, and 28]. Similarly, the capture of charges and their transport by solitons in quasi-1D DS of lipid membranes may result in lateral transport in cell membranes. The possibility of particle transport by solitons has been confirmed in experimental studies of solitons in planar cholesteric LC structures [25]. It was established in the paper that the soliton corresponding to the local defect in LC structure is an attraction region for impurity particles, resulting in the capture of particles and their transport by the moving soliton. Further progress and application of the developed model to the description of soliton transport of particles in LC membranes will be discussed in the next paper.

CONCLUSIONS

The simulation of dynamic properties of LC domain structures of lipid membranes, carried out in the paper, showed that these structures exhibit the properties of active media, wherein the formation of localized coherent excitations on macroscopic spatial and temporal scales occurs. The formation process of localized soliton-type excitations in quasi-linear domain structures represents the formation of the local deformation region in the PG system and the formation of topological defects in the AC system of lipid molecules. The simulation results revealed the possibility of a soliton motion along quasi-1D DSs as the non-dissipative motion of the local deformation region in the chain of lipid PGs, accompanied by the cooperative motion of the defect (kink) in the region of acyl chains of lipid molecules. The molecular mechanism herein proposed may be used for describing the elastic energy directed transfer along LC membranes and the cooperative behaviour of membrane bioenergetic complexes. Further development of the model will be targeted at describing the molecular mechanisms of particle capture by moving solitons and directed transport of charged particles (protons and electrons) along quasi-linear domain structures in biological and artificial polymeric membranes.

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RESEARCH ARTICLE

Nonreciprocal propagation of spin waves in a bilayer magnonic waveguide based on yttrium-iron garnet films

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Abstract

Objectives. Nonreciprocal spin wave effects can manifest themselves in metalized films of ferrite garnets. By studying the dynamics of spin waves in micro- and nano-scale magnetic films, the possibility of using multilayer dielectric films of yttrium iron garnet (YIG) to ensure the manifestation of the nonreciprocity effect is demonstrated. This approach offers advantages compared to the use of a layered YIG/metal structure due to significantly lower spin-wave losses in the two-layer YIG film consisting of layers with different values of magnetization. Such films can be used in logical elements to create controllable Mach–Zehnder interferometers based on magnonic principles. The purpose of this work is to reconcile the concept of nonreciprocal spin-wave propagation of a signal with the simultaneous manifestation of the effects arising from the propagation of spin waves in microwave guides formed by finite-width YIG films.

Methods. We used an experimental microwave spectroscopy method based on a vector network analyzer along with a finite difference method to perform a numerical simulation of the dispersion characteristics of spin waves in two-layer magnonic microwave guides. An analytical model was also used to obtain a dispersion equation based on the magnetostatic approximation.

Results. Based on measurements of the amplitude and phase responses, the possible coexistence of two frequency ranges for the propagation of a spin-wave signal in a two-layer magnon microwave guide based on a YIG film formed by two layers with different values of saturation magnetization was demonstrated. Regimes of nonreciprocal propagation of a spin-wave signal were revealed. A numerical model was using to study the formation mechanisms of spin wave modes in the spectrum of a two-layer structure formed due to the finite dimensions of the microwave guide. An analytical model was used to evaluate the transformation of the mode spectrum. The experimental data are in good agreement with the results of the proposed numerical and analytical models.

Conclusions. The possibility of frequency-selective propagation of spin waves in a magnon microwaveguide consisting of two layers with different saturation magnetization values is demonstrated. Multimode propagation of spin waves can occur inside a two-layer structure in two frequency ranges. At the same time, this process is accompanied by a strong nonreciprocity of spin-wave signal propagation, which manifests itself in a change in the amplitude and phase responses when the direction of the external magnetic field is reversed. The proposed two-layer spin-wave waveguide concept can be used in the manufacture of magnon interconnects and magnon interferometers with the support of multiband regimes of operation.

Keywords: spin waves, nonreciprocity, microstructures, waveguide, magnonics

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НАУЧНАЯ СТАТЬЯ

Эффекты невзаимности при распространении спиновых волн в двухслойном магнонном микроволноводе на основе пленок железо-иттриевого граната

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Резюме

Цели. Эффекты невзаимности спиновых волн могут проявляться в металлизированных пленках феррит-гранатов. В настоящее время актуальной задачей является исследование динамики спиновых волн в микро- и наноразмерных магнитных пленках. Использование многослойных диэлектрических пленок железо-иттриевого граната (ЖИГ) обеспечивает проявление эффекта невзаимности и в то же время дает большее преимущество по сравнению со слоистой структурой ЖИГ/металл ввиду значительно меньших спин-волновых потерь в двуслойной пленке ЖИГ, состоящей из слоев с различными значениями намагниченности. Такие пленки могут найти применение в задачах магнонной логики для создания управляемых интерферометров типа Маха – Цендера на основе принципов магноники. Цель настоящей работы – объединение концепции невзаимного спин-волнового распространения сигнала и одновременного проявления эффектов, возникающих при распространении спиновых волн в микроволноводах, образованных пленками ЖИГ конечной ширины.

Методы. В работе используются экспериментальный метод микроволновой спектроскопии на основе векторного анализатора цепей и метод конечных разностей для численного моделирования дисперсионных характеристик спиновых волн в двуслойных магнонных микроволноводах. Также использована аналитическая модель, в рамках которой получено дисперсионное уравнение на основе магнитостатического приближения.

Результаты. На основе измерений амплитудно-частотных и фазо-частотных характеристик показана возможность сосуществования двух частотных диапазонов для распространения спин-волнового сигнала в двуслойном магнонном микроволноводе на основе пленки ЖИГ, образованной двумя слоями с различными значениями намагниченности насыщения. Выявлены режимы невзаимного распространения спин-волнового сигнала. С помощью численной модели исследованы механизмы формирования в спектре двуслойной структуры ширинных мод спиновых волн, образующихся вследствие конечных размеров микроволновода. Оценка трансформации спектра мод также проведена при использовании аналитической модели. Экспериментальные данные хорошо согласуются с результатами предложенных численной и аналитической моделей.
Выводы. Продемонстрирована возможность частотно-селективного распространения спиновых волн в магнонном микроволноводе, состоящем из двух слоев с различным значением величины намагниченности насыщения. Показано, что многомодовое распространение спиновых волн может осуществляться внутри двухслойной структуры в двух диапазонах частот. В то же время этот процесс сопровождается сильной невзаимностью распространений спин-волнового сигнала, что проявляется в изменении амплитудно- и фазо-частотных характеристик при изменении направления внешнего магнитного поля на противоположное. Предложенная концепция двухслойного спин-волнового волновода может лежать в основе изготовления магнонных межсоединений и магнонных интерферометров с поддержкой многополосных режимов работы.

Ключевые слова: спиновые волны, невзаимность, микроструктуры, волновод, магноника

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INTRODUCTION

Magnetic thin film systems (MTFS) are used for signal processing [1], magnetic recording and information storage [2, 3], and new applications of metamaterials [4]. The variety of MTFS includes systems of single magnetic films, double magnetic films, and multilayer magnetic films consisting of ferromagnetic (FM), antiferromagnetic, as well as nonmagnetic (NM) films of various thicknesses and arrangements of layers, of which FM/NM multilayers have recently attracted the greatest interest [5]. The study of relaxation processes in magnetic spin systems is one of the most interesting and topical problems. In particular, this is due to recent active research revealing prospects for the practical use of multilayer magnetic film structures.

When creating information processing systems at microwave frequencies, in which information is encoded through the amplitude and phase of magnetostatic spin waves (SW) [6–8] propagating in ferrite films, it is important to study the dispersion of various types of magnetostatic SW, which determines the characteristics of such devices. The concept of magnon logic is being developed for use in a large number of magnon elements, such as majority gates, half-adders, NOR, XOR logic elements [9]. The possibility of creating such elements is due to the linear modes of SW interference in magnonic microwave guides. In particular, the forming block of magnon networks is based on the Mach–Zehnder interferometer, demonstrating the possibility of both constructive and destructive interference of different SW modes in the output section of the interferometer [10]. The use of multilayer dielectric films of yttrium iron garnet (YIG) ensures the manifestation of the nonreciprocity effect as well as offering an advantage over the well-known YIG/metal layered structures due to significantly lower spin-wave losses in a two-layer YIG film consisting of layers having different magnetization values. Ferromagnetic thin YIG films have a significantly lower dynamic damping of SW compared to metallic magnetic films, which has been shown even for the case of YIG of nanometer thickness [20]. Such films can be used in problems of magnon logic to create controllable Mach–Zehnder type interferometers based on magnonic principles.

SW dynamics in nanoscale FM films have been the subject of research in recent decades [11]. One of the promising areas of study is the application of SW for signal processing devices, since the wavelength of SW is shorter than that of electromagnetic waves in the gigahertz frequency range [8]. Thus, the miniaturization of magnonic devices becomes an urgent problem [12]. The concept of dielectric magnonics represents an alternative to semiconductor signal processing devices [14, 17–19]. In magnonic media, information is carried by SW (or magnons) instead of electrons. Thus, the use of structured YIG provides the basis for the

next generation of low power computing [14, 21, 22]. A magnonic microwave guide is a universal element of interconnection between magnonic functional blocks within a magnon network [23, 24]. The lateral limitations of a magnonic waveguide [25, 26] comprise an internal feature that determines the characteristics of SW propagation along the junction. The simultaneous use of lateral restrictions and multilayer structure for SW propagation has application in frequency- and space-selective modes of waveguide operation.

The nonreciprocity of SW has been known since the work of Damon and Eshbach [8], in which it was predicted that the magnetization precession amplitude of surface modes should be asymmetric with respect to the propagation direction. This now well-known behaviour has been experimentally measured in micro- and nano-sized magnetic films using, for example, the Mandelstam–Brillouin spectroscopy method [27, 28]. The nonreciprocal behaviour of SW has also been studied for FM films with different magnetic anisotropy on the surface [28–32], for films with interband magnon transitions [33], as well as for exchange-coupled films [34]. In addition, it has been theoretically and experimentally shown that the Dzyaloshinskii–Moriya interfacial interaction [37–39] induced in ultrathin FM layers coated with heavy metal films has a remarkable effect on SW spectra, causing nonreciprocity in the dispersion characteristics. However, the use of YIG dielectric films provides a greater advantage over metal films due to significantly lower spin-wave losses in YIG.

On the other hand, SW nonreciprocity, which can manifest itself in the phase, amplitude, or frequency dependence of the direction of SW propagation, is a potentially powerful tool for applications in communication and logic devices used in data processing [39–41]. Nonreciprocal wave propagation phenomena have been the focus of research on photonic and electronic structures. It was found that such structures provide operating modes in insulators, circulators, and gyrators [42, 43]. In the same way, nonreciprocal effects that manifest themselves during SW propagation determine the functional modes of operation of magnonic devices [39, 44, 45]. In order to create interferometers of the Mach–Zehnder type, it will be decisive to study the modes of SW propagation in a magnon microwaveguide of finite width made of a multilayer ferrite film.

In this paper, we study the spin-wave dynamics in a two-layer magnon waveguide using a numerical model, as well as micromagnetic simulation and an experimental study based on microwave spectroscopy. By analyzing the magnetic properties of each layer and their equilibrium configurations, optimal conditions are predicted for increasing the frequency nonreciprocity coefficient of counter SWs in the Damon–Eshbach configuration, which are then confirmed by simulation. Such counter SWs can be measured using microwave spectroscopy for a prototype two-layer YIG-based microwave guide. The proposed concept of a two-layer spin-wave waveguide can inform the manufacture of magnon interconnectors and magnon interferometers with the support of multiband regimes of operation.

1. STRUCTURE AND EXPERIMENTAL RESULTS

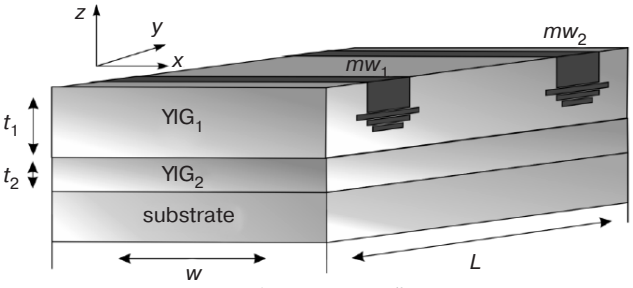

Fig. 1. Schematic representation of a two-layer magnon microwave waveguide with microwave antennas on top of one of the layers

Figure 1 shows the scheme of the investigated two-layer spin-waveguide structure. Single-crystal ferromagnetic two-layer ferrite YIG [$Y_3Fe_5O_{12}$] films (NII MV, Zelenograd, Russia) 0.5 × 7 mm^2 in size, epitaxially grown on gallium gadolinium garnet (GGG) [$Gd_3Ga_5O_{12}$(GGG)] substrates (NII MV), whose plane coincided with the (111) crystallographic plane, were used for the study. When creating a film on a GGG substrate, we first grew a pure YIG layer 7 μm thick with a saturation magnetization of $4\pi M_1$ = 1738 G (we will call this layer YIG$_1$), and a 9 μm thick YIG layer doped with gallium and lanthanum was grown on it with a saturation magnetization $4\pi M_2$ = 904 G (we will call this layer YIG$_2$). The structure is placed in a uniform external magnetic field H_0 = 670 Oe, oriented along the positive or negative direction of the x axis. The width of both samples was w = 500 μm, and the length was L = 7 mm. Input and output microwave transducers (Mikran, Russia) with a width of 30 μm were attached to the structure and marked in Fig. 1 as "mw_1" and "mw_2."

Using the vector network analyzer (model E8362C PNA, Keysight Technologies, USA), an experimental study of the characteristics of the SW was carried out. Figures 2a and 2b show the frequency dependence of the modulus of the gain $|S_{21}|$ in the positive direction of the external magnetic field (red curve), as well as in the negative direction (blue curve), which was measured when the output transducer is located at the end of the structure. Two well-defined frequency bands can be observed: the low frequency (LF) band (2.92–3.01 GHz) in Fig. 2a and the high frequency (HF) band (3.61–4.0 GHz) in Fig. 2b. When the direction of

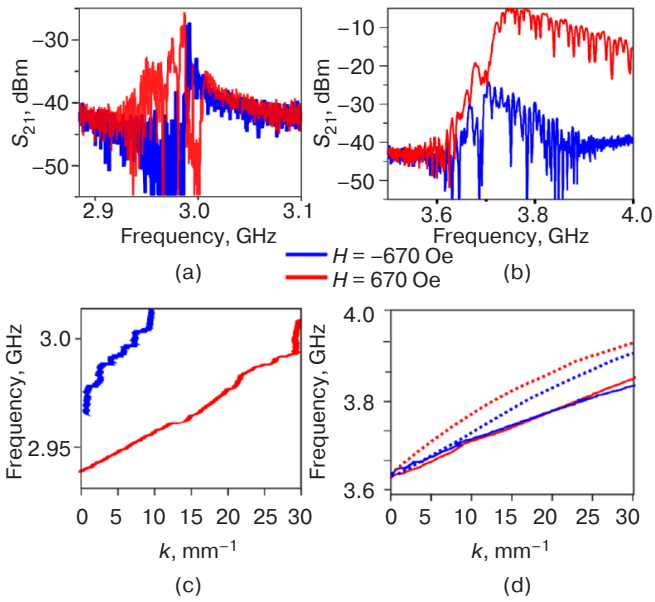

Fig. 2. Transmission coefficient modulus and dispersion characteristics of SW at the output of the structure

the external magnetic field changes, the bandwidth can be seen to change in the LF and HF regions. The SW amplitude decreases in the case of a negative direction of the external magnetic field due to the fact that the microstrip converter was located on one side of the sample, namely, on the YIG_1 side.

Figures 2d and 2c show the measured dispersion characteristics of SWs propagating along a two-layer structure for the positive (solid red curve) and negative (solid blue curve) directions of the external magnetic field in different frequency ranges: low-frequency and high-frequency, respectively. The dotted lines show the results of micromagnetic modeling of the dispersion characteristic in the HF range. A change in the direction of the external magnetic field alters the characteristics of SW propagation in a two-layer structure as a result of different values of magnetization saturation in the layers of the structure under study. All measurements were carried out at a magnetic field value of 670 Oe.

2. NUMERICAL SIMULATION

An analytical model of the dispersion equation was developed based on the magnetostatic approximation for a YIG waveguide of finite width and a dispersion of a two-layer film FM1/FM2, described in [25]. Equation (3) from [19] was used with the replacement of $k_x^2 + k_y^2 - k$ and $k_z = \frac{n\pi}{\omega}$, $n = 1, 2, 3, ...$, where n is the mode index of the transversal SW. Figure 3a shows the results of solving the SW dispersion equations in a two-layer structure for w = 500 μm. With the help of numerical simulation using the finite element method, a direct solution of the system of Maxwell equations for the first three SW modes for a two-layer system was obtained. This result corresponds to the dispersion characteristic for Fig. 3a, where each mode is indicated by color: red curve corresponds to n = 1; blue curve corresponds to n = 2; green curve corresponds to n = 3. Good agreement was found between the solution of the eigenmode problem and the analytical approach. Although the modes appear to be the same for the lower branch of the dispersion characteristic, the SW propagates in the YIG layer with a lower saturation of magnetization.

To estimate the nonreciprocity phenomenon, we use the nonreciprocity coefficient in the form $\kappa_{HF} = f_+ - f_-$, where f_+ is the frequency of SW propagation in the positive direction of the y axis, while f_- is the frequency of SW propagation in the negative direction of the y axis with the same wavenumber k. The nonreciprocity coefficient for the lower branch of the dispersion characteristic is determined in the same way: $\kappa_{HF} = f_+ - f_-$. Both coefficients are shown in Fig. 3b and Fig. 3c for w = 500 μm. Thus, as the wavenumber increases, the nonreciprocity coefficient decreases for the upper branch of the dispersion characteristic but increases for the lower one. This opens up opportunities for creating waveguide structures offering the function of signal demultiplexing, filtering and parallel data processing across two separate frequency ranges.

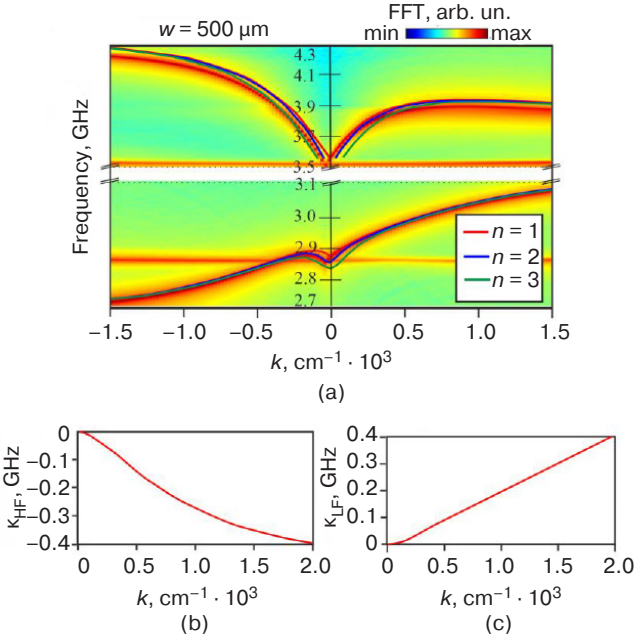

Fig. 3. (a) Dispersion characteristics measured using the analytical model and as a result of micromagnetic modeling; (b) nonreciprocity coefficient κ_{HF} for the HF region; (c) nonreciprocity coefficient κ_{LF} for the LF region

The distribution of the internal magnetic field was estimated by means of a micromagnetic simulation performed using the *MuMax3* program code [47].

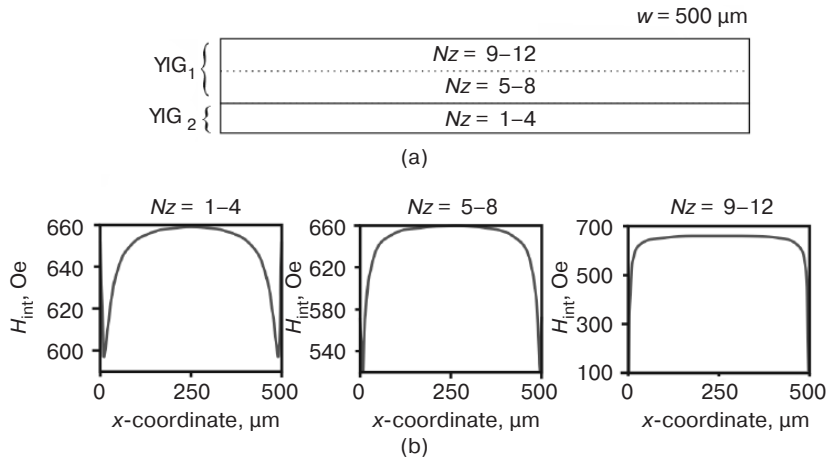

Fig. 4. (a) Schematic representation of simulation along the *z*-axis in *MuMax3*; (b) profiles of internal magnetic fields in layers for $w = 500$ μm

For this, a model corresponding to the experimental sample of the structure under study is considered. The cell size in the system was $4.00 \times 4.00 \times 1.25$ μm^3, while the damping constant $\alpha = 10^{-4}$. The material and the configuration were chosen according to the parameters used in the experiment. The resolution of the computational domain along the *Nz* axis was numbered by 12 layers, which is shown in the diagram in Fig. 4a. The coordinate system is based on the global coordinate system shown in Fig. 1. Figure 4b shows the results of numerical simulation of the profiles of internal magnetic fields in corresponding layers *Nz*, $w = 500$ μm. As the structure's width changes, the internal magnetic fields can be seen to critically decrease by *Nz* = 1–4. Even in the upper layers, internal magnetic fields are impacted by demagnetizing fields and structure boundaries, which in turn strongly affects the propagation spectra of SW in this type of the structure.

The inhomogeneous distribution of the internal magnetic field leads to a more pronounced nonreciprocal behavior of the spin-wave signal. In the two-layer system proposed in [48], frequency nonreciprocity can be turned on and off by simply switching from antiparallel to parallel magnetization without any rotation of the applied magnetic field. Such switching can be conveniently controlled by applying, for example, spin-transfer or spin-orbit torques via a local current. In addition, both parallel and antiparallel states are well known from giant magnetoresistance and tunneling magnetoresistance applications and can be tuned to ensure stability under remanent magnetization. For a real two-layer waveguide, such switching becomes possible by replacing YIG material, for example, by CoFeB [48, 49] and NiFe [50]. This would make it possible to realize an additional degree of freedom for dual-band communication. On the other hand, such replacement can lead to higher losses of SW propagation in metal films. Thus, two-layer YIG waveguides demonstrate the ability to imitate the widely studied dynamic properties of FM-heavy metal layers at the same time as representing a simple approach for controlling the value of nonreciprocity through geometry and equilibrium configuration.

CONCLUSIONS

Thus, the propagation modes of a spin-wave signal in a coupled two-layer ferromagnetic system have been studied. Microwave spectroscopy was used to study the transmission characteristics of SW in a two-layer YIG waveguide. Using the magnetostatic approach along with numerical simulation of the eigenvalue problem, it was demonstrated that the dipole interaction between FM layers, which is created by dynamic magnetizations, is a significant source of nonreciprocity in SW frequencies. The distribution profiles of the internal field and the nonreciprocity coefficient for a two-layer structure are calculated. A transformation of dispersion curves propagating in two opposite directions is revealed. It is shown that two-layer structures support two frequency bands of SW propagation. The formation mechanisms of SW width modes in the spectrum of a two-layer structure, which are formed due to the finite dimensions of the microwaveguide, are studied in a magnonic microwaveguide. In this case, modes corresponding to waves with different group velocity signs are observed in the wave spectrum.

The confirmation of the obtained results by micromagnetic simulation demonstrates the possibility of SW propagation in the low-frequency and high-frequency ranges of two layers in experimentally observed localization of SW modes. As well as opening up new ways to fabricate nonreciprocal magnonic devices, these results encourage a deeper study of this type of system with the aim of optimizing their design to meet the desired application requirements. In this case, the proposed concept of a two-layer spin-wave

waveguide can underlie the manufacture of magnon interconnectors and magnon interferometers with the support of multiband regimes of operation.

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Authors' contributions

S.A. Odintsov—condicting, prosessing, and analyzing the numerical and experimental studies, writing the text of the article.

E.H. Lock—creating the experimantal model.

E.N. Beginin—development of numerical research methodology.

A.V. Sadovnikov—development of the research concept, conducting the experimental studies, and editing the article.

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RESEARCH ARTICLE

Spline approximation of multivalued functions in linear structures routing

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Abstract

Objectives. The theory and methods of spline approximation of plane curves given by a sequence of points are currently undergoing rapid development. Despite fundamental differences between used splines and those considered in the theory and its applications, results published earlier demonstrate the possibility of using spline approximation when designing routes of linear structures. The main difference here consists in the impossibility of assuming in advance the number of spline elements when designing the routes. Here, in contrast to widely use polynomial splines, the repeating element is the link "segment of a straight line + arc of a circle" or "segment of a straight line + arc of a clothoid + arc of a circle + arc of a clothoid." Previously, a two-stage scheme consisting of a determination of the number of elements of the desired spline and subsequent optimization of its parameters was proposed. Although an algorithm for solving the problem in relation to the design of a longitudinal profile has been implemented and published, this is not suitable for designing a route plan, since, unlike a profile, a route plan is generally a multivalued function. The present paper aims to generalize the algorithm for the case of spline approximation of multivalued functions making allowance for the design features of the routes of linear structures.

Methods. At the first stage, a novel mathematical model is developed to apply the dynamic programming method taking into account the constraints on the desired spline parameters. At the second stage, nonlinear programming is used. In this case, it is possible to analytically calculate the derivatives of the objective function with respect to the spline parameters in the absence of its analytical expression through these parameters.

Results. An algorithm developed for approximating multivalued functions given by a discrete series of points using a spline consisting of arcs of circles conjugated by line segments for solving the first stage of the problem is presented. An additional nonlinear programming algorithm was also used to optimize the parameters of the resulting spline as an initial approximation. However, in the present paper, the first stage is considered only, since the complex algorithm of the second stage and its justification require separate consideration.

Conclusions. The presented two-stage spline approximation scheme with an unknown number of spline elements is also suitable for approximating multivalued functions given by a sequence of points on a plane, in particular, for designing a route plan for linear structures.

Keywords: route, plan, longitudinal profile, spline, dynamic programming, objective function, constraints

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НАУЧНАЯ СТАТЬЯ

Сплайн-аппроксимация многозначных функций в проектировании трасс линейных сооружений

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Резюме

Цели. В настоящее время наблюдается бурное развитие теории и методов сплайн-аппроксимации плоских кривых, заданных последовательностью точек. Проведенные исследования, первые результаты которых были опубликованы ранее, показали возможность применения сплайн-аппроксимации в проектировании трасс линейных сооружений, несмотря на принципиальные отличия используемых сплайнов от рассматриваемых в теории и ее приложениях. Главное отличие состоит в том, что в проектировании трасс нельзя заранее считать известным число элементов сплайна. Кроме того, в отличие от получивших широкое распространение полиномиальных сплайнов, повторяющимся элементом является связка «отрезок прямой + + дуга окружности» или «отрезок прямой + дуга клотоиды + дуга окружности + дуга клотоиды». Ранее была предложена двухэтапная схема: определение числа элементов искомого сплайна, затем – оптимизация его параметров. Алгоритм решения задачи применительно к проектированию продольного профиля реализован и опубликован. Но этот алгоритм непригоден для проектирования плана трассы, т.к. план трассы, в отличие от профиля, в общем случае является многозначной функцией. Цель работы – обобщить алгоритм на случай сплайн-аппроксимации многозначных функций с учетом особенностей проектирования трасс линейных сооружений.

Методы. На первом этапе используется новая математическая модель, позволяющая применить метод динамического программирования с учетом ограничений на параметры искомого сплайна. На втором этапе используется нелинейное программирование. При этом удается вычислять аналитически производные целевой функции по параметрам сплайна при отсутствии ее аналитического выражения через эти параметры.

Результаты. Разработаны алгоритм аппроксимации многозначных функций, заданных дискретным рядом точек, сплайном, состоящим из дуг окружностей, сопрягаемых отрезками прямых, для решения задачи на первом этапе и алгоритм нелинейного программирования для оптимизации параметров полученного сплайна как начального приближения. В настоящей статье рассматривается только первый этап, т.к. сложный алгоритм второго этапа и его обоснование требуют отдельного рассмотрения.

Выводы. Двухэтапная схема сплайн-аппроксимации при неизвестном числе элементов сплайна пригодна и для аппроксимации многозначных функций, заданных последовательностью точек на плоскости, в частности для проектирования плана трасс линейных сооружений.

Ключевые слова: трасса, план, продольный профиль, сплайн, динамическое программирование, целевая функция, ограничения

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INTRODUCTION

The present paper comprises a continuation of the work [1] in which the problem of approximating functions given by a sequence of points on a plane by the spline of special form was considered. There, arcs of circles conjugated by line segments comprised spline elements. The problem was analyzed in relation to the design of the longitudinal profile of linear structures (railways, highways, pipelines for various purposes, etc.). Since a route comprises a plane curve whose plan is its projection on a plane *XOY*, while the longitudinal profile is the function $Z(s)$, where s is the arc length from a given origin in the plan; then, the longitudinal profile comprises a flat curve representing a graph of a single-valued function. The algorithm for spline approximation discussed in [1] is based on this circumstance. Here, the route plan may or may not be the graph of a single-valued function. However, the earlier implemented algorithms turn out to be generally unsuitable for multivalued functions. Thus, other mathematical models and methods are required.

The theory of splines, which appeared in the late 1960s, had been initially considered as a problem of interpolating given points (nodes) of some curve consisting of elements of the same given kind, which would have a common ordinate—and, as a rule, a common tangent—at the spline nodes [2].

From this point on, only the abscissas of nodes needed to be recorded, and researchers became to solve spline approximation problems instead of using interpolation. Then, spline approximation problems began to be solved when varying not only the ordinates but also the abscissas of nodes. In this case, the number of spline elements was taken as known. The most commonly used splines were polynomial and, in particular, cubic [3].

Spline approximation problems arising when designing railway and highway routes and other linear structures differ in that the repeating spline elements comprise groups of elements. When designing the route plan, it is the "straight line + clothoid + circle + + clothoid", etc. Finding the number of spline elements is a separate and rather complex task, as is optimizing the spline parameters that determine its position on a plane.

As noted by Professor Hao Pu in [4], China currently has more than 120 000 km of operating railways, with about 20 000 km of existing railways to be reconstructed by 2025. It is noted that Chinese design engineers are very interested in the emergence of an automatic and accurate method for designing route plans.

When designing the Baikal-Amur Mainline (BAM) in the USSR in the 1970s, the first longitudinal profile design programs were used in all three BESM-4 computers available at the design institutes of the Ministry of Transport Construction in Moscow, Leningrad, and Novosibirsk [5]. Due to the extremely limited technical capabilities of the best computer available at that time (4 096 random access memory cells and 40 000 floating-point operations per second), the absence of visualization tools, and difficulties in input of initial data (punched cards), no significant cost reduction in design was achieved. However, the results obtained at various sections of the BAM proved the efficiency of applying mathematical optimization methods, which was above all due to the improved quality of design solutions [5]. In the 1980s, the domestic system of computer-aided design (CAD) of new railways, which used design programs but without visualization of initial data and results, was developed on ES EVM (the Unified System of Electronic Computers) computers. Consequently, imported systems having such tools and programs but without using optimization methods became widespread during the transition to personal computers. Since then, despite the establishment of a myth that optimization is unnecessary due to designers obtaining optimal solutions interactively, authors such as Hao Pu have shown that this is far from being the case.

At present, the problem of optimizing spline parameters is solved interactively in existing CAD systems[1, 2, 3, 4, 5], with the designer specifying information that uniquely determines the desired design spline. This is essentially the method of element selection in graphics mode with visual control: the computer is used in place of template and ruler without the application of mathematical optimization methods. Therefore, the quality of the results depends on the experience, intuition, and motivation of the designer. Moreover, such "screen crawling" is a rather labor-intensive process. This would seem to justify research on formalizing the problem in mathematical models and applying mathematically correct optimization algorithms. However, in its place, various heuristic algorithms have been proposed both in Russia and abroad. The given points are connected by line segments to obtain a broken line (first-order spline) that must be replaced by a spline with circles conjugated by lines or clothoids and lines at the smallest (in a certain sense) deviation from the original spline (broken line). At the same time, technical constraints have been imposed on the desired spline parameters to ensure normal operation of the designed new or reconstructed structure.

[1] Bentley Rail Track. URL: https://www.bentley.com/-media/1EA2B937CB5B42BEA5EAE802620C0BA3.ashx. Accessed January 15, 2022.

[2] CARD/1. URL: http://card-1.ru/. Accessed January 15, 2022 (in Russ.).

[3] Autodesk. URL: https://www.architect-design.ru/autodesk/autocad/. Accessed January 15, 2022 (in Russ.).

[4] Topomatic Robur. URL: http://www.topomatic.ru/. Accessed January 15, 2022 (in Russ.).

[5] Credo-Dialog. URL: https://credo-dialogue.ru/. Accessed January 15, 2022 (in Russ.).

The first studies on designing a route plan considered curvature plots [6–8] used as a basis to determine straight inserts. However, this idea has not been developed further due to the extreme difficulty of obtaining, even visually, a straight insert of 30–35 m length on the disrupted route; this is especially true when the curves of the same sign are conjugated in complex cases of surveying points every 20 m.

Next, software developers moved towards the construction of angle diagrams [9], i.e., graphs of the angle of the current polyline element with the *OX* axis against the distance (polyline length) from the starting point. In such graphs, the straight line, circle, and clothoid correspond to the horizontal line, sloping line, and second-degree parabola in the route plan, respectively. The task then becomes to determine element boundaries and perform spline calculations.

Here, the recent work on automated designing the route plan of reconstructed railways by Hao Pu et al. [4] should be noted. The paper deals with the analysis of studies in this field concluding that existing methods do not allow the problem to be solved automatically but are only capable of generating a local optimal solution with allowance for several constraints. In addition, it is noted in [4] that automatic determination of the number of curves, lengths of circles, clothoids, and straight inserts is a complex task. For this reason, it is proposed to find the number of spline elements (circular curves with no allowance for the presence of clothoids) at the first stage using a heuristic algorithm with further result optimization using genetic algorithms [10–19]. According to [4], after preliminarily approximating the boundaries of the straight line by the angle diagram, a heuristic algorithm called a "swing iteration" is proposed for reclassifying point location and determining the position of straight lines more precisely, along with subsequent circular and transitive curves. In a swing iteration, the segment boundary of a geometric element is repeatedly changed from left to right, then right to left, and finally stabilized. It follows from [4] that genetic algorithms have allowed significant improvements to the first stage result while solving the real problem.

An apparently more reliable approach utilizes the same two-stage scheme for solving the problem, but with mathematically correct algorithms: dynamic programming algorithms for determining the number of elements and their parameter approximates at the first stage and nonlinear programming algorithms for optimizing the obtained spline parameters at the second stage. This scheme has been successfully used in designing the longitudinal profiles of railways and highways. When designing railways, the spline in the form of a broken line was originally used [20]; when moving to the design of highways, a spline consisting of vertical circular curves conjugated by straight lines was used [1]. For designing the longitudinal profiles of roads, a spline having elements of second-degree parabolas has also been used [21].

The problem of spline approximation of multivalued functions is relevant for computer-aided design of a route plan, which in general comprises a graph of precisely this function.

Spline becomes a multivalued function not only in the presence of curves having tangent line angles with the *OX* axis greater than 90° but also in the case of several curves of the same sign having small rotation angles, but at a large total angle of rotation. In general, it is also necessary to consider curves with rotation angles greater than 180°.

In this paper, we present dynamic programming features for solving this problem. First, we consider spline consisting of arcs of circles conjugated by straight lines as a multivalued function. This is a separate problem, since variable curvature curves that include clothoids are not used when designing route plans of some linear structures, for example, pipeline trenches of different purposes. This much simpler problem requires significantly less computation at the first stage than when using a spline with clothoids. In addition, when using clothoids of short lengths and large circular curve radii their insertion results in insignificant shifts of the resulting spline with circles, since deviation p of the circle of radius R from the angle side to which it fits with a clothoid of length l into may be calculated by the well-known formula $p = l^2/(24R)$. Thus, $p < 0.08$ m is satisfied at $l = 30$ m and $R = 500$ m.

Therefore, a spline with circles may be considered generally as the initial approximation for the second stage. In any case, the number of curves is not further changed; the first stage may be repeated at a known number of elements to find a spline with clothoids.

This drastically reduces the number of calculations with the use of dynamic programming, since it is not necessary to consider replacing two curves by one at a known number of elements.

Optimizing parameters of the spline as a multivalued function using nonlinear programming is a complex problem with solution to be discussed in a separate paper.

PROBLEM STATEMENT AND FORMALIZATION

For a given sequence of points on a plane (Fig. 1), we shall obtain a spline consisting of arcs of circles conjugated by line segments, whose parameters satisfy the constraint system, while the sum of deviation squares of given points from the spline is minimal. If there are areas where it is necessary to obtain small deviations, the weighted sum of squares can be used instead of the

simple solution. In addition, the constraints in the form of inequalities can be imposed on deviations at separate points. Unfortunately, it is impossible to fix the point within the discrete search at this stage.

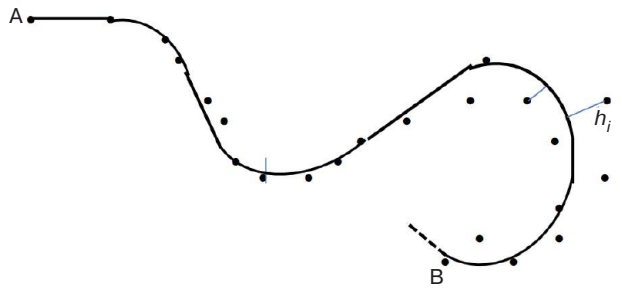

Fig. 1. Starting points and approximating spline

The starting point A and end point B are set along with their directions and not changed during the spline search. These may or may not coincide with origins.

The deviations are calculated for normal to spline. If the number of points is n and their deviations from the spline are h_i (i = 1, 2, ..., n), then the sum $\sum_{i=1}^{n} h_i^2$ must be minimal, subject to the following constraints on spline parameters: the lengths of line segments and arcs of circles must not be less than the specified values, while the radii of circular curves must be within the specified limits.

At the first stage, it would be convenient to consider the elements in the following order: curve + straight line, etc. If the number of these links is k, the line lengths are L_j^{sl}, the curve lengths are L_j^{c}, and the radii are R_j, then the constraints on spline parameters may be formalized by the following system of inequalities:

$$L_j^{\text{sl}} \geq L_{\min}^{\text{sl}}, \quad (1)$$

$$L_j^{\text{c}} \geq L_{\min}^{\text{c}}, \quad (2)$$

$$R_{\min} \leq |R_j| \leq R_{\max} \ (j = 1, 2, \ldots k). \quad (3)$$

The radii of the curves are positive when moving counterclockwise and negative otherwise. All limit values $L_{\min}^{\text{sl}}$, $L_{\min}^{\text{c}}$, $R_{\min}$, and $R_{\max}$ are given.

Clearly, it would be sufficient to find the coordinates of each curve origin and the tangent direction in it. The first curve origin is considered given. This may be point A (Fig. 1) or another point on the tangent drawn from point A. However, if the initial line length is considered unknown at this stage, then the problem becomes much more complex, as can be seen below. However, it is possible to avoid significant complications by specifying several possible points for the first curve origin from which the initial line length may be consequently derived. The same procedure may be carried out with the end point along with the specification of several starting and ending directions.

The basic concept in dynamic programming—"system state"—may be defined as an aggregate of the starting point of the next curve and the tangent direction to the curve at this point. To that end, normals to the given polyline should be constructed at starting points. These comprise a line connecting a given point to the center of a circle drawn through three adjacent points if they are not on the same line, or a normal to this line (Fig. 2). However, it is not necessary to construct normals at the beginning and end of the route in sections of length $L_{\min} = L_{\min}^{\text{sl}} + L_{\min}^{\text{c}}$ from the starting and end points, respectively, since the desired points of curve origins cannot in any case be located in these sections due to constraints (1)–(3).

Since the initial direction is given, moving from the beginning to the end at each point, the direction of the external normal—and, respectively, the tangent—may be determined so that they constitute the right-hand triple. The angles of external normals with the OX axis (γ_j in Fig. 2) are precalculated. The tangent direction is determined by angle ($\gamma_j - \pi/2$) with the OX axis. The starting point coordinates along with the tangent direction determine one "system state" on each normal. Since the curve origin does not necessarily coincide with the starting point, several points on each normal with step Δ (Fig. 2) and several possible tangent directions at each point on each normal (the angle side which the circle fits into) may be set.

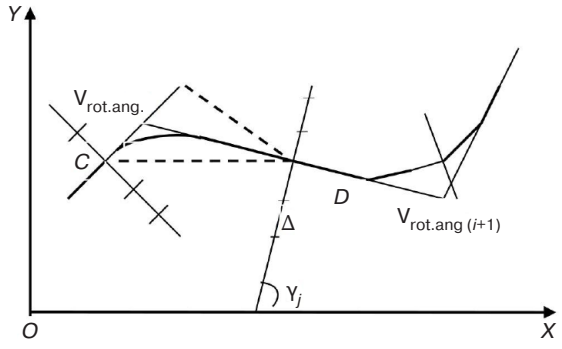

Fig. 2. Defining the normals and sets of "system states"
$V_{\text{rot.ang.}}$ is the rotation angle vertex

In this way, a set of possible states may be constructed. The process of obtaining the spline is reduced to a dynamic programming problem: construct a path (sequence of states) to transfer the "system" from the initial state to the final one with minimum costs (at the minimum of the objective function). Sequential states should be selected with allowance for constraints (1)–(3) and constraints on displacements at separate points, if given.

CONSTRUCTING A SPLINE USING THE DYNAMIC PROGRAMMING METHOD

When constructing a path from the initial to the final point in accordance with R. Bellman's optimality principle [22], options for achieving the same state by different paths allowed by constraints are considered and compared; eventually, one option with a smaller value of the objective function is left in each state.

Implementing this rule requires setting some more parameters: the already mentioned discretes by normals Δ and angles φ, as well as their numbers per normal; *maxrix* is the maximum allowed deviation of the spline from surveying points, while L_{max} is the maximum length of the link "circle + straight line," i.e., the maximum distance (by initial broken line) between two subsequent states (curve origins). Typically, $L_{max} = (3–4)L_{min}$, but it may be greater in the presence of long curves. Due to the simplicity of the algorithm (in terms of low computational resources), it is reasonable to set L_{max} "with a margin" and limit the link length, if L_{max} already contains two curves with different sign, since these curves cannot be replaced by a single link with admissible deviations. The *maxrix* value, which specifies the search range on a plane with respect to the original polyline, should also be set with care when analyzing specific data. If small values are set, there may be no solution in the corresponding area due to constraints. Setting large *maxrix* values does not affect the search accuracy but results in the increased amount of computation that is not very significant in this case.

First stage of the algorithm

For the starting point A (if there are several starting points given, then for each of them sequentially), the normals in the range from L_{min} to L_{max} (points C and D in Fig. 3) are considered. For every point on every normal and every tangent direction at this point, the corresponding vertex of the angle of rotation at the intersection with the initial direction is determined. These comprise the points V_1 and V_2 in Fig. 3. Some other directions are shown as dashed lines.

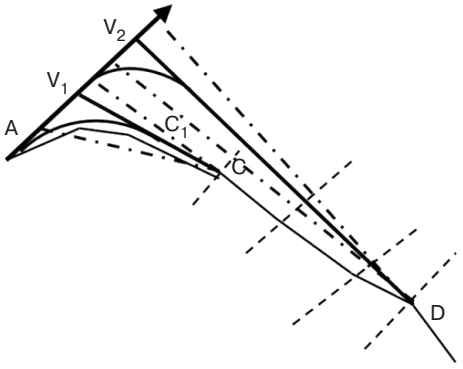

Fig. 3. Option construction at the first stage of the algorithm

The distances from each angle vertex to the starting point and to the point on the normal may be obtained as follows. For the first vertex, the distances are AV_1 and V_1C, respectively. If $AV_1 > V_1C_1 - L^{sl}_{min}$, then this option of selecting starting points is rejected. Otherwise, point C_1 on the angle side V_1C is found such that $AV_1 = V_1C_1$

The distance CC_1 is the length of the straight line in the desired link "circle + straight line."

$$AV_1 = R\mathrm{tg}(\alpha/2),$$

where α is the rotation angle, i.e., the difference between the angles of the angle sides and the *OX* axis. From here, value *R*, followed by the center of the circle using point A and the normal to the initial direction, may be obtained. Since a search of the radius values is not required, the starting point of the curve has also been fixed, along with several options to be used if finding it is not possible. When constraint (3) (on radius) or constraint (2) (on curve length) is not satisfied, the next state may be considered. Here, it should be noted that if the constraints are violated, many states could be excluded from consideration.

If constraints (1)–(3) are satisfied, then distances h_i to the arc of the circle (before going beyond the arc) and then distances to the straight insert for remaining points are found. Should $h_i > maxrix$ or the constraints on displacement of some points be violated, the remaining distances are not calculated, while this option of locating starting points of the curve is rejected. Otherwise, the objective function value is calculated and memorized along with all data required to subsequently restore the spline (radius, coordinates of arc end C_1, etc.).

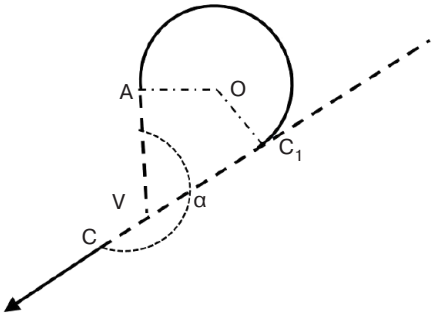

Fig. 4. Calculation at angles of rotation greater than π

If rotation angle $\alpha > \pi$ (Fig. 4), no particular difficulties arise. In this case, $AV = R\left|\mathrm{tg}(\pi - \alpha/2)\right| = R\left|\mathrm{tg}(\alpha/2)\right|$, CC_1 is straight insert, while the arc length $L = R\alpha$. Hence, checking constraints (1)–(3) is performed in the same way as for small rotation angles. In the theoretically possible case of $\alpha = \pi$ (Fig. 5), there is no angle vortex, the radius is half the distance between parallel lines; the arc length $L = \pi R$. Straight insert CC_1 as well as values *R* and *L* may be unacceptable. Deviations from survey points are calculated in the same way as above.

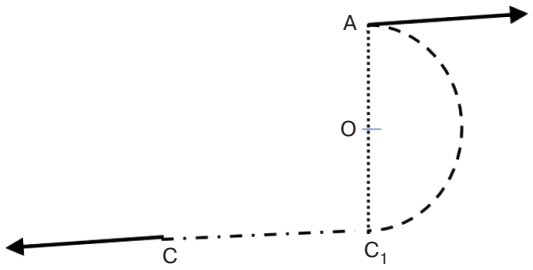

Fig. 5. Calculation when parallel lines

It should be noted that there is no option comparison and their rejection by the objective function value at the first stage.

General stage of the algorithm

At next stages, all normals ranging from $2L_{min}$ to S is L_{min}, where S is the length of the original polyline are considered. For each such normal, the possibility of constructing the link "circle + straight line" with the starting point belonging to the preceding normal that is at least L_{min} and at most L_{max} away from the considered normal is analyzed. The difference from the first stage of the algorithm is that now there are many options of the left angle side instead of one for each point and direction on the considered normal. All acceptable options of transition to the considered state from previous states are compared by the objective function and the best one memorized. The corresponding state of the constructed link origin is also memorized. In other words, transitions not only unacceptable by constraints but also ineffective are rejected. It may turn out that two admissible paths consisting of different number of links result in the same state. This means that dynamic programming considers paths with different number of elements to eventually determine the number of elements for the approximating spline, having previously been unknown.

At the last stage, the same actions are performed for the final state or several such states, if given. As a result, the comparison yields the objective function value for the best option of the path. The path, i.e., the desired spline, is defined by the usual reversal from the found final best state along the chain of links used in dynamic programming, since the corresponding curve origin has been memorized for each state [20, 21].

REDUCING THE SEARCH OF OPTIONS

The considered problem and the dynamic programming algorithm may be characterized by the presence of constraints not only avoiding an unnecessary complication of the problem but also allowing the search of options to be significantly reduced. When the attempt to construct the link "arc circle + line segment" is unsuccessful, many transitions to another state (displacements along the right normal or rotations of the tangent, Fig. 3) are obviously inefficient due to the constraints remaining violated during this transition. For example, the minimum radius constraint is violated when fitting into the angle. Obviously, with the rotation angle α unchanged, the tangent T (the distance from the tangent point to the angle vertex) cannot be reduced since $R = T/\mathrm{tg}(\alpha/2)$. Accordingly, displacements along the right normal reducing T are unacceptable.

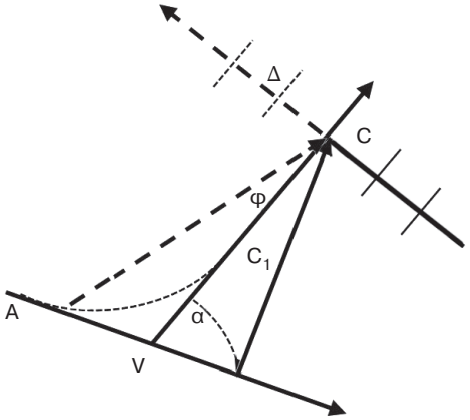

Fig. 6. Rejecting transitions when constraints are violated

In Fig. 6, T = AV. Transitions to the new state from point C (displacements along the normal and rotations of the tangent) unnecessary $R < R_{min}$ are shown dashed (e.g., to the left of point C). If straight insert C_1C is less than the acceptable one, the constraints on radii and curve lengths are satisfied; then, conversely, only dashed displacements and rotations result in its increase. However, due to the reduction in tangent AV and curve length, the "margin" for these parameters may be insufficient.

At any arrangement of normals and different rotation angles, each violated constraint provides information concerning which states cannot be efficiently transferred to on the given normal. Although this analysis slightly complicates the algorithm for spline construction, it is fully compensated by reducing the search of options.

CONCLUSIONS

The method for approximating the sequence of points on a plane by a spline with circles and straight lines described in this paper may not only be used in designing routes of linear structures but also in processing generally any type of data when constructing paths. As for its practical application in designing routes of linear structures, the question remains open and is the lack of interested users.

In Russia, the number of design works may increase in future due to new railway and highway construction and reconstruction projects. This may result in the growing interest of relevant authorities in reducing

construction costs by optimizing design solutions, thus giving relevance to developing new design algorithms and programs.

As was the case during the Soviet period, the development of such design approaches requires theoretical and experimental research by specialized scientific departments. The first Russian developments in optimization of design solutions were significantly ahead of their foreign equivalents. However, foreign authors even now propose mainly various heuristic algorithms without using modern mathematical achievements. The present paper and its sequel dealing with the optimization of splines with arcs of circles and straight lines for the approximation of multivalued functions using nonlinear programming paves the way for a solution of the more complex and important—in theoretical and practical terms—problem of approximating multivalued functions using composite splines with clothoids. This is a relevant topic for further research in this field.

Authors' contribution. All authors equally contributed to the research work.

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RESEARCH ARTICLE

Properties of objective functions and search algorithms in multi-objective optimization problems

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Abstract

Objectives. A frequently used method for obtaining Pareto-optimal solutions is to minimize a selected quality index under restrictions of the other quality indices, whose values are thus preset. For a scalar objective function, the global minimum is sought that contains the restricted indices as penalty terms. However, the landscape of such a function has steep-ascent areas, which significantly complicate the search for the global minimum. This work compared the results of various heuristic algorithms in solving problems of this type. In addition, the possibility of solving such problems using the sequential quadratic programming (SQP) method, in which the restrictions are not imposed as the penalty terms, but included into the Lagrange function, was investigated.

Methods. The experiments were conducted using two analytically defined objective functions and two objective functions that are encountered in problems of multi-objective optimization of characteristics of analog filters. The corresponding algorithms were realized in the MATLAB environment.

Results. The only heuristic algorithm shown to obtain the optimal solutions for all the functions is the particle swarm optimization algorithm. The sequential quadratic programming (SQP) algorithm was applicable to one of the analytically defined objective functions and one of the filter optimization objective functions, as well as appearing to be significantly superior to heuristic algorithms in speed and accuracy of solutions search. However, for the other two functions, this method was found to be incapable of finding correct solutions.

Conclusions. A topical problem is the estimation of the applicability of the considered methods to obtaining Pareto-optimal solutions based on preliminary analysis of properties of functions that determine the quality indices.

Keywords: multi-objective optimization, Pareto optimality, quality index, objective function, fitness landscape, heuristic algorithm, quadratic programming

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НАУЧНАЯ СТАТЬЯ

Свойства целевых функций и алгоритмов поиска в задачах многокритериальной оптимизации

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Резюме

Цели. Часто применяемый метод поиска оптимальных по Парето решений состоит в минимизации выбранного показателя качества при задании ограничений на остальные показатели, значения которых, таким образом, оказываются заранее определенными. При этом выполняется поиск глобального минимума скалярной целевой функции, в которую ограничиваемые показатели входят в виде штрафных слагаемых. Рельеф такой функции содержит участки быстрого роста, значительно затрудняющие поиск глобального минимума. В работе сравниваются результаты различных эвристических алгоритмов при решении задач этого типа. Кроме того, исследуется возможность использования алгоритма последовательного квадратичного программирования (SQP), в котором ограничения учитываются не через штрафные слагаемые, а включаются в функцию Лагранжа.

Методы. В экспериментах использовались две аналитически заданные целевые функции и две целевые функции, встречающиеся в задачах многокритериальной оптимизации характеристик аналоговых фильтров. Исследуемые алгоритмы были реализованы программами в среде *MATLAB*.

Результаты. Установлено, что единственным эвристическим алгоритмом, который нашел оптимальные решения для всех функций, оказался алгоритм роя частиц. Алгоритм SQP оказался применим для одной из аналитически определенных функций и для одной из целевых функций оптимизации фильтров, существенно превзойдя при этом эвристические алгоритмы по точности и скорости поиска решения. Но для двух других функций данный алгоритм оказался неспособным находить правильные решения.

Выводы. Актуальной является задача оценки применимости рассмотренных методов для поиска Парето-оптимальных решений на основе предварительного анализа свойств функций, определяющих показатели качества.

Ключевые слова: многокритериальная оптимизация, оптимальность по Парето, показатель качества, целевая функция, рельеф целевой функции, эвристический алгоритм, квадратичное программирование

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Автор заявляет об отсутствии конфликта интересов.

INTRODUCTION

The global extrema of multimodal objective functions (OFs) having many local extrema can be obtained using heuristic algorithms [1, 2]. Unlike classical optimization methods, heuristic algorithms have not yet been subjected to comprehensive theoretical analysis [2–4]. Their characteristics can be evaluated and compared experimentally using sets of test functions [5, 6]. Different algorithms show the best characteristics on different test functions, which leads to the problem of choosing the most appropriate algorithm for an OF with certain properties. Methods have recently been developed for automatic analysis of the properties of the OF relief (exploratory landscape analysis, ELA) and machine learning to select an algorithm and/or adjust its parameters according to the results of such an analysis [7, 8]. However, the complete solution of this problem is still far away.

In radio engineering and other sciences, of considerable interest are multi-objective optimization problems [9]. As a rule, it is impossible to simultaneously optimize all quality indices (QI) because improvement of some of the QIs leads to impairment of others. Therefore, the goal of multi-objective optimization is to

find a set of Pareto-optimal solutions [1, 10]. A widely used way to search for them is to solve the problem

$$\mathbf{x}^* = \arg\min_{\mathbf{x}\in D'}\left(Q_k(\mathbf{x})\right),$$
$$D' = \left\{\mathbf{x}\in D \mid Q_j(\mathbf{x}) \le Q_{jt};\ i = 1,\ldots,M;\ j \ne k\right\}, \quad (1)$$

where $\mathbf{x}$ is the coordinate vector in the search space, D is the set (defined by inequality and/or equality restrictions) of allowable values of $\mathbf{x}$ in the search space, $Q_j(\mathbf{x})$ are functions that describe the QIs, M is the number of QIs, and $\mathbf{x}^*$ is the coordinate vector of the optimal solution. Without loss of generality, the problem of minimizing all the QIs was considered here.

In problem (1), all the QIs, except Q_k, are restricted from above, while Q_k is minimized. If the QIs are competing, then the minimum of Q_k is at the point $\mathbf{x}^*$ at which the other QIs reach the restrictions Q_{jt} imposed on them. This makes it possible to obtain solutions in which all the coordinates in the space of QIs, except the kth, are fixed at the objective values of Q_{jt}. It is known that this method can find any Pareto-optimal solution [10].

One of the methods to solve problem (1) is based on minimizing a scalar OF of the form

$$f(\mathbf{x}) = \sum_{j=1}^{M}\left(W_j \cdot \max\left(\frac{\left(Q_j(\mathbf{x}) - Q_{jt}\right)}{Q_{jt}^{\,q_j}}, 0\right)\right), \quad (2)$$

where $Q_j(\mathbf{x})$ and Q_{jt} are the current and objective values of the jth QI, respectively; and W_j is the weighting factor of the jth QI [2, 10]. If it is necessary to normalize the deviation of a QI from the objective value to reduce the terms in (2) to the same range of values, the exponent $q_j = 1$. If such a normalization is unnecessary, then the exponent $q_k = 0$. At $x > 0$, $\max(x, 0) = x$; otherwise, $\max(x, 0) = 0$.

The objective value Q_{kt} of the QI being minimized is given sufficiently low, e.g., equal to its minimum possible value, and the weighting factor is taken to be $W_k = 1$. The terms containing the other QIs are penalties for violation of restrictions imposed on them. The weighting factors at them should meet the conditions $W_j >> 1$ for such QI to be fixed near the objective values.

Problems of multi-objective optimization of the characteristics of analog and digital filters by the scalar OF method were considered earlier [11, 12].

The relief of OF (2) can be complex. If the objective values of the QIs to be fixed are exceeded, the OF value rapidly increases; for this reason, the relief has areas hereinafter referred to as "walls." In the available works aimed at analyzing the properties of OFs and selecting optimization algorithms, such OF properties were not studied. In view of the importance of multi-objective optimization, this gap needs to be addressed.

Another approach to solving problem (1) is based on nonlinear programming methods, in which restrictions on QIs are not imposed as penalty terms, but included in the Lagrange function; as applied to problem (1), this function has the form

$$L(\mathbf{x},\boldsymbol{\lambda}) = Q_k(\mathbf{x}) + \sum_{i=1}^{M-1}\lambda_i g_i(\mathbf{x}),$$
$$g_i(\mathbf{x}) = Q_j(\mathbf{x}) - Q_{jt},\ i = 1,\ldots,M-1,\ j = 1,\ldots,M,\ j \ne k, \quad (3)$$
$$\mathbf{x}\in D,$$

where λ_i are the Lagrange multipliers. The minimum of function (3) is found, in particular, using sequential quadratic programming (SQP) algorithm [3], provided that the Lagrange function $L(\mathbf{x}, \boldsymbol{\lambda})$ has continuous second derivatives.

Population algorithms, which comprise an alternative to the scalar OF method, can give an approximation of the Pareto set containing a given number of elements within one search cycle [1]. The main advantage of these methods is their significantly accelerated search. However, there are difficulties in obtaining solutions with given values of some of the QIs. Moreover, with increasing number of QIs, the quality of the found approximations of the Pareto set may decrease. For example, by comparing the results of solving the problem of multi-objective optimization of the characteristics of electric filters using population algorithms and the scalar OF method, it was shown that, at the number of QIs $M = 2$, population algorithms are advantageous not only in terms of search speed, but also in quality of the solutions obtained. At the same time, at $M = 3$, they are inferior in quality to the approximation of the Pareto set to the scalar function method [13]. The prospects for the use of population algorithms for multi-objective optimization require further research and will not be considered here.

The purpose of the present work was to study the characteristics of various optimization algorithms of searching for the global minimum of scalar OF of type (2) whose relief has walls, as well as to develop recommendations for choosing algorithms for solving such problems. In addition, we studied the possibilities of applying methods for solving problem (1) that do not use penalty terms.

METHODS OF INVESTIGATION

First of all, let us define OFs with necessary properties, i.e., with walls. The first two OFs are defined analytically:

$$f_1(\mathbf{x}) = \sum_{i=1}^{ND} x_i + W_1 \cdot \max\left(\sum_{i=1}^{ND} x_i^2 - a_1, 0\right), \quad (4)$$

$$f_2(\mathbf{x}) = \sum_{i=1}^{ND} x_i + \\ + W_2 \cdot \max\left(ND + \sum_{i=1}^{ND} \left(x_i^2 - \cos 2\pi x_i \right) - a_2, 0 \right). \quad (5)$$

In these expressions, ND is the dimension of the search space. In both functions, the QI being minimized is calculated as the sum of the coordinates of the vector $\mathbf{x}$. In function $f_1(\mathbf{x})$, the QI being fixed is defined as the sum of the squares of the coordinates; while in function $f_2(\mathbf{x})$, it is represented by the known Rastrigin test function [5]. The parameters a_1 and a_2 are the objective values of the QI being fixed, while the parameters W_1 and W_2 are the weighting factors of the penalty terms.

Figure 1 presents the graphs of the OFs $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$ at $ND = 2$, $a_1 = 1$, $a_2 = 2$, $W_1 = W_2 = 100$, $-2 \le x_i \le 2$, and $i = 1, 2$. In the graphs, the values of the functions are bounded from above at the levels $f_1(\mathbf{x}) = 1$ and $f_2(\mathbf{x}) = 2$. The reliefs of both functions contain pronounced walls. The number of local extrema of $f_2(\mathbf{x})$ increases exponentially with increasing dimension ND.

Let us further define two OFs that are encountered in the problems of multi-objective optimization of the characteristics of analog electric filter [11]. The first of them has the form

$$f_3(\mathbf{x}) = \frac{DTd(\mathbf{x}) - DTd_t}{DTd_t} + \\ + WHp \cdot \max\left(\frac{DHp(\mathbf{x}) - DHp_t}{DHp_t}, 0 \right) + \\ + WHs \cdot \max\left(\frac{HS_t - Hs(\mathbf{x})}{Hs_t}, 0 \right) + \\ + WHt \cdot \max\left(DHt(\mathbf{x}) - DHt_t, 0 \right). \quad (6)$$

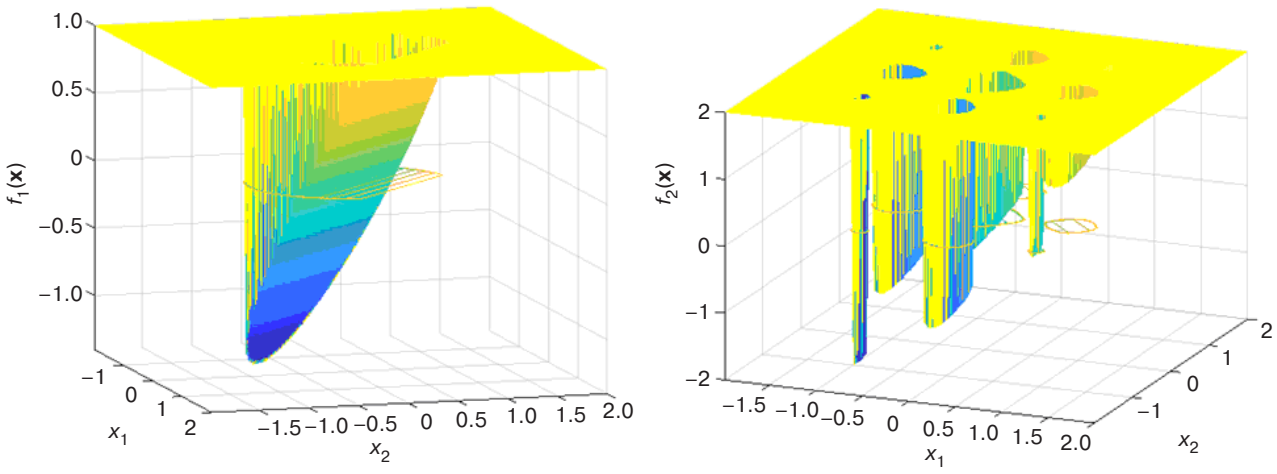
Here, DHp is the passband attenuation ripple (dB), Hs is the stopband attenuation (dB), DHt is the excess of the frequency response over the permissible level in the transition band between the passband and the stopband (dimensionless), and DTd is the relative passband delay time ripple (%). The coordinate vector $\mathbf{x}$ consists of the real and imaginary coordinates of the poles and zeros of the transfer function (one each from the complex conjugate pair). Methods to calculate the listed QIs were described in the literature [11, 14].

OF $f_3(\mathbf{x})$ (6) is obtained in the problem of minimizing the DTd QI under restrictions on the other three QIs. Since the Hs value should be maximized, this QI is subtracted from its objective value. In the experiments below, the values of the following quantities were given: the number of filter poles, $NP = 6$; the number of zeros, $NZ = 0$; the objective values of QI, $DHp_t = 0.5$, $Hs_t = 40$, $DHt_t = 1$, and $DTd_t = 10$; and the weighting factors, $WHp = 20$, $WHs = 500$, and $WHt = 1000$. The search space in all the coordinates was bounded by the inequalities $-3 \le x_i \le -0.01$.

The last OF has the form

$$f_4(\mathbf{x}) = \frac{Tss(\mathbf{x}) - Tss_t}{Tss_t} + \\ + WTfr \cdot \max\left(\frac{Tfr(\mathbf{x}) - Tfr_t}{Tfr_t}, 0 \right) + \\ + WUm \cdot \max\left(\frac{Um(\mathbf{x}) - Um_t}{Um_t}, 0 \right) + \\ + WHs \cdot \max\left(\frac{HS_t - Hs(\mathbf{x})}{Hs_t}, 0 \right) + \\ + WHt \cdot \max\left(DHt(\mathbf{x}) - DHt_t, 0 \right). \quad (7)$$

Here, Tss is the transient-process time; Tfr is the rise time of the transient front; and Um is the maximum



(a) (b)

Fig. 1. Graphs of the test functions (a) $f_1(\mathbf{x})$ and (b) $f_2(\mathbf{x})$ at the dimension $ND = 2$

value (surge) of the transient voltage. The time intervals and the voltage are measured on normalized scales and are expressed in dimensionless quantities. The other QIs are defined above.

OF $f_4(\mathbf{x})$ (7) is obtained in the problem of minimizing the transition-process time *Tss* under restrictions on the front rise time *Tfr*, the maximum transient voltage *Um*, the stopband attenuation *Hs*, and the excess of the frequency response in the transition band *DHt*. In the experiments, the values of the following quantities were given: number of poles, $NP = 6$; number of zeros, $NZ = 0$; objective values of QIs, $Tss_t = 0.1$, $Tfr_t = 0.5$, $Um_t = 1.1$, $Hs_t = 40$, and $DHt_t = 0$; the weighting factors, $WTfr = 100$, $WUm = 10$, $WHs = 100$, and $WHt = 1000$. The boundaries of the search space are the same as for $f_3(\mathbf{x})$. Information on the methods to calculate the QIs is available in the literature [11, 14].

The graphs of these OFs are not presented here since solving the problems of optimizing OFs (6) and (7) at $ND = 2$, i.e., for filters of the second order, is of no interest; moreover, at higher dimensions, the graphical representation is complicated.

Let us further list the studied optimization algorithms. All of them were implemented in the *MATLAB* software environment[1]. For each algorithm, an abbreviated notation is introduced, as presented below:

- SS (Step Search)—a simple coordinate search algorithm with the step size bound from above [2, 3].
- PS—*patternsearch*(..) function from the *Global Optimization Toolbox* in *MATLAB*. An improved coordinate search with the possibility of transition between the domains of attraction of local extrema [2].
- MS—*fminsearch*(..) function from the *Optimization Toolbox*. A search for a minimum of an OF using the Nelder–Mead simplex algorithm [2].
- SA—*simulannealbnd*(..) function from the *Global Optimization Toolbox*. A search for the global minimum of an OF using the simulated annealing algorithm [1, 2].
- GA—*ga*(..) function from the *Global Optimization Toolbox*. A search for the global minimum of an OF using a genetic algorithm [1, 2].
- PSO—*particleswarm*(..) function from the *Global Optimization Toolbox*. A search for the global minimum of an OF by the particle swarm optimization algorithm [1, 2].
- CS—a function realizing the cuckoo search algorithm for searching for the global minimum of an OF [1]. The function is not included in the *MATLAB* toolboxes and is written based on a published example [15].
- MC1—*fmincon*(..) function that is included in the *Optimization Toolbox* and realizes the SQP algorithm. In this case, an OF is minimized with penalties (4)–(7), and restrictions are imposed only on the coordinates of the search space.
- MC2—*fmincon*(..) function from the *Optimization Toolbox*, too. But in this case, a selected QI is minimized, and functions used to calculate the fixed QIs are introduced in the arguments of *fmincon*(..) as inequality restrictions.

Each algorithm was run $NT = 100$ times for the functions $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$ and $NT = 40$ times for $f_3(\mathbf{x})$ and $f_4(\mathbf{x})$. The starting points in the search space for each run of the non-population algorithms were given using the *lhsdesign*(*NT*, *ND*) function, which returns a Latin hypercube sample matrix; random starting positions of agents of the population algorithms GA, PSO, and CS were given by their realizing functions. The algorithms included in the *MATLAB* toolbox were set by default. The end condition of the search was the absence of changes in the function being minimized that exceeded the $DGF_{\min}$ level, which was one of the settings and, as noted above, was set by default. For the CS algorithm, the population size $Npop = 20$ and the number of generations $maxgenN = 400$ were given. The search was ended after all the generations had been sought.

RESULTS AND DISCUSSION

Table 1 presents the results of the experiments with the OF $f_1(\mathbf{x})$. The first and second subcolumns of each column show the minimum and maximum values, respectively, of the found solutions over 100 search cycles at the dimensions $ND = 2$, 4, and 8. The third subcolumns present the numbers *Neval* of calculations of the OF in the course of the search. The top row shows the analytically found exact values of the global minimum.

Additional information on the operation of the algorithms is provided by the maps of the positions of the starting points of the search cycles, which are connected by straight line segments to the corresponding end points; examples are given in Fig. 2. For the population algorithms, in particular, for PSO, only the positions of the found optimal solutions are shown, since each agent in the population has its own starting position.

The non-population algorithms SS, PS, MS, and MC1 move toward a point of minimum until they reach a wall. Their results over the search cycles have a significant scatter. The population algorithms PSO and CS turned out to be significantly better. Since most of the solutions they found are in the immediate vicinity of the global minimum, it does not take many iterations of the search to get a good result. The best results were shown by the MC2 algorithm. This is understandable because $f_1(\mathbf{x})$ has no local minima. In this case, both the QI to be minimized and the restricted QI are described by twice

[1] http://www.mathworks.com. Accessed December 14, 2021.

Table 1. Results of the experiments with the OF $f_1(\mathbf{x})$

Algorithm	$ND = 2$, $\min(f_1) = -1.414$			$ND = 4$, $\min(f_1) = -2.000$			$ND = 8$, $\min(f_1) = -2.828$		
	$\min(f_1)$	$\max(f_1)$	*Neval*	$\min(f_1)$	$\max(f_1)$	*Neval*	$\min(f_1)$	$\max(f_1)$	*Neval*
SS	−1.414	−1.017	84844	−2.000	−1.396	320100	−2.717	−2.327	1280948
PS	−1.414	−1.126	14503	−1.998	−1.540	30330	−2.780	−1.833	70876
MS	−1.414	−1.052	23623	−2.000	0.053	60650	−2.806	1.010	147627
SA	−1.414	−1.386	192039	−1.998	−1.873	381223	−2.782	−2.340	752386
GA	−1.414	−1.372	631387	−2.000	−1.946	1456566	−2.827	−2.821	5748740
PSO	−1.414	−1.412	187060	−2.000	−1.996	541760	−2.828	−2.821	1508800
CS	−1.414	−1.413	1677900	−2.000	−1.984	1677900	−2.825	−2.793	1677900
MC1	−1.414	−0.756	29340	−1.999	−0.542	72418	−2.828	−0.440	100494
MC2	−1.414	−1.414	3465	−2.000	−2.000	7201	−2.828	−2.828	16211

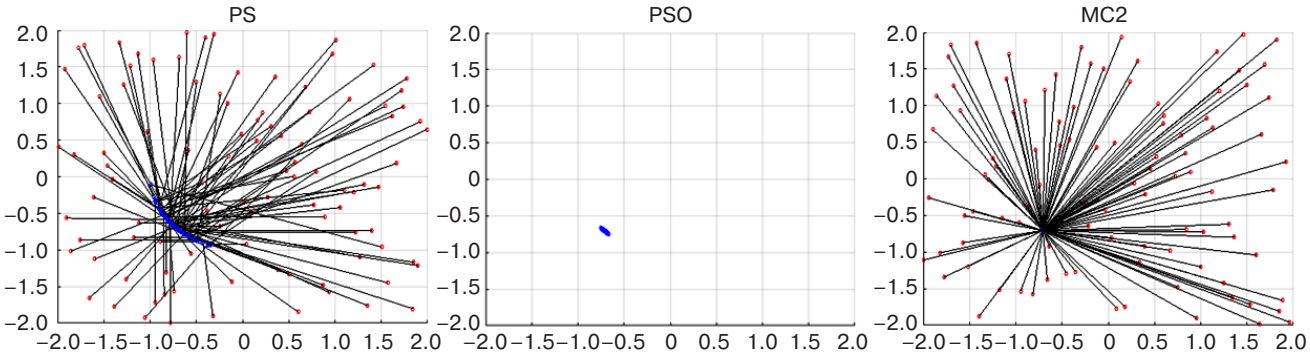


Fig. 2. Starting points of search and the positions of solutions (blue) for $f_1(\mathbf{x})$ at $ND = 2$

differentiable functions. Under such conditions, the SQP algorithm quickly and accurately finds the optimal solution in each run at all the dimensions of the search space.

Table 2 presents the results of the experiments with the OF $f_2(\mathbf{x})$. The estimated values of the global minimum in the top row were obtained by an additional search within the restricted neighborhoods of the best of the found solutions. Figure 3 gives the examples of the position maps of the starting and end points of search. Figure 4 presents the examples of the histograms of the found optimal solutions at $ND = 8$.

The algorithms SS, MS, and MC1 end the search at the local minimum closest to the starting point (Fig. 3). To obtain the global minimum or at least a minimum close to it, a significant number of search cycles should be performed. At the same time, the algorithms SA, GA, PSO, and CS end all the search cycles either at the global minimum or at two local minimums closest to it. This was to be expected, since these algorithms are intended for global optimization.

At the dimension $ND = 8$, the exact value of the global minimum is only found using the PSO algorithm. However, as the histogram in Fig. 4 shows, this value is found once in a hundred attempts. At the same time, the CS algorithm repeatedly ended the search near the global minimum, while, in the other cases, it hit local minima closest to the global one.

The results of the MC2 algorithm should be noted. Among them are many values that are significantly smaller than the global minimum of $f_2(\mathbf{x})$ (Fig. 4). A check shows that these solutions violate the restrictions imposed on the fixed QI. Thus, although both QIs are described by twice differentiable functions in the vicinity of any of its local minima, the MC2 algorithm turned out to be unsuitable for optimizing this function.

Let us turn to the results of optimizing the OF $f_3(\mathbf{x})$ (6) and $f_4(\mathbf{x})$ (7). These problems belong to Black Box Optimization problems, for which neither the exact solutions nor any information on the properties of the OF is known before the start of the search. Tables 3 and 4 present the best solutions for each algorithm, respectively. Significant violations of the restrictions imposed on the OF are marked in italics. The best results are highlighted in bold. Figures 5 and 6 show the examples of the histograms of the OF values for the found solutions. For the MC2 algorithm, the scale of the horizontal axis presents the values of the QI being minimized, rather than the scalar OF.

Table 2. Results of the experiments with the OF $f_2(\mathbf{x})$

Algorithm	$ND = 2$, $\min(f_2) = -2.000$			$ND = 4$, $\min(f_2) = -2.040$			$ND = 8$, $\min(f_2) = -2.097$		
	$\min(f_2)$	$\max(f_2)$	*Neval*	$\min(f_2)$	$\max(f_2)$	*Neval*	$\min(f_2)$	$\max(f_2)$	*Neval*
SS	−2.000	560.2	24313	−2.016	1036.3	94421	86.4	1892.6	376213
PS	−1.999	−0.475	15173	−2.034	−0.545	34606	−1.559	−0.690	87668
MS	−2.000	564.0	10383	−1.998	1042.0	20267	−2.082	1896.4	88995
SA	−2.000	−0.924	190021	−2.039	1.765	455552	−2.089	372.8	819478
GA	−2.000	−1.269	535649	−2.040	−0.633	1400355	−1.593	−0.895	6594051
PSO	−2.000	−1.277	208501	−2.040	−0.647	593081	−2.097	0.304	1603361
CS	−2.000	−1.279	31960	−2.040	−1.404	31960	−2.091	−1.566	31960
MC1	−1.998	278.1	15445	−2.036	942.1	20946	−0.609	1608.6	36057
MC2	−2.848	1.897	130078	−5.696	5.696	329294	−11.386	5.701	577958

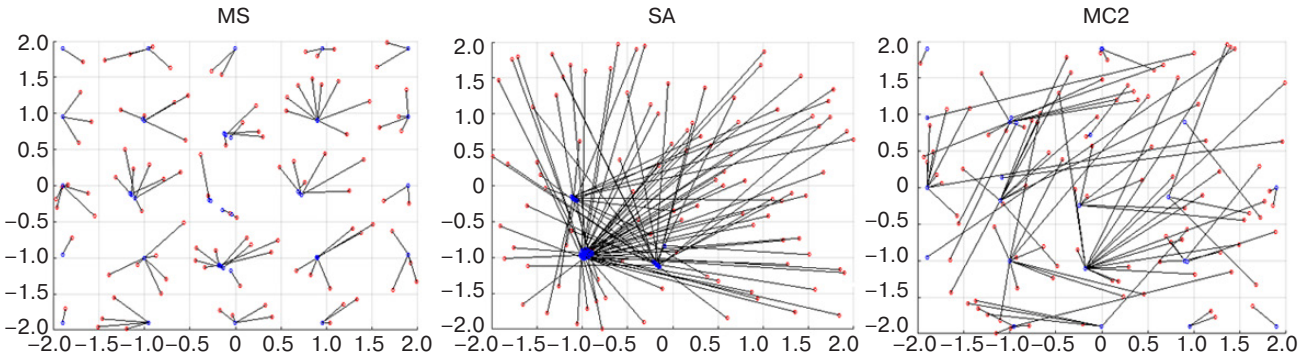


Fig. 3. Starting points of search and the positions of solutions (blue) for $f_2(\mathbf{x})$ at $ND = 2$

Table 3. Results of the experiments with the OF $f_3(\mathbf{x})$

Algorithm	min(OF)	*DHp*, dB	*Hs*, dB	*DHt*	*DTd* %	*Neval*
SS	5.070	0.500	40.040	0.000	60.699	332488
PS	5.615	0.510	40.000	0.000	62.103	46699
MS	6.708	0.500	40.000	0.000	77.084	33887
SA	2.552	0.500	40.009	0.000	35.515	280390
GA	2.253	0.500	40.881	0.000	32.530	3009450
PSO	**2.127**	0.500	40.000	0.000	**31.266**	1211160
CS	62.124	*1.752*	39.559	0.000	75.268	1278400
MC1	2.913	0.500	40.533	0.000	39.128	40771
MC2	**31.126**	0.500	40.000	0.000	**31.126**	39828

The problem of optimizing $f_3(\mathbf{x})$ consisted in minimizing the *DTd* QI under the restrictions $DHp \le 0.5$ dB, $Hs \ge 40$ dB, and $DHt \le 0$. These restrictions are satisfied by all the algorithms, except CS. The minimum value of *DTd* was found by the MC2 method, which also outperformed the other algorithms in number of solutions coinciding with the best one (Fig. 5). But at the same time, among the results of the search by this method, there are several solutions violating the restrictions. Because of this, the *DTd* QI turned out to be less than the correct optimal value.

The problem of optimizing $f_4(\mathbf{x})$ consisted in minimizing the *Tss* QI under the restrictions $Hs \ge 40$ dB, $DHt \le 0$, $Tfr \le 0.5$, and $Um_t \le 1.1$. The restrictions are only satisfied with acceptable accuracy by the population algorithms GA and PSO (Table 4), for which the best results of searching for the minimum of *Tss* are

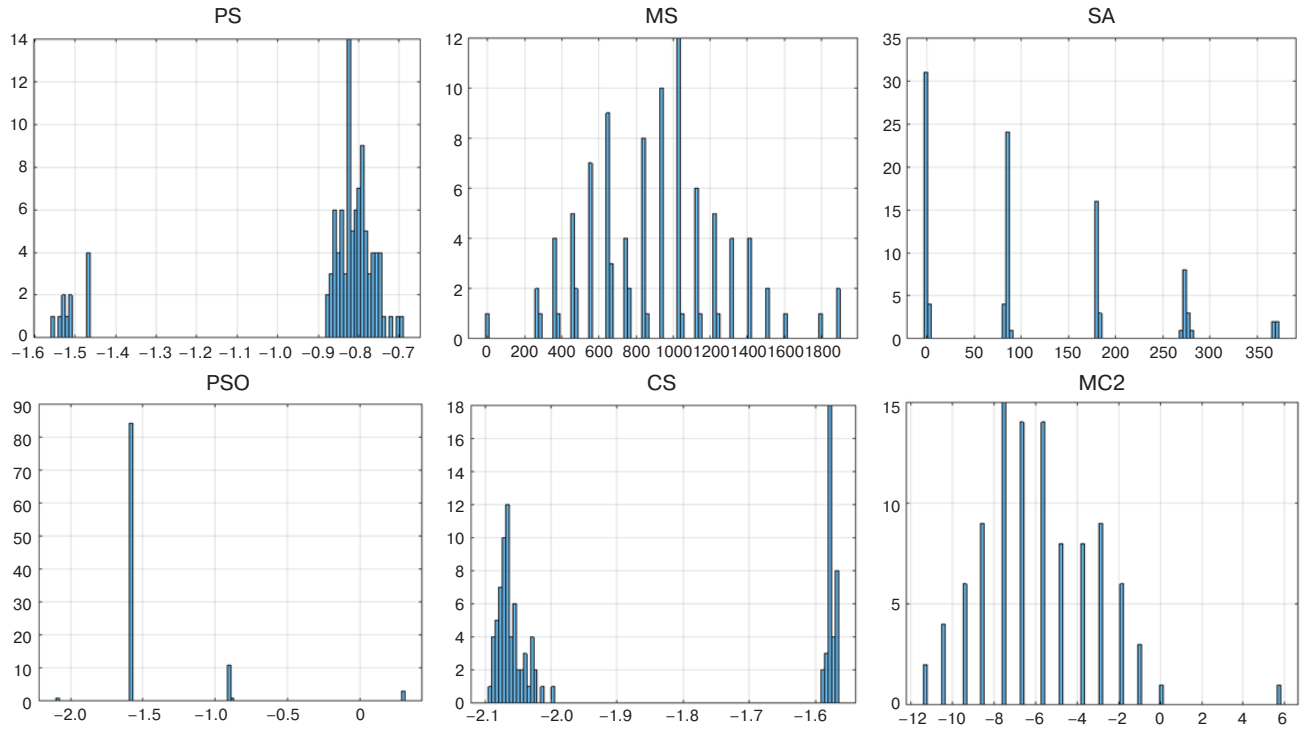


Fig. 4. Histograms of the found solutions for $f_2(\mathbf{x})$ at $ND = 8$

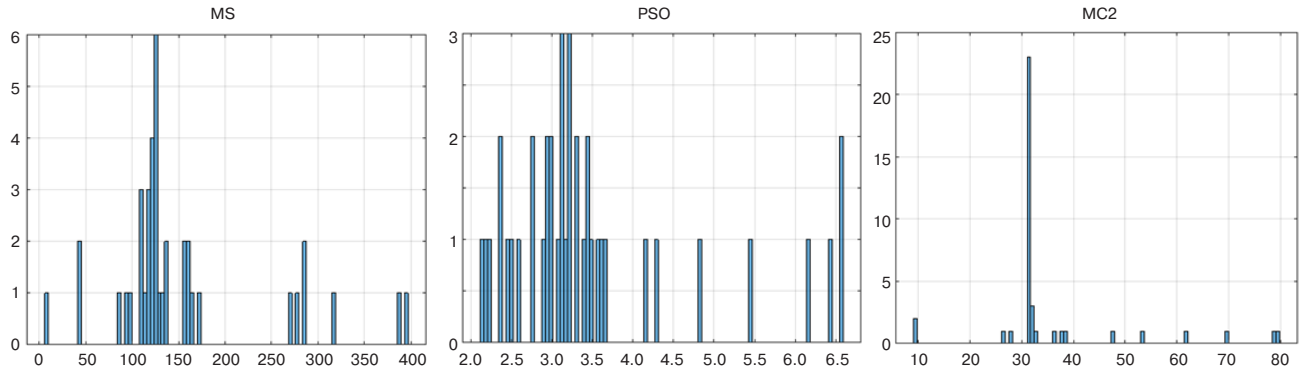


Fig. 5. Histograms of the found solutions for $f_3(\mathbf{x})$

Table 4. Results of the experiments with the OF $f_4(\mathbf{x})$

Algorithm	min(OF)	*Hs*, dB	*DHt*	*Tfr*	*Tss*	*Um*	*Neval*
SS	38.283	*33.821*	0.000	*0.528*	1.681	*1.235*	75904
PS	11.888	40.247	0.000	0.500	1.273	*1.116*	41477
MS	16.378	40.000	0.000	0.500	1.569	1.269	30440
SA	12.747	40.003	0.000	0.500	1.324	*1.151*	227064
GA	**11.287**	40.001	0.000	0.500	**1.229**	1.100	1512630
PSO	**11.301**	40.000	0.000	0.500	**1.229**	1.101	548280
CS	20.796	*35.942*	0.000	0.500	1.165	1.080	1278400
MC1	33.355	40.267	0.000	*0.551*	2.391	*1.132*	15107
MC2	1.480	43.663	0.000	*1.044*	1.480	1.006	19902

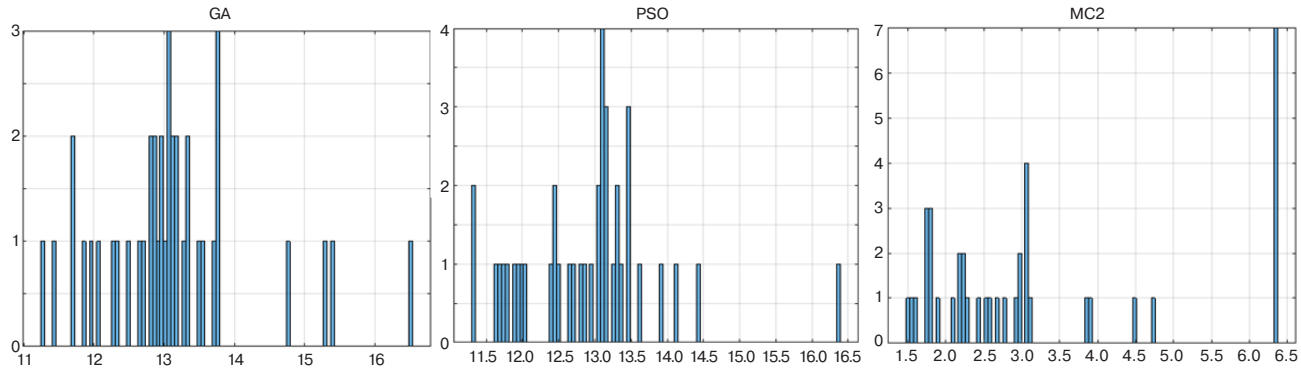


Fig. 6. Histograms of the found solutions for $f_4(\mathbf{x})$

the same. According to the statistics of the results, the two algorithms are also equivalent (Fig. 6), and in the required number of computational operations, the PSO algorithm turned out to be noticeably better than GA. The MC2 algorithm proved to be completely unsuitable for solving this problem.

CONCLUSIONS

The obtained results showed that the search for Pareto-optimal solutions by solving problem (1) can be performed by different methods, which should be selected based on the properties of the functions contained in (1). Since, out of the considered algorithms, the best solutions for all functions were only obtained by the heuristic algorithm PSO, this can be recommended as the main method to solve problems of type (1).

For the functions $f_1(\mathbf{x})$ and $f_3(\mathbf{x})$, the nonlinear programming algorithm MC2 turned out to be applicable. For these functions, this method not only finds the optimal solution in most of the search cycles, but also requires much less computation resources for the search than the heuristic algorithms that optimize scalar OF (2). However, for the functions $f_2(\mathbf{x})$ and $f_4(\mathbf{x})$, the MC2 algorithm proved to be unsuitable. For the function $f_2(\mathbf{x})$, this can be explained in terms of its multimodality. For the function $f_4(\mathbf{x})$, there is still no explanation because nothing can be said about the properties of functions contained in (7).

One of the approaches for assessing the applicability of nonlinear programming methods of the MC2 type to solving problem (1) is to preliminarily study the properties of the functions that determine the values of the QIs contained in (1). However, this approach also entails certain problems, for example, in terms of how to check the multimodality of an OF. The commonly used approach is based on multiple searches for local extrema from uniformly distributed starting points. In this case, it is recommended to use the Nelder–Mead algorithm (referred to as MS above) [7]. However, if the relief of the OF has "valleys," i.e., areas in which the rate of change in the function in one direction is much lower than in others, then the local search algorithms will stop at various points of the bottom of the valley, which are not local minima [10]. Methods for detecting walls, valleys, and plateaus in the relief of an OF, as well as those that search for extrema in the presence of such areas, are still poorly developed.

Thus, the issue of assessing the applicability of MC2-type nonlinear programming algorithms to solving problem (1) requires additional research. In the meantime, the following course of action can be proposed. First, it is necessary to run a certain number of search iterations for a solution to problem (1) using the MC2 method. If most of the solutions are close to each other and the imposed restrictions are not violated, then the best of these solutions can be taken as the desired optimum. Moreover, if the solutions have a significant scatter and the majority have violated restrictions, then one should proceed to the optimization of scalar OF (2) using the PSO algorithm.

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RESEARCH ARTICLE

Applying a reproducible research approach to distance education

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Abstract

Objectives. Emerging as a response to the global threats presented by the COVID-19 pandemic**,** the changing nature of problem-solving in the field of information technology associated with economic globalization, including possibilities of remote working, imposes new requirements on the competencies and skills of future professionals. This, in turn, requires adjustments to the higher education process. Agile project management methodologies such as Scrum, along with Infrastructure-as-Code approaches in information and telecommunication infrastructure management, and Documentation-as-Code approaches in documentation development, aim to present design, development, testing, and documentation as short cycle iterative processes to permit the rapid and transparent addition of new product value in discrete portions. Applied to the education sphere, this approach implies new knowledge and practical skills of students that can be easily and transparently measured in the process of mastering a discipline. The present paper aims to develop methods of applying modern software development techniques to training students of technical specialties.

Methods. The use of reproducible research methods and agile design practices while organizing and managing practical tasks for students is proposed.

Results. Contemporary tools used in software development based on Git hosting services (GitLab and GitHub) are presented alongside reproducible research paradigms in distance education using the R Markdown format by RStudio.

Conclusions. In addition to increasing the involvement of students in the process of practical tasks, the proposed approach can be used to reduce the workload of teachers when checking and evaluating student working results.

Keywords: reproducible research, R Markdown in education, Git in education, Agile in education

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НАУЧНАЯ СТАТЬЯ

Применение подхода воспроизводимых исследований в процессе дистанционного обучения

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Резюме

Цели. Изменение характера решения задач в сфере информационных технологий, связанное с глобализацией экономики, возможностями удаленной работы, а также глобальными угрозами пандемии COVID-19, накладывает новые требования к компетенциям и навыкам будущих специалистов, что, в свою очередь, требует внесения корректив и в процесс подготовки специалистов в высших учебных заведениях. В настоящее время широко известны различные методики проектного управления Agile и Scrum (часто еще называемые «методологиями гибкой разработки»), подходы в управлении информационно-телекоммуникационной инфраструктурой Infrastructure-as-Code, а также подходы в разработке документации Documentation-as-Code. Их общая цель – представить процесс проектирования, разработки, тестирования и документирования в итеративном виде с короткими периодами цикла, позволяющего прозрачно добавлять новую ценность продукта небольшими порциями. В области образования этой ценностью являются новые знания, умения и практические навыки обучающихся, которые можно легко и прозрачно измерить в процессе освоения ими дисциплины. Цель исследования – разработать способы применения современных методик разработки программного обеспечения в процессе обучения студентов технических специальностей.

Методы. Использовались методы воспроизводимых исследований (reproducible research) и практик гибкого проектирования при организации и руководстве выполнением обучающимися практических работ.

Результаты. Представлен подход к использованию современных инструментов, применяемых при разработке программного обеспечения на базе онлайн-сервисов git-хостинга (GitLab и GitHub), а также парадигмы «воспроизводимых исследований» в процессе дистанционного обучения с использованием формата R Markdown компании RStudio.

Вывод. Применение предложенного подхода позволяет, помимо увеличения вовлеченности обучающихся в процесс выполнения практических заданий, снизить нагрузку на преподавателя по проверке и оцениванию результатов работы студентов.

Ключевые слова: воспроизводимые исследования, R Markdown в обучении, Git в обучении, Agile в обучении

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INTRODUCTION

Evolving information technologies have the possibility to transform conventional approaches to solving various tasks and problems arising in the course of human life. The sudden increase in risks to humanity associated with the COVID-19 pandemic stimulates the search for new approaches to improve the efficiency of activities including those in the education sphere. In addition to the convenience and flexibility of managing the learning process, the technical ability to support teacher–student interaction remotely through communication channels acquires a fundamentally new meaning.

A major trend in development and rationalization of modern education based on the use of electronic and mobile learning tools is the so-called collaborative learning approach, comprising the independent work of students in collaboration with other students with the participation of a teacher [1, 2]. The transition of Russian education system to a competence-based approach implies creating conditions for students to master a set of competencies to determine graduate readiness for sustainable professional activities [3–6]. The idea of applying the technologies used in software development to other spheres is not new. Various Agile project management methodologies[1] such as Scrum[2], along with Infrastructure-as-Code (IaC)[3] approaches in information and telecommunication infrastructure management, and Documentation-as-Code (Docs as Code)[4] approaches in documentation development are widely known. The use of proven tools, such as the Git[5] version control system, Wiki[6] and Markdown[7] markup languages, as well as task management systems such as Jira[8], Asana[9], and Trello[10], allows:

1) creation of a unified storage for the common knowledge product and provision of simultaneous access for all participants in the process of its creation;
2) the possibility of parallel work on competing solutions to the same problem and experiments that allow the possibility of reverting to any initial state;
3) the use of the knowledge and experience of all team members when making decisions, not just those directly involved in the project;
4) recording decisions for further retrospective analysis with a view to developing best practices in this area and disseminating them;
5) ensuring asynchronous interaction of the participants;
6) the possibility to evaluate the contribution of each participant to the result more objectively.

The present paper summarizes the experience of conducting practical and laboratory works using R Markdown interactive electronic report technologies [7] along with the Git version control system. Here, the main aim is to develop educational technologies that develop skills associated with the use of contemporary tools that support individual, independent learning paths at the same time as demonstrating the possibility of collective work in a unified information space. The possibility of combining these seemingly contradictory tendencies focuses exclusively on software products used in IT industry without the need to deploy special education software. By instilling engineering skills involved in building new information architectures, this eliminates the impression of "artificiality" in works performed by students, as well as increasing their commitment and activity. In addition to improving the quality of training, the use of standard technologies should increase the attractiveness of the educational institution for applicants [8].

In the aftermath of the COVID-19 pandemic, issues of organizing remote work and learning are becoming more relevant than ever before. However, the main focus has been on teleconferencing technologies (e.g., Zoom[11], Microsoft Teams[12], and Cisco Webex[13]), which preserve the traditional structure of teacher–student interaction. While preserving this important element, the approach proposed in the present paper also aims to facilitate the active interaction of students by introducing mechanisms of gamification and competition.

Of particular note here is the property of asynchronous interaction in the learning process, which allows all process participants to manage their individual time resources flexibly, including supporting interactions from anywhere in the world regardless of time zone. By encouraging students to schedule and organize their work independently, synchronous interaction removes formal restrictions concerning the timing and length of classes: only synchronization points (i.e., reporting deadlines) are required to be observed by university students.

[1] https://www.atlassian.com/ru/agile/manifesto. Accessed May 23, 2021 (in Russ.).
[2] https://www.scrum.org/. Accessed May 23, 2021.
[3] https://docs.microsoft.com/en-us/devops/deliver/what-is-infrastructure-as-code. Accessed May 23, 2021.
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[13] https://www.webex.com/. Accessed May 23, 2021.

R MARKDOWN TECHNOLOGY FOR CREATING INTERACTIVE DIGITAL REPORTS

The product of contemporary scientific research increasingly involves the participation of entire teams, with new knowledge emerging from long chains of smaller studies based on each other's the results. For this reason, the costs of mistakes made at any particular stages can be significant. The problem of reproducibility of scientific research is not only acute in natural and engineering sciences, but also increasingly in the humanities.

The reproducibility of scientific research implies the possibility of repeating experiments, calculations, and carrying out modeling on basis of the same initial data used in the original experiment to obtain a similar result. To this end, all initial data should be made publicly available for studying along with a sufficiently detailed documentation of methods and materials used[14] [9]. In the case of modeling approaches, the source code of any software tools should be also presented. One of the most suitable options for realizing these requirements involves the use of R Markdown technology [10, 11].

By specifying the syntax of markup language, R Markdown presents a technology for processing specially generated documents, which include authoring text, formulas, and program code whose results are automatically inserted into a generated report. The results of executing such code may be tables, graphs, charts, diagrams, geographical maps, heat maps, etc.

As well as the automated generation of reports or articles, the advantages of this approach include minimization of error probability when transferring results to the report. In addition, since the program code is contained in the report itself, other specialists can check and reproduce repeatedly performed calculations. Moreover, the use of already written program code facilitates the reuse of the performed calculations, developed algorithms and methods in other in other works and spheres.

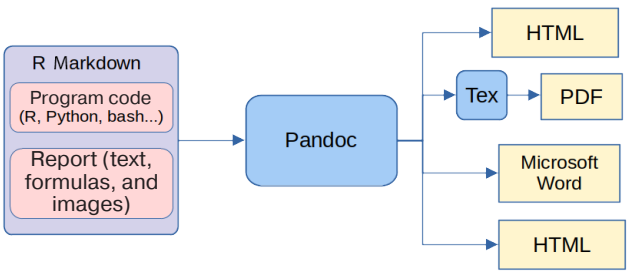

Figure. A scheme for the resulting document generation

[14] Zaitsev V.S. *Modern pedagogical technologies: textbook*. In 2 books. Chelyabinsk: ChSPU; 2012. 411 p. (in Russ.).

The report can be generated as a MS Word file, a MS PowerPoint presentation or Reveal.js, in TeX typesetting system format, in PDF format, or as an interactive Web application (see figure).

GIT VERSION CONTROL SYSTEM

Created in 2005 by Linus Torvalds, the founder of the Linux operating system, as a replacement for similar closed source software, Git was originally intended as the distributed version control system for software source code. Since then, it has quickly gained popularity due to its distributed version control structure and simple architecture. The following may be also mentioned among Git's main advantages:

1) support for a non-linear process of writing the source code of a software product with the possibility of branching, working on each branch in parallel, and merging;
2) use of existing widespread protocols (SSH, FTP, and HTTPS) to provide communication channels between repositories;
3) high working speed;
4) cryptographic protection of change history integrity.

With Git, the history of source code changes consists of sequential "checkpoints" (commits). This sequence branches out when working on different code versions in parallel and converges when the changes are merged.

Today, there are many online source code hosting services, GitHub.com and GitLab.com being the best known. They are web applications allowing not only setting up Git code repositories but also performing a wide range of design, code writing, testing, documentation, integration, and software delivery tasks.

ORGANIZING THE EDUCATIONAL PROCESS USING R MARKDOWN AND GIT

When combining these technologies, the following main objectives are pursued:

1) mastering student teamwork and interaction skills at all stages of project implementation, from planning to report writing;
2) familiarity with modern technologies as well as analytical and software development tools [12];
3) increase motivation of students for high-quality performance of tasks due to their interest in the possible reuse of developments, including in other disciplines [13];
4) controlling the performance history of the assigned tasks and evaluating the contribution of each participant;
5) facilitating validation of presented calculations and excluding "fitting" data to the desired result, which stimulates students to study the topic deeper and more detailed [14].

During training sessions, trainees are divided into teams (crews) of 4–6 people. Each team creates its own central repository (using GitHub or GitLab services), in which participants can organize their work on a task or project. The repository is added by the report template and initial data. Team members may add any materials related to the assigned task on their own: references, links to literature and Internet resources, schematics, etc. Thus, the repository becomes a logical focal point for student interaction, helping them to acquire and strengthen remote interaction skills using modern information technologies.

The working results of each team are used to write the R Markdown report in RMD format for subsequent output in HTML or PDF format. The main requirement for the resulting report is its reproducibility, i.e., the ability to compile an identical report document on the teacher's PC using the input data. During this process, an automatic validation of the methods and tools used by students is carried out. According to the commits (checkpoints) in the group repository, the teacher may evaluate the efficiency of each group member along with his or her contribution to the resulting product. Each team member must participate in the task and report-writing process by creating at least one meaningful commit. This encourages participants to get involved as early as possible doing the most obvious work on the assignment. Conversely, low activity in the course of doing the work forces participants to supplement and improve the already posted working results: to comment and design the program code, study and describe alternatives for the task, and improve the design of charts, i.e., perform work requiring more detailed and in-depth study of material.

Among the advantages of this approach to training, it is worth noting asynchronous interaction of the teacher with students and students with each other. This allows each student to organize and schedule study time individually, while maintaining process interactivity and a sense of involvement in the common work. Thus, an individual educational path may be built while preserving the main "reference points" of curriculum subjects.

Combining organizational tools for distributed work with those for documenting and "packaging" knowledge in a reproducible format helps to increase the efficiency of learning and mastering competencies while maintaining flexibility in managing the student time management.

CONCLUSIONS

By organizing practical and laboratory works according to the approach proposed in the paper, a number of advantages may be realized as compared to the conventional approach of dividing students into teams. Firstly, the overall activity of students increases; they get interested in using contemporary means of management, time-tracking, as well as management of documents and program code. Secondly, the work yields a reproducible result that excludes the possibility of fitting the solution to the desired result or searching for a ready-made solution due to the need to perform all search and decision-making stages; thus, the overall credibility of the system for evaluating student success is greatly enhanced. Thirdly, evaluating student works is facilitated for the teacher, as well as presenting wide opportunities for the automated evaluation of the learning process and creation of its results. This trend appears a very promising direction for further research.

Authors' contributions

M.A. Eremeev—research of the distance learning processes.

O.V. Trubienko—study of the possibility of using software tools to organize the distance learning process.

I.I. Zakharchuk—research idea, the development of aims and objectives, the formulation of conclusions.

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LETTERS

Nanoelectronics and nanotechnology: promising approaches in the educational process

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Abstract

Objectives. Nanoelectronics is concerned with the development of physical and technological foundations for the creation of integrated circuits comprised of elements whose topological dimensions do not exceed 100 nm. Nanotechnology includes the creation and use of materials, devices and technical systems whose functioning is determined by their nanostructure, i.e., comprising ordered fragments ranging from 1 to 100 nm in size. The present research is aimed at developing a concept for training highly qualified specialists in the field of nanoelectronics and nanotechnologies on the example of the Department of Nanoelectronics of the Institute of Advanced Technologies and Industrial Programming at the MIREA – Russian Technological University.

Methods. Promising approaches for supporting the educational process within the nanoindustry are analyzed and compared.

Results. Three fundamental components of education in the field of nanoindustry can be distinguished: physical (the study and search for new promising physical effects); materials science, related to the study, search, and synthesis of new advanced materials; informatics (including mastering of modern software packages and programming languages for modeling a wide range of nanoindustry elements and materials).

Conclusions. All three fundamental components of education within nanoindustry have been effectively implemented by combining scientific laboratories and centers at the Department of Nanoelectronics. After graduating from the Department of Nanoelectronics, graduates can work for leading scientific institutes and technical organizations in Russia, intern at specialized organizations in neighboring and other countries, teach at leading universities, and start their own knowledge-intensive business.

Keywords: nanoelectronics, nanotechnology, education

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ПИСЬМО В РЕДАКЦИЮ

Наноэлектроника и нанотехнологии: перспективные подходы в образовательном процессе

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Резюме

Цели. Наноэлектроника – область современной электроники, занимающаяся разработкой физических и технологических основ создания интегральных схем с характерными топологическими размерами элементов, не превышающими 100 нм. Нанотехнологии включают создание и использование материалов, устройств и технических систем, функционирование которых определяется наноструктурой, то есть ее упорядоченными фрагментами размером от 1 до 100 нм. Цель работы – раскрыть концепцию подготовки высококвалифицированных специалистов в сфере наноэлектроники и нанотехнологий на примере кафедры наноэлектроники Института перспективных технологий и индустриального программирования РТУ МИРЭА.

Методы. Анализ перспективных подходов в образовательном процессе в рамках наноиндустрии.

Результаты. В статье выделены три фундаментальные составляющие образования в сфере наноиндустрии: физическая (изучение и поиск новых перспективных физических эффектов); материаловедческая, связанная с изучением, поиском и синтезом новых перспективных материалов; информационная (освоение современных пакетов программ и языков программирования для моделирования широкого спектра элементов и материалов наноиндустрии).

Выводы. Сочетание научных лабораторий и центров на кафедре наноэлектроники позволило эффективно реализовать все три фундаментальные составляющие образования в сфере наноиндустрии. После окончания кафедры наноэлектроники выпускники могут работать в ведущих институтах и научно-технических организациях России, стажироваться в организациях ближнего и дальнего зарубежья, преподавать в ведущих вузах и создавать собственные наукоемкие предприятия.

Ключевые слова: наноэлектроника, нанотехнологии, образование

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INTRODUCTION

Nanoelectronics is a field of modern electronics aimed at developing the physical and technological foundations for integrated circuits comprised of elements whose characteristic topological dimensions do not exceed 100 nm. For elements having such dimensions, the increasingly dominant role played by quantum effects starts to become a fundamentally important issue. Electronic devices that use such quantum effects form the basis of emerging nanoheterostructural electronics. In this connection, the following primary objectives of nanoelectronics may be distinguished: 1) developing the physical foundations for operation of nanoscale devices, especially quantum devices; 2) developing the necessary physical foundations for technological processes; 3) developing the devices themselves along with the relevant manufacturing technologies; 4) developing

nanoscale integrated circuits and electronic products based on a nanoelectronics element base [1, 2].

Although representing a relatively new direction in science and technology, nanotechnology has been under active development in recent decades. Nanotechnology involves the creation and utilization of materials, devices, and technical systems whose function is determined by their nanostructure, that is, by their ordered fragments ranging from 1 to 100 nm. The term "nano" comes from the Greek word "nanos," meaning "dwarf." One nanometer (nm) is one billionth of a meter or 10 Å. The term "nanotechnology" was defined in 1974 by Norio Taniguchi, Professor of Materials Science at Tokyo Science University as "production technology to get extra high accuracy and ultrafine dimensions … on the order of 1 nm…" [1].

Nanoindustry opens up wide horizons and a range of opportunities in many industries and national economy including, but not limited to, the following:

- nanoelectronic and nanophotonic elements (semiconductor transistors and lasers, photodetectors, solar cells, and various sensors);
- ultra-dense data recording devices;
- telecommunications, information, and computing technologies; supercomputers;
- video equipment (flat screens, monitors, and video projectors);
- molecular electronic devices including switches and electronic circuits at the molecular level;
- nanolithography and nanoimprinting;
- fuel cells and energy storage devices; micro- and nanomechanical devices including molecular motors, nanomotors, and nanorobots;
- nanochemistry and catalysis including combustion control, coating process, electrochemistry, and pharmaceuticals;
- aerospace and defense applications; environmental monitoring devices;
- targeted drug and protein delivery, biopolymers and biological tissue healing, clinical and medical diagnostics, creation of artificial muscles and bones, and implantation of living organs;
- biomechanics;
- genomics;
- bioinformatics;
- bioinstrumentation;
- registration and identification of carcinogenic tissues, pathogens, and biologically harmful agents;
- safety in agriculture and food production.

While recent advances in nanoelectronics and nanotechnology are especially applicable to the defense industry, the nanoindustry continues to expand into new areas of science, techniques, and manufacture with the discovery of new physical effects and the synthesis of promising materials. Therefore, the training of highly qualified specialists in nanoindustry becomes an important task in the contemporary world [2].

PROMISING APPROACHES TO NANOINDUSTRY EDUCATION AT THE DEPARTMENT OF NANOELECTRONICS

At MIREA – Russian Technological University (RTU MIREA), specialists in nanoelectronics and nanotechnologies are trained in the Department of Nanoelectronics of the Institute of Advanced Technologies and Industrial Programming. Currently, there are two areas of training: 11.03.04 "Electronics and nanoelectronics" and 28.03.01 "Nanotechnologies and microsystems engineering." RTU MIREA is the only Russian higher education institution awarded the 2017 UNESCO Medal for its contributions to the development of nanoscience and nanotechnologies. The award was given, among other things, for excellence in training students in this area. Educational programs related to nanoelectronics and nanotechnologies are implemented by the Department of Nanoelectronics.

Within the 11.03.04 "Electronics and nanoelectronics" program, students are educated in modern technologies, materials and electronic products, as well as the design and use of electronic devices and appliances. In addition, they acquire knowledge and professional skills in conducting theoretical and experimental research, computer modeling, design, engineering, manufacture engineering, use and application of materials, components, electronic instruments and devices, and vacuum, plasma, solid-state, microwave, optical, micro- and nanoelectronic devices with various functionalities and purposes.

The program subjects are:

- Electronics and microprocessor technology;
- Fundamentals of electronic component platform design;
- Computer-aided design in electronics;
- Electronic materials and equipment;
- Electronic component platform technologies;
- Advanced technological processes of micro- and nanoelectronics;
- Nanoelectronics;
- Physics of low-dimensional structures;
- Condensed matter physics;
- Quantum mechanics and statistical physics;
- Research management.

Within the 28.03.01 "Nanotechnologies and microsystems engineering" program, the area of professional activity comprises theoretical and experimental research, mathematical and computer modeling, design, manufacture engineering and application of materials, instruments and devices of nano- and microsystems engineering having various

functionalities and purposes, as well as the development and application of nanotechnology processes and nanodiagnostic methods. Students study materials and devices of nano- and microsystems engineering, units and appliances based on them, nanoelectronics technology and nanodiagnostic methods, as well as equipment for synthesis processes, diagnostics and testing of materials and components of nano- and microsystem materials and components.

The program subjects are:

- Experiment planning, data processing and interpretation;
- Physical principles of nanotechnology and microsystems engineering;
- Quantum mechanics and statistical physics;
- Condensed state physics;
- Micro- and nanosystem diagnostics and analysis methods;
- Modeling and design of micro- and nanosystems;
- Materials science and processes of nanostructured material production;
- Micro- and nanosystem devices;
- Advanced nanomaterials;
- Structure of materials;
- Research management.

In the present job market, the greatest chances for career success are enjoyed by specialists who are not only versed in modern technology, but who also have a grounding in the fundamental sciences; this is likely to become an even more pronounced trend in the future. Here, physics, which forms the primary basis of new high technologies, is increasingly penetrating into other applied sciences. There is particular interest in quantum physics, due to forming the basis for nanotechnology and the creation of new devices and appliances in nanoelectronics. Here, the concept of the so-called "quantum computer" capable of revolutionizing informatics and communications may serve as an example. The ability of physicists to quickly retrain and master new disciplines is highly valued. Many young specialists who have received a good physics education work successfully not only in science and production but also in economics and business.

The contemporary nanoindustry is characterized by the search for new materials with promising properties that simultaneously permit the miniaturization of nanoelectronic devices and increased response speed of their elements. Moreover, the development of nanosystems is fundamentally dependent on modern computer technologies for analyzing large amounts of complex data.

Thus, three fundamental components of education in nanoindustry can be distinguished: physical (the study of and search for new promising physical effects); materials science related to the study, search, and synthesis of new advanced materials; and informative (including mastering of modern software packages and programming languages for modeling a wide range of nanoindustry elements and materials).

At the Department of Nanoelectronics, sufficient time is devoted to all three components while implementing educational programs. The training process is carried out in departmental laboratories, including the specialized training and scientific Superfast Ferroic Dynamics and Nanotechnology Femtosecond Optics laboratories. These laboratories carry out the following educational and scientific activities:

- training students and postgraduates to use modern laser equipment;
- conducting research in superfast dynamics of ferroic materials for micro-, opto-, and nanoelectronics;
- research in the field of terahertz radiation;
- development of elements and devices for modern electronics;
- research in the field of nanomaterials and nanosystems for two-dimensional electronics.

Many lecturers of the department are also the members of the research staff of RTU MIREA scientific centers, such as the Magnetoelectric Materials and Devices research and educational center (REC), the Integrated Circuits, Nanoelectronics Devices and Microsystems Design Center, the Research Institute of Solid-State Electronics Materials, and the Technology Center.

The following educational and scientific activities are carried out at the Magnetoelectric Materials and Devices:

- training students to operate modern measuring equipment;
- conducting research in the field of magnetism and ferroelectricity;
- studying magnetoelectric effect, magnetostriction;
- developing modern nanoelectronic devices and appliances.

The main activity areas of the Integrated Circuits, Nanoelectronics Devices and Microsystems Design Center are:

- education, training, retraining, and advanced training of specialists in the field of integrated systems for computer-aided design of electronic component platform and devices;
- design of very large scale integration systems, "systems-on-a-chip", and "systems-in-package";
- research on methodology of computer-aided design based on the development of theory and practice of system abstraction layer for describing integrated circuits;
- modeling and development of new devices and instruments of microsystems engineering;
- implementation of integrated circuit prototypes and design of electronic modules based on programmable

logic circuits, and development of control and measuring systems with various functionalities and purposes;
- instrumental and technological modeling of new microwave solid-state electronics devices based on AlGaN nanoheterostructures.

The Research Institute of Solid-State Electronics Materials carries out activities in the following areas:
- training students to work with modern equipment (laboratory work);
- conducting research in the field of condensed state physics and solid-state electronics;
- research of optical, structural, and magnetic properties of modern materials and elements of electronics;
- research in the field of nanomaterials and nanosystems for modern electronics.

The Technology Center REC is active in research and training in the following technologies:
- technologies of dielectric thin films and nanostructures, including active dielectrics;
- film-forming solutions and methods for the formation of ferroelectric heterostructures (PZT[1], BST[2], etc.);
- film-forming solutions and methods for the formation of porous insulating dielectrics with low dielectric constant (low-k) using molecular self-assembly methods;
- film-forming solutions for producing various oxides (Si, Ti, Zr, etc.) and inorganic-organic hybrids;
- planarization in BEOL[3] and FEOL[4] processes;
- segnetoelectric thin films, hetero- and nanostructures, and composites;
- CSD[5] and ALD[6] technologies.

In addition to activities carried in RTU MIREA laboratories and research centers, students undergo practical training, participate in R&D, and carry out their final qualification works at a wide range of partner enterprises and universities, which are also their potential employers. Such organizations include: Roselektronika, NPP Pulsar, Pluton, NPP TORII, MICRON, the Institute of Physics and Technology of Russian Academy of Sciences (RAS), Lomonosov Moscow State University, National Research Center "Kurchatov Institute," Central Research and Technology Institute "Tekhnomash," I.P. Bardin Central Research Institute for Ferrous Metallurgy, and many others.

[1] PZT is lead zirconate titanate, chemical formula $Pb[Zr_xTi_{1-x}]O_3$ $(0 \le x \le 1)$.

[2] BST is barium strontium titanate, chemical formula $Ba_{1-x}Sr_xTiO_3$ $(0 \le x \le 1)$.

[3] BEOL (back end of line) is the second portion of IC fabrication.

[4] FEOL (front end of line) is the first portion of IC fabrication.

[5] CVD is chemical vapor deposition of coatings.

[6] ALD is atomic layer deposition.

Along with the corresponding postgraduate programs, the Department of Nanoelectronics offers bachelor's and master's degrees, i.e., there is a full educational cycle in areas related to nanotechnology and nanoelectronics.

Students and graduate students of the Department of Nanoelectronics are actively published in leading international journals (indexed in Web of Science and Scopus) including Q1 journals [3–6] and in leading Russian journals (included in the List of the peer-reviewed science press of the State Commission for Academic Degrees and Titles of the Russian Federation), present their work at international and national conferences, become winners and medalists of all-Russian and international competitions, and receive grants, including megagrants.

A significant personal contribution to the training and development of the department, the institute, and the entire RTU MIREA is made by teachers, who are also leading scientists and specialists in their field. Here, we would especially like to remember those who, unfortunately, are no longer with us. The loss of Aleksander Igorevich Morozov is especially poignant: Professor, Doctor of Physical and Mathematical Sciences, RTU MIREA Vice-Rector for Science, a remarkable teacher and author of a large number of scientific works (in particular, [7–9]). The scientific group led by Professor A.I. Morozov has predicted a new type of domain walls formed by frustrations in these nanostructures, as well as constructing their magnetic phase diagram. The contribution of "unusual" domain walls to the giant magnetoresistance has been calculated. Professor Vladimir Georgievich Morozov, Doctor of Physical and Mathematical Sciences, is one of the world's leading experts in nonequilibrium thermodynamics, the author of the two-volume book "Statistical Mechanics of Nonequilibrium Processes" being in demand among professionals, and a remarkable teacher and methodologist. We should also mention Vladimir Fyodorovich Meshcheryakov, Doctor of Physical and Mathematical Sciences, a leading specialist in the field of electron paramagnetic resonance, Andrei Fyodorovich Volkov, Doctor of Physical and Mathematical Sciences, Professor, and Iosif Grigorievich Yerusalimchik, Doctor of Chemical Sciences, Professor, as well as Boris Vladimirovich Magnitskii and Aleksandr Borisovich Romanov, associate professors. All of them have devoted their lives to training highly qualified specialists. Their students continue to work and teach at the Department today.

At present, active scientific work is carried out by scientific groups under the leadership of A.S. Sigov, Academician of the RAS, Professors E.D. Mishina, Y.K. Fetisov and L.Y. Fetisov, A.A. Bush, V.S. Pokatilov, K.A. Vorotilov, V.I. Kapustin, M.S. Blanter, A.N. Yurasov, Associate Professor E.F. Pevtsov [10–20].

CONCLUSIONS

In conclusion, we note that all fundamental components of education in the field of nanoindustry are effectively implemented by taking a balanced approach of combining scientific laboratories and centers in the university structure. Graduates of the Department of Nanoelectronics have many and varied career opportunities, including:

- teaching and research work in leading national universities;
- working for Russian scientific and technical institutions;
- traineeship and work in specialized institutions in neighboring and other countries;
- starting their own knowledge-intensive business.

Authors' contributions

A.S. Sigov—conceptualization, description of the methodology, and editing the text of the article.

I.V. Gladyshev—data curation, conducting research.

A.N. Yurasov—the main idea, data curation, conducting research, writing and editing the text of the article.

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