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RESEARCH ARTICLE

Generation of keyboard handwriting during user authentication on mobile devices

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Abstract

Objectives. This article discusses a new way of generating keyboard handwriting using a touch keyboard for authentication in currently existing mobile systems.

Methods. Due to the insufficient reliability of single password authentication, the proposal is to use it in combination with characteristics which correspond to handwriting on mobile devices. This article demonstrates the possibility of using individual user characteristics in the formulation of keyboard handwriting on devices with touch keyboards. The type of keyboard used affects the characteristics of keyboard handwriting, so this aspect can be used to improve password authentication reliability. The authentication process in the information environment can be supplemented with data on the nature of the impact on a touch keyboard. The use of the built-in 3D Touch function is also of interest. This is available when working on mobile devices and appliances equipped with a touch keyboard. The paper demonstrates that the use of one parameter only is insufficient for accurate authentication. The study proposes a method of determining an acceptable error range for both the touch force and the intermediate interval during authentication. For this purpose, the Laplace function which formulates the interval of each characteristic depending on the required probability of user recognition is used.

Results. Touch force and the intermediate interval are sufficient to obtain the necessary characteristics, in order to formulate a refined user portrait depending on the user's keyboard handwriting. Experimental statistics are given separately for an average sample of three different users depending on touch force. They also provide the results of authentication when using both standard deviations of pressing and the intervals when using the touch keyboard for the iOSXcode platform.

Conclusions. The conclusion relates to the possibility of user authentication by keyboard handwriting, formulated on the basis of both the touch force on the keyboard symbols and intervals between pressing. Using the values of the sample mean and standard deviations allows authentication according to the required recognition probability.

Keywords: authentication, mobile devices, keyboard handwriting, touch force, time interval between character clicks

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НАУЧНАЯ СТАТЬЯ

Формирование клавиатурного почерка при аутентификации на мобильных устройствах

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Резюме
Цели. В статье рассматривается новый способ формирования клавиатурного почерка при использовании сенсорной клавиатуры для аутентификации в существующих на данный момент мобильных системах.
Методы. В силу недостаточной надежности отдельно взятой парольной аутентификации предлагается использовать ее комбинацию с характеристиками, которые соответствуют почерку на мобильных устройствах. В статье продемонстрирована возможность использования индивидуальных характеристик пользователя при формировании клавиатурного почерка на устройствах с сенсорной клавиатурой. Показано, что тип используемой клавиатуры влияет на характеристики клавиатурного почерка, поэтому данный аспект можно использовать для повышения надежности парольной аутентификации. Предлагается дополнить процесс аутентификации в информационной среде данными о характере воздействия на сенсорную клавиатуру. Интерес представляет использование встроенной функции 3D Touch, которая доступна при работе на мобильных устройствах и технике, оснащенной сенсорной клавиатурой. В статье продемонстрировано, что использования только одного параметра недостаточно для точной аутентификации. Предложен способ определения допустимого диапазона погрешности, в который должны укладываться как сила нажатия, так и промежуточный интервал при проведении аутентификации. Для этого используется функция Лапласа, позволяющая сформировать интервал каждой характеристики в зависимости от требуемой вероятности распознавания пользователя.
Результаты. Показано, что силы нажатия и промежуточного интервала достаточно для получения необходимых характеристик, позволяющих сформировать уточненный портрет пользователя по его клавиатурному почерку. Приведены экспериментальные статистические данные отдельно среднего выборки для трех различных пользователей согласно силе нажатия, а также результаты аутентификации при использовании одновременно среднеквадратичных отклонений силы нажатий и интервалов между ними при использовании сенсорной клавиатуры для платформы iOSXcode.
Выводы. Сделан вывод о возможности применения способа аутентификации пользователей по клавиатурному почерку, сформированному на основе одновременно силы нажатий на символы клавиатуры и интервалов между нажатиями. Использование значений среднего выборки и среднеквадратичных отклонений позволяет проводить аутентификацию согласно требуемой вероятности распознавания.

Ключевые слова: аутентификация, мобильное устройство, клавиатурный почерк, сила нажатия, временной интервал между нажатиями

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INTRODUCTION

Authentication systems on mobile devices today are usually based on knowledge possessed by the user (password or graphical authentication) or on the user's biometric characteristics (fingerprint or face authentication) [1, 2]. However, the above methods, as a rule, do not provide the required accuracy[1] and do not have the functionality of customizing the required level of security [3–5]. There may also be situations when it is not possible to use a biometric authentication device. For example, such situations may arise when a person is in non-standard conditions, for example when the user is unable to raise the Smartphone to face level [6, 7]. In this regard, it seems reasonable to use multi-factor authentication using the keyboard handwriting of mobile device users. Since the owner of the device enters text regularly, the handwriting can remain pertinent at all times. Also, if necessary, it allows the use of handwriting not only for authentication.

Keyboard handwriting can be formulated based on the use of user preferences and modern technologies available for these types of gadgets. Such technologies include 3D Touch[2] technology based on determining the touch force on various characters on the touch keyboard [8, 9]. The capabilities of this development can be used on all modern iPhone devices[3] and on most smartphones. 3D Touch makes it possible to personalize the way the user interacts with the device.

Keyboard handwriting generation and recognition systems are usually based on software signal processing [10–12]. Therefore, the method of authentication on mobile devices based on keyboard handwriting, including the use of 3D Touch technology, is relatively inexpensive and well integrated into existing systems.

Biometric handwriting includes the statistical processing of data obtained when a user enters a given phrase [13, 14]. When a user performs password authentication, the phrase entered is usually fixed. However, when the passwords of different users roughly coincide, there is an increased probability of matching the keyboard handwriting, based on the duration of pressing a certain symbol. Studies have shown that the use of keyboard handwriting alone does not guarantee the necessary authentication reliability [15, 16]. Moreover, with the widespread use of mobile devices, the duration of pressing is gradually changing. Thus, this parameter cannot be considered as a determinant [17].

When determining the keyboard handwriting of a user, the following factors should be taken into account: identity of a smartphone or other authentication device, and psychophysical characteristics of the state of the device owner [18, 19]. However, if handwriting statistics are requisite for authentication on a particular device, the first aspect can be neglected [20].

GENERATING INFORMATION ON KEYBOARD HANDWRITING

With the rapid evolution of software in the use of password authentication, factors such as how the user interacts with the touchscreen keyboard should also be taken into consideration.

The following characteristics can be used to generate the keyboard handwriting: input speed and dynamics, frequency of errors, duration of pauses/signal overlapping, and 3D Touch value when working with a touch keyboard.

There are several types of touch keyboards in mobile devices. Most of the time, the user uses the same layout to which he or she is accustomed. However, the keyboard type may sometimes be altered for ease of input. Depending on the type of keyboard, it is not so much the duration of pressing the keys which changes, but rather the interval between significant keys. When entering a password, the spacing also changes, if the user has to switch from a character keyboard to a numeric keyboard. On mobile devices, the duration or the touch force applied upon the character may be different when selecting digits or service characters. This depends on the use of the keyboard, since they can be selected on the basic layout by holding down the finger or by including a special corresponding character set.

The results of the 3D Touch mechanism can be used to gradate the touch force and several levels can be defined according to the value obtained. It is simplest of all to follow the gradation of normal pressure and strong pressure. In the first case, the user is operating the screen of the mobile device in a standard way when performing actions. In the second case, there is a stronger pressure on the characters, leading to a physical impact accompanied by deflection of the glass panel. The 3D Touch mechanism can differentiate between these levels of impact force. In order to determine touch force, Force property of the UITouch object can be used. This function is present in the objects of iPhone version 6 and above and characterizes touch force. The MaximumPossibleForce property characterizes the maximum possible value of the touch force. Using both values, the relative value of the character's touch force can be defined. A value of 1.0 represents the average force defined by the system.

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[1] Golubkova V.B., Braginskii A.I. *Issues of theoretical and applied computer science*: textbook. Moscow: MADI; 2018. 72 p. (in Russ.).

[2] *What Is 3D Touch and How It Works*. https://itechguidesad.pages.dev/posts/what-is-3d-touch-and-how-it-works-/. Accessed April 22, 2023.

[3] https://www.apple.com/iphone/. Accessed April 22, 2023.

For increased passphrase security, Latin characters should be used in combination with numbers and service characters. Different mobile devices use different types of keyboards. However, in all devices special characters are placed in a separate keyboard. Sometimes there are also numeric keys on a special tab. It is proposed, therefore, to supplement the touch force applied on the characters with information about the duration of pauses between informational (included in the password) characters which require keyboard switching.

User recognition is a two-stage process. The first stage is required for initial generation of the user's keyboard handwriting. The resulting data is then used in the next stage for authentication. The combination of the two stages makes it possible to conclude that either the user is legitimate or that an intruder has attempted to log on to the system.

In accordance with the above, the proposal is to formulate keyboard handwriting by taking characteristics of the sample mean and standard deviation of the touch force and the intervals between pressing characters. This pair of statistical data is characterized by their heterogeneity which allows for more accurate estimation.

At the first stage, each user enters a passphrase which meets the security requirements several times. In order to increase the representativeness of the sample, additional password requirements can be formulated to include not only generalized rules, but also to define the sequence of typing. For example, the need to switch repeatedly from one character type to another can be included.

Depending on the parameters selected, the required characteristics are calculated character by character and then grouped (Tables 1, 2).

Table 1. Format for character touch force data presentation

Character (x_i)	Sample mean ($\bar{x}$)	Standard deviation (σ_x)
...	...	...

Table 2. Format for presenting data on intervals between pressing characters

Sequential characters (x_i)	Sample mean ($\bar{x}$)	Standard deviation (σ_x)
...	...	...

Calculation of the values of the second and third columns of the tables is carried out by means of the following formulae:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}, \quad \sigma_x = \sqrt{\frac{\sum_{i}^{n} \left(x_i - \bar{x}\right)^2}{n-1}},$$

where the variable n shows how many times the passphrase has been repeated.

Since during authentication, the received data x_{n+1} will differ, a possible range of values ($x_{\min}$, $x_{\max}$) needs to be established within which user legitimacy is indicated. The ability to vary the length of the interval depending on the required probability of errors will also be useful. Therefore, when determining the interval boundaries, it seems reasonable to take into account the value of the standard deviation:

$$P\left(x_{\min} < x_{n+1} < x_{\max}\right) = = F\left(\frac{x_{\max} - \bar{x}}{\sigma_x}\right) - F\left(\frac{\bar{x} - x_{\min}}{\sigma_x}\right),$$

where $F(\cdot)$ is the Laplace function and the distribution of the random variable x is normal.

During authentication, errors of the first kind (i.e., a legitimate user is not recognized as such) and of the second kind (an attacker is recognized as a registered user) are possible. In order to reduce errors of the second kind, the value of the probability of erroneous recognition of the user will be reduced.

Since in recognition systems the deviations from the mean value in both directions are equivalent, the probability of hitting the required interval can be written as:

$$P\left(x_{\min} < x_{n+1} < x_{\max}\right) = 2F\left(\frac{\bar{x} - x_{\min}}{\sigma_x}\right).$$

Thus, the values of the acceptable range limits can be adjusted depending on tolerance of errors of the first or second kind.

After formulating the keyboard handwriting, user authentication is performed by entering a password. For a new phrase, the same statistical characteristics are defined and they are checked to to see whether they fall within the specified interval. Depending on the result, a decision about the user's legitimacy is to be made.

EXPERIMENTAL AUTHENTICATION

In order to test the performance of the proposed method of user control, a program to obtain information about the intensity of data input and the force of pressing the characters on the keyboard of the mobile device was written. In this work, the iOSXcode[4] platform was used. Calculations were performed for 10 consecutive inputs performed under the same conditions. For three different users (User1, User2, User3), the corresponding statistical characteristics were calculated for the input data "1@35f1" (Tables 3–5).

[4] Xcode. https://developer.apple.com/xcode/. Accessed April 22, 2023.

Table 3. Character touch force data (User1)

Character	Sample mean	Standard deviation
1	0.4334	0.034916
@	0.4872	0.033796
3	0.558444	0.033623
5	0.539917	0.033619
f	0.492778	0.031256
1	0.479875	0.018871274

Table 4. Character touch force data (User2)

Character	Sample mean	Standard deviation
1	0.35947	0.024012
@	0.460015	0.031145
3	0.501201	0.035001
5	0.54102	0.032115
f	0.402495	0.030598
1	0.483985	0.032012

Table 5. Character touch force data (User3)

Character	Sample mean	Standard deviation
1	0.590235	0.034985
@	0.58098	0.032998
3	0.6001	0.025198
5	0.63101	0.028957
f	0.56398	0.032015
1	0.55356	0.030011

The value 1.0 of the pressing force represents the average force determined by the system.

Figure 1 shows data obtained on the magnitude of the touch force on different characters in the form of a comparison chart for each of the three users. The results were obtained for a user recognition probability equal to 0.95.

According to this data, only for the character "3" do the ranges obtained not overlap. However, a single character sample cannot be considered sufficient. Therefore, it is suggested that s data about the pressing intervals of significant characters be added to the analysis without taking into account the keyboard type switch presses (Tables 6–8).

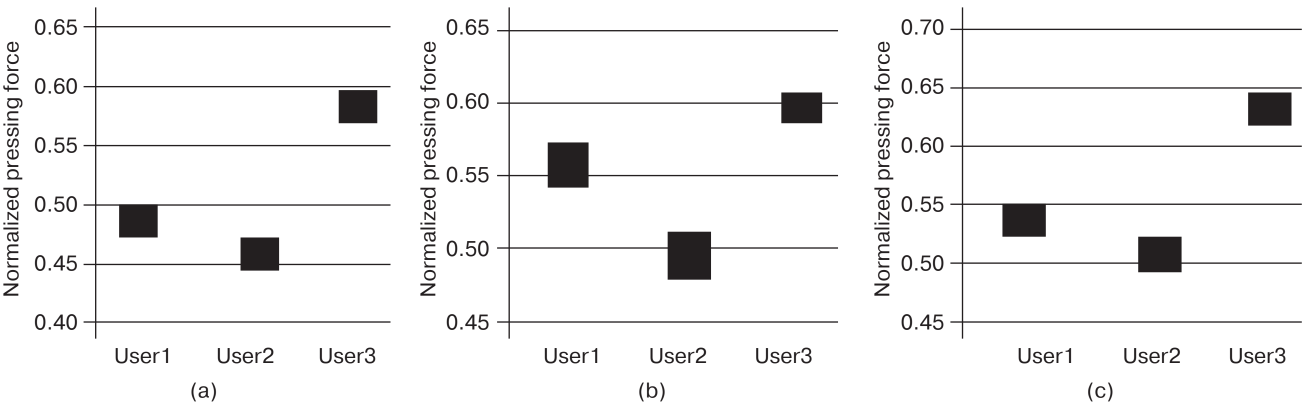

Fig. 1. Permissible touch force ranges: (a) character "@", (b) character "3", (c) character "5"

Table 6. Data on interval between pressing characters (User1)

Sequential characters	Sample mean (10^{-6}, s)	Standard deviation (10^{-6}, s)
1–@	46915.5	143.2862
@–3	47625.13	141.8598
3–5	46764.5	139.9112
5–f	47696.38	133.5322
f–1	46917.25	118.9138

Table 7. Data on interval between pressing characters (User2)

Sequential characters	Sample mean (10^{-6}, s)	Standard deviation (10^{-6}, s)
1–@	59807.5	181.7389
@–3	69081.63	171.6768
3–5	46779.13	158.8777
5–f	69025.38	106.3336
f–1	59943.13	144.3076

Table 8. Data on interval between pressing characters (User3)

Sequential characters	Sample mean (10^{-6}, s)	Standard deviation (10^{-6}, s)
1–@	57835.25	152.0627
@–3	67866.13	150.8391
3–5	45906.38	137.8881
5–f	67908	162.6047
f–1	57937.25	104.8996

Analysis of the data obtained shows that the time interval between pressing the symbols located on the same keyboard does not guarantee the required differentiation of values (Fig. 2c). Switching the keyboard from symbolic to numeric (User2, User3) or selecting numeric or service symbols with the help of increased pressure on the symbols of the main keyboard (User1) enables the required difference in the characteristics of keyboard handwriting (Fig. 2a, 2b) to be attained.

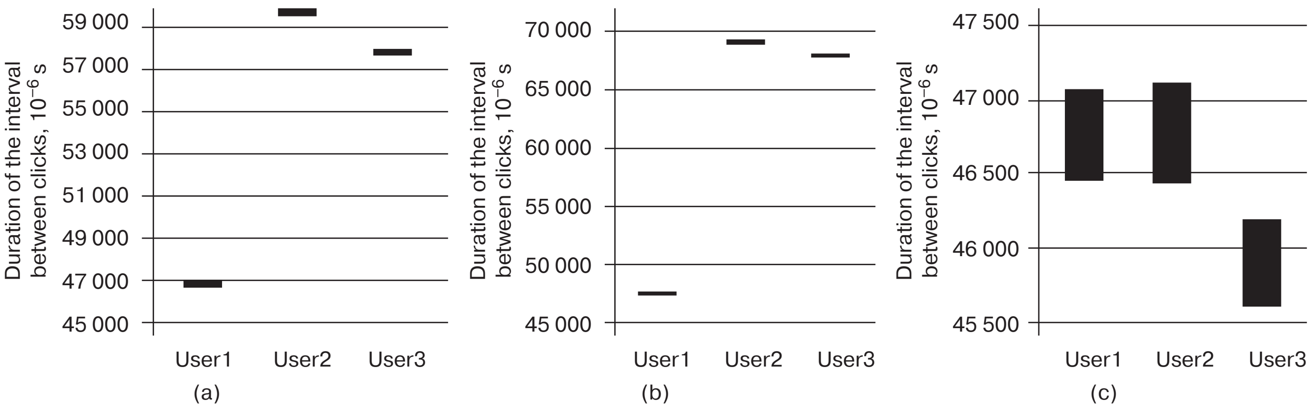

Fig. 2. Permissible ranges for interval between pressing characters (a) “1–@”, (b) “@–3”, (c) “3–5”

CONCLUSIONS

When using password authentication, the use of additional information about keyboard handwriting, based on the touch force applied on the keys and the duration between successive presses, allows the accuracy of recognition to be increased to the requisite probability. The advantages of the method proposed include the possibility of modifying the parameters to balance between first and second type errors. Obtaining new information in the same format as the original information, allows data to be updated, if necessary.

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Authors' contributions

S.M. Ivanova—development of key goals and objectives; conducting research, including analysis of the specifics of using mobile devices in the formation of the keyboard handwriting; development of mathematical apparatus for data analysis.

Z.V. Ilyichenkova—forming an idea for the article; conducting research, including analyzing the possibility of using a combination of several characteristics to form the keyboard handwriting; processing and analyzing of the statistical data.

All authors—writing the text of the article; approval of the final version of the article; interpretation of the research results; formulation of conclusions.

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RESEARCH ARTICLE

Features and perspectives of application of the rapidly exploring random tree method for motion planning of autonomous robotic manipulators

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Abstract

Objectives. The work analyzes features of one of the most promising approaches to solve the problems for motion planning of autonomous robotic manipulators of various types and purposes using the rapidly exploring random tree (RRT) method. The development of modern robotics is shown to be inextricably linked with the improvement of the designs of the created samples, for which the placement of a manipulator on platform becomes a typical layout option. Prospects for using the RRT method as a constructive basis for creating a universal motion planner are evaluated for mobile and robotic manipulators, including autonomous robotic systems with a manipulator on a moving platform.

Methods. The object of the research is the RRT method and its well-known modifications RRT* and RRT-Connect. The effectiveness of applying such methods for solving problems associated with planning the motions of robotic manipulators of various types was evaluated using computer and natural simulation methods.

Results. Based on a review of the literature and the results of the research, the wide possibilities of the RRT method can be used for solving motion planning problems not only for mobile and robotic manipulators, but also for robotic systems on whose transport platform an onboard manipulator has been installed (including those having a redundant or reconfigurable structure). The effectiveness of the applied application of the RRT method is confirmed by examples of modeling a mobile platform with an onboard manipulator and the results of full-scale experiments with a prototype of the ARAKS reconfigurable mechatronic-modular robotic manipulators (RTU MIREA, Russia). It can be experimentally demonstrated and theoretically substantiated that the final dimension of the exploring tree, and hence the time of its construction up to reaching a given target state, is largely determined by the value of the growth factor.

Conclusions. The generalization of the results obtained opens up real prospects for using the RRT method as a constructive basis not only for creating universal means for motion planning mobile robotic systems with an onboard manipulator, but also for solving the problems of automating the docking of autonomous mobile platforms.

Keywords: autonomous robotic manipulator, intelligent control, reconfigurable robotic manipulator, variable kinematic structure, rapidly exploring random tree method

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НАУЧНАЯ СТАТЬЯ

Особенности и перспективы применения метода поисковых случайных деревьев для планирования перемещений автономных роботов

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Резюме

Цели. Статья посвящена анализу особенностей одного из наиболее многообещающих подходов к решению задач планирования перемещений автономных роботов различных типов и назначения с помощью метода поисковых случайных деревьев. Показано, что развитие современной робототехники неразрывно сопряжено с совершенствованием конструкций создаваемых образцов, для которых размещение манипулятора на подвижной платформе становится типовым вариантом компоновки. Целью работы является оценка перспектив использования метода поисковых случайных деревьев в качестве конструктивной основы для создания универсального планировщика перемещений мобильных и манипуляционных роботов, включая автономные робототехнические системы с манипулятором на подвижной платформе.

Методы. Объектом проводимых исследований является метод поисковых случайных деревьев RRT (rapidly exploring random trees) и его известные модификации RRT* и RRT-Connect. Оценка эффективности их прикладного применения для решения задач планирования перемещений роботов различных типов проводилась с помощью методов компьютерного и натурного моделирования.

Результаты. На основе обзора литературы и по итогам проведенных исследований показано, что широкие возможности метода поисковых случайных деревьев позволяют обеспечить решение задач планирования перемещений не только для мобильных и манипуляционных роботов, но и для робототехнических систем с размещением бортового манипулятора (в т.ч. с избыточной или реконфигурируемой структурой) на транспортной платформе. Эффективность прикладного применения метода поисковых случайных деревьев подтверждается примерами моделирования мобильной платформы с бортовым манипулятором и результатами натурных экспериментов с опытным образцом реконфигурируемого мехатронно-модульного робота «АРАКС» (РТУ МИРЭА, Россия). Экспериментально установлено и теоретически обосновано, что конечная размерность дерева поиска, а, следовательно, и время его построения, вплоть до достижения заданного целевого состояния, во многом определяются величиной фактора роста.

Выводы. Обобщение полученных результатов открывает реальные перспективы использования метода поисковых случайных деревьев в качестве конструктивной основы не только для создания универсальных средств планирования перемещений мобильных робототехнических систем с бортовым манипулятором, но и для решения задач автоматизации стыковки автономных подвижных платформ.

Ключевые слова: автономный робот, интеллектуальное управление, реконфигурируемый робот, изменяемая кинематическая структура, метод поисковых случайных деревьев

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INTRODUCTION

Prospective models of semi-automatic and autonomous robotic manipulators designed to work under conditions of uncertainty should offer a wide range of functional capabilities for analyzing sensory information, assessing the environment, as well as planning appropriate actions and their subsequent elaboration.

Among problems that arise, one of the most acute is related to the development of principles of construction and composition of software and algorithmic tools for solving the tasks of motion planning and motion control of manipulators of various types and layouts, taking into account a variety of constraints determined by the type of trajectories to be formed, the nature of the external environment, the peculiarities of the working scenario, and other factors. Research actively conducted in this area since the early 1960s represents a consistent accumulation of theoretical and applied achievements, which in one or another combination find their practical application in modern robotic control systems.

Nevertheless, the search for ways to improve the efficiency of software-algorithmic means of constructing routes of purposeful movement and motion planning of autonomous manipulators continues to remain relevant.

It should be noted that the steady development of robotics technologies, as well as the expansion of their areas of applications and the range of tasks to be solved, are inextricably linked with the improvement of the created samples, increasing the level of their functional capabilities and consequent complication of design layouts.

Thus, in particular, for manipulators of special and industrial purposes, the placement of a multifunctional manipulator on a mobile platform has become one of the typical construction schemes (Fig. 1).

Another type of robotic manipulators can be illustrated by the mechatronic modular ones capable of automatically transforming their structure from a mobile platform configuration to a mobile manipulator configuration as shown in Fig. 2.

In this regard, rapidly exploring random tree (RRT) method [1, 2] is of particular interest. Its specific features open up the prospects of creating a universal motion planner for mobile and robotic manipulators, including robotic systems with manipulator layout on a transportation platform.

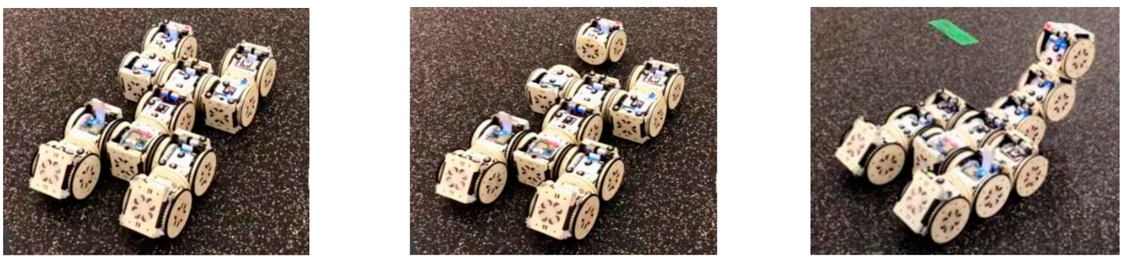
ANALYSIS OF FEATURES AND EVALUATION OF PROSPECTS FOR APPLICATION OF THE RRT METHOD FOR MOTION PLANNING OF MOBILE AND ROBOTIC MANIPULATORS

Use of the RRT method [3, 4] implies the construction of a route of purposeful robotic motion on the set of operatively generated examples from the number of admissible states in the configuration space. The generated tree, which acts as a discrete reconstruction of the manipulator's configuration space, is built randomly from the root vertex corresponding to a given initial state.

Each synthesized branch of the tree defines a possible transition to one of the new states, whose generation is performed in the configuration space taking into account

(a) (b) (c)

Fig. 1. Autonomous robotic manipulators for special (a), (b), and industrial (c) purposes with on-board manipulator: (a) autonomous robotic manipulator for special purposes (N.E. Bauman Moscow State Technical University, Russia); (b) Curiosity Mars rover (NASA, USA); (c) KMRiiwa (KUKA Roboter GmbH, Germany)



(a) (b) (c)

Fig. 2. Automatic transformation of the SMORES-EP mechatronic-modular robotic manipulator (University of Pennsylvania, USA) from a mobile platform configuration to a mobile manipulator configuration

the check for its admissibility and continues until the target position is reached. In generalized form, the corresponding algorithm is described by a sequence of key steps.

1. Point c_{init} corresponding to the initial state of the manipulator in its configuration space C is set as the root vertex of the tree T being formed.
2. During a priori given number of iterations N or until the target state c_{goal} is reached, the following sequence of actions is performed (cyclically):

- generation of a random point $c_{rand} \in$ C;
- finding the vertex of the tree $c_{near} \in$ T, which is the closest to the selected point c_{rand} (as shown in Fig. 3);
- finding the point c' lying on the ray $p(c_{near}, c_{rand})$ and remote from the vertex c_{near} at the distance Δc (given by the tree growth parameter) (Fig. 3):

$$c' : [c_{near}, c'] \in p, \left\| c_{near}, c' \right\| = \Delta c;$$

- checking the conflict of the transition between the states c_{near} and c' for getting into the region of the configuration space $C_{obs} \in C$, which corresponds to the intersections with obstacles with the accuracy up to the a priori established value ε, characterizing the error of conflict detection (Fig. 4);
- finding the point c_{stop} nearest to c_{near} on the boundary of the admissible states area $C_{free} = C \backslash C_{obs}$ along the ray $p(c_{near}, c_{rand})$ (Fig. 4):

$$c_{stop} : [c_{near}, c_{stop}] \in p \cap C_{free}; \left\| c_{stop}, C_{obs} \cap p \right\| \le \varepsilon;$$

- finding the point c_{new} as a new configuration state:

$$c_{new} = \begin{cases} c', [c_{near}, c'] \in C_{free}, \\ c_{stop}, [c_{near}, c'] \notin C_{free}; \end{cases}$$

- updating the tree by adding new elements c_{near}, c_{new} and $[c_{near}, c_{new}]$ to the description lists of its vertices and branches, respectively, provided that $c_{new} \in c_{near}$;
- check the found point c_{new} for remoteness with respect to the target point; if the condition $\left\| c_{new}, c_{goal} \right\| \le \delta$ is met (δ is a priori accuracy), the path search problem is considered to be solved.

During the tree building process, periodic attempts are made to include the target configuration into the composition of its vertices by repeating all the actions of step 2 once, provided that $c_{rand} = c_{goal}$.

3. If no solution is found, then return to step 2 is to be performed.

Figure 5 shows an example of route planning in a two-dimensional configuration space C(x, y) using the RRT method.

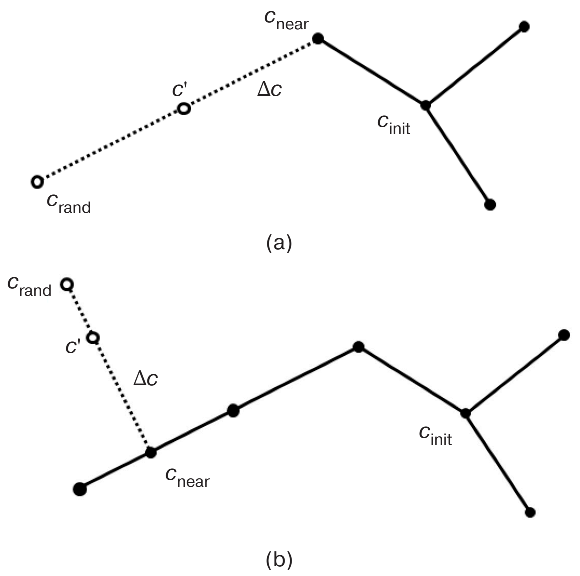


Fig. 3. Options for finding the vertex of the tree nearest to a randomly chosen point

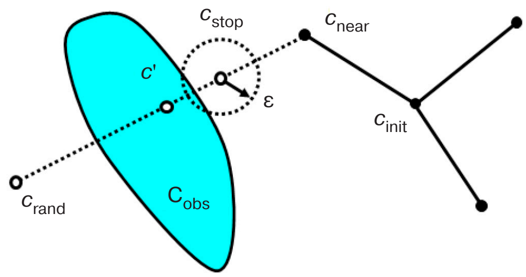


Fig. 4. Checking for transition conflicts between adjacent configuration states

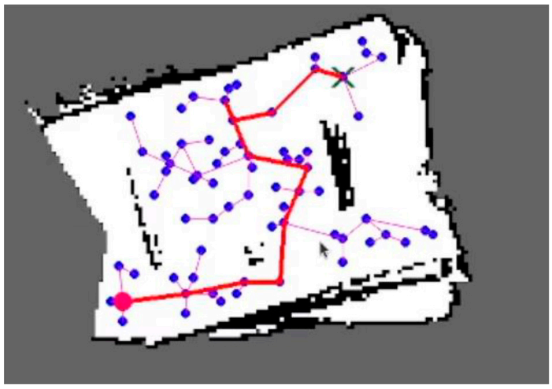


Fig. 5. Using the RRT method to plan a route for purposeful motion of an autonomous mobile manipulator on an automatically synthesized map

In general, the practical application of the RRT method involves additional procedures for smoothing the found tracks.

It should be noted that the ideological basis and features of the method make it possible to use it in solving the motion planning problems, not only for mobile, but also for robotic manipulators, including those with redundant kinematic structure [5, 6].

Obviously, the final dimensionality of the exploring tree, and, consequently, the time of its construction, will largely depend on the given growth factor, which characterizes the values of increments of coordinates of child points relative to parent points in the configuration space of the manipulator. Thus, at small increments, randomly generated points will be located quite close to each other, determining the corresponding dimensionality of the exploring tree. With successive increases in increments, the remoteness between the synthesized points will also increase, resulting in a higher propagation speed of the tree branches and a steady decrease in the total number of its vertices, whose density ensures achievement of the target position. However, a further increase in increments leads to a gradual change in the very nature of the algorithm, when the generation of a new point, which is carried out in reference to the parameters of the parent point, becomes essentially equivalent to the selection of random coordinates having a significant dispersion. The corresponding increase in the length of tree branches is accompanied by a significant acceleration of its growth with a proportional decrease in the density of the exploring space coverage. In this connection, the parameters of the search process duration as well as the finite dimensionality of the tree, both of which are determined by the level of coverage density at which the desired target state will be achievable, will steadily increase. The objectivity of such dependence of the finite dimensionality of the exploring tree on the choice of the value of random increments of the coordinates of the parent points to obtain the children points is convincingly confirmed by the experimental data shown in Fig. 6.

However, the specificity of application of the RRT method in application to robotic manipulators is connected with the necessity to organize indirect checking of selected points of the configuration space for belonging to free, forbidden or target areas. The unavoidability of such an approach is due to the complexity of mapping the peculiarities of the real working environment in the configuration space of a robotic manipulators. Therefore, in the general case, the evaluation of a particular point of the configuration space implies the need to solve the direct kinematics problem $X_M = F(c)$ to calculate the current state of the manipulator X_M using the known values of the generalized coordinates $c \in (q_1, \ldots, q_n)$.

Obtained data allow providing control of the parameters of the manipulator remoteness in relation to the objects of the external environment and the given target position. In the formal form of the record, the conditions of such a check can be represented as follows:

$$c \in \mathrm{C}_{obs}, \text{ if } X_{obs} \cap X_M \neq \varnothing,$$

$$c \in \mathrm{C}_{free}, \text{ if } X_{obs} \cap X_M = \varnothing,$$

$$c \in \mathrm{C}_{goal}, \text{ if } |X_M - X_{goal}| < r,$$

where X_M and X_{obs} are geometric locations of the points occupied by the manipulator and the objects of the external environment acting as obstacles; X_{goal} is the goal position of the manipulator; r is the a priori established accuracy of the goal position.

Figure 7 shows fragments of model experiments on planning of purposeful movements of the manipulator based on the RRT method. The use of heuristics to determine a reasonable choice of parent nodes (such as

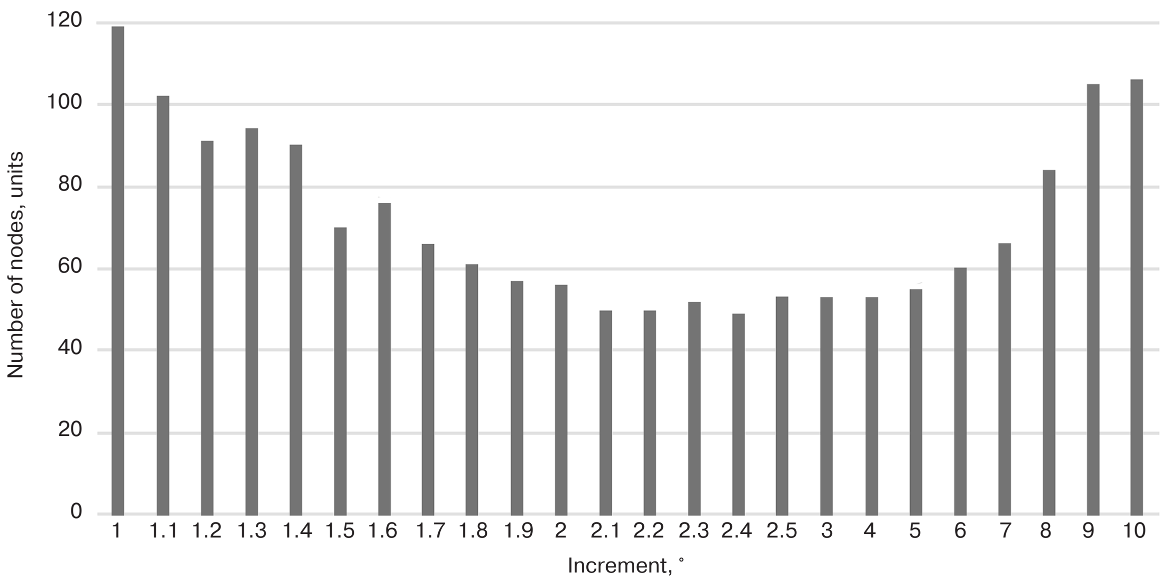
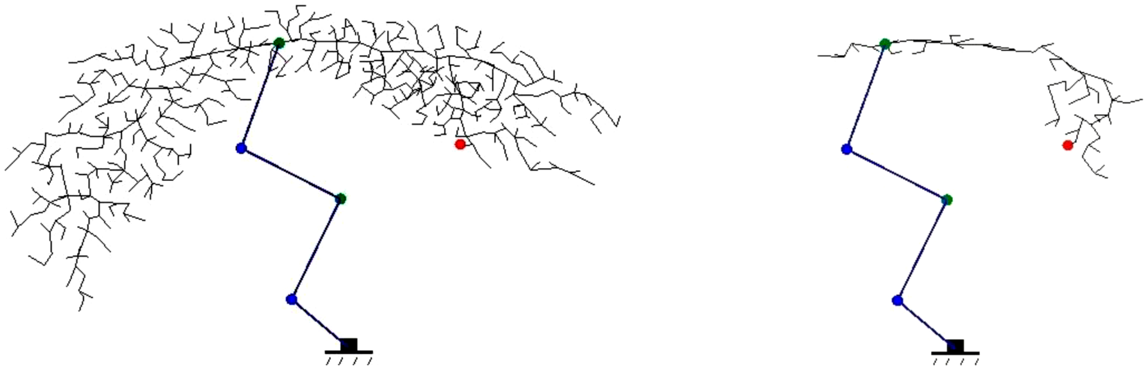
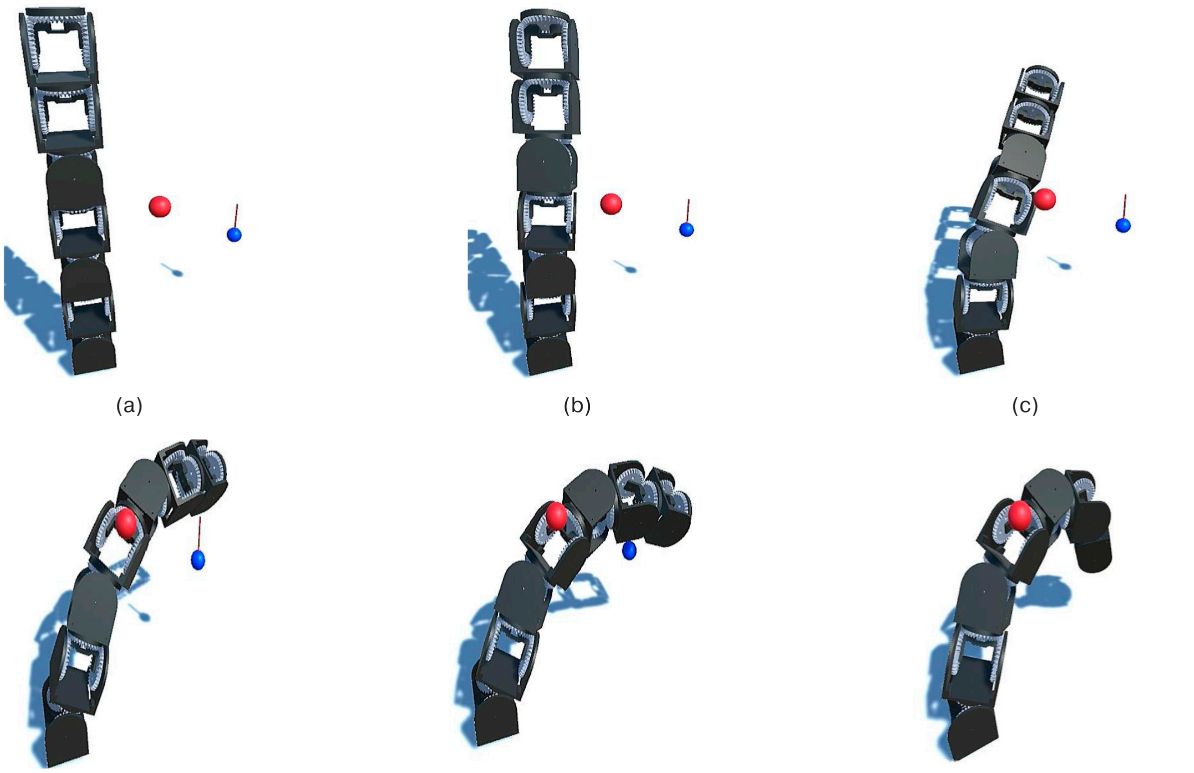


Fig. 6. Changing the dimensionality of the exploring tree depending on the value of the range of the random coordinate increments of the parent points for obtaining the children points in the manipulator configuration space



(a) (b)

Fig. 7. Fragments of model experiments on planning of purposeful movements of the manipulator based on the RRT method: in the original version (a); with the involvement of heuristics determining a reasonable choice of the parent configuration (b)



(a) (b) (c)

(d) (e) (f)

Fig. 8. Fragments of modeling of the purposeful motion formed on the basis of the RRT method for a seven-link manipulator in the environment with a point obstacle: evasion from the obstacle while moving to a given target state (a–d); processing of the required positioning point with a given approach vector (e–f)

those closest to the target state) permits a significantly reduction in the dimensionality of the generated tree (Fig. 7b) with simultaneous reduction of the problem solution time.

Invariance to the dimensionality of the configuration space in which the necessary solutions are searched is one of the most important advantages of the RRT method, which opens up possibilities and prospects of its application for manipulators, not only those having redundant, but also with variable kinematic structures.

Thus, in particular, the modeling results presented in Fig. 8 clearly confirm the effectiveness of the RRT method for the example of planning the purposeful movement of a seven-link mechatronic-modular robotic manipulator in an environment with a point obstacle.

In turn, Fig. 9 shows fragments of field experiments on the use of the RRT method for motion planning of a reconfigurable robotic manipulator, when modification of its kinematic structure is carried out through automatic docking with an additional mechatronic module.

The data of the conducted research represent a practical confirmation of the reality of the development of unified means for motion planning and motion control of robotic manipulators taking into account the requirements for invariance to the composition and operational changes of the existing kinematic structure.

In application to special robotics, many samples of which are built according to the "manipulator on a mobile base" scheme, the application of the RRT method is of special interest. For example, in automatic search, capture and evacuation of objects of target interest, the tasks of planning the movements of the mobile platform and the manipulator are closely interrelated. It is obvious that a successful choice of platform location will not only determine the nature of the manipulator movement, but also the principal achievability of the required point of the working scene with the given parameters of the approach and orientation vectors. In particular, as shown in Fig. 10, the use of the RRT method in its original version provides the possibility of motion planning, not only for the mobile platform and the manipulator considered in a certain order, but also in the case of their representation in a common configuration space as a single system.

The high computational efficiency of the algorithms implementing the RRT method makes it possible to solve the problems of route formation without, however, guaranteeing its optimality with respect to any quality criterion. Attempts to eliminate this disadvantage led to the emergence of the RRT* method focused on finding asymptotically optimal solutions [7–9]. The key features that distinguish the RRT* method from its prototype are related to the introduction of a number of additions and modifications to the basic principles of search tree generation. Thus, in particular, the main innovation consists in establishing the notion of the cost of a path to a particular vertex of the tree.

Finding a new vertex c_{new} in the course of tree construction by the RRT* method is done by analogy with the RRT method. Integration of the found node c_{new} into the synthesized structure implies the choice of such a variant at which the cost of the path $cost(c_{init}, c_{new})$ leading to it in the direction from the root node c_{init} would have a minimum value. In this regard, in the neighborhood centered at the point c_{new} and with a given radius r the search is carried out for such a vertex c_{min} which meets the following condition:

$$c_{min} = \mathrm{argmin}_{c \in C^*}(cost(c_{init}, c) + cost(c, c_{new})),$$

where C* is the subset of tree vertices lying inside the neighborhood of radius r centered at the point c_{new}.

The vertex c_{new} is included in the tree element lists as a child of the vertex c_{min}.

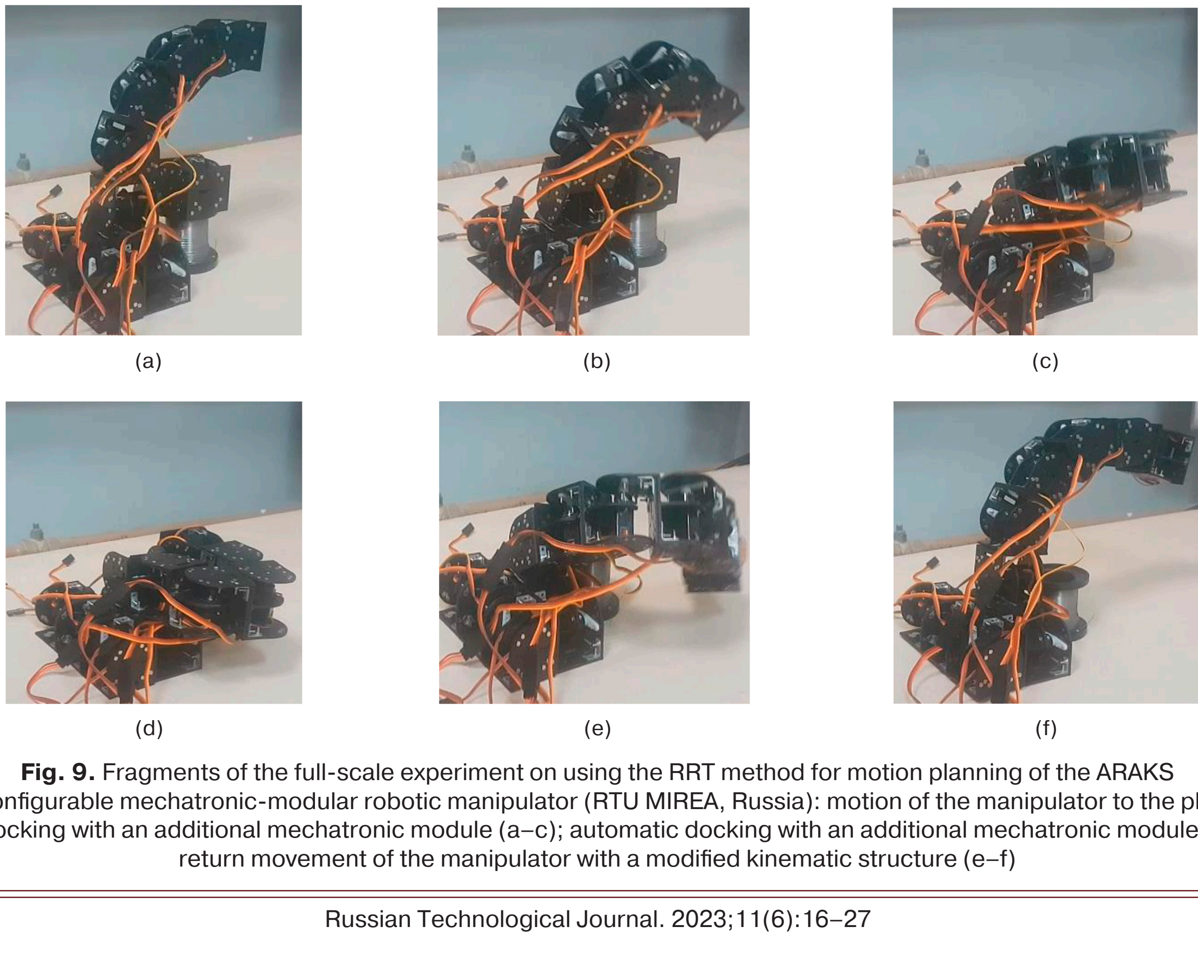


Fig. 9. Fragments of the full-scale experiment on using the RRT method for motion planning of the ARAKS reconfigurable mechatronic-modular robotic manipulator (RTU MIREA, Russia): motion of the manipulator to the place of docking with an additional mechatronic module (a–c); automatic docking with an additional mechatronic module (d); return movement of the manipulator with a modified kinematic structure (e–f)

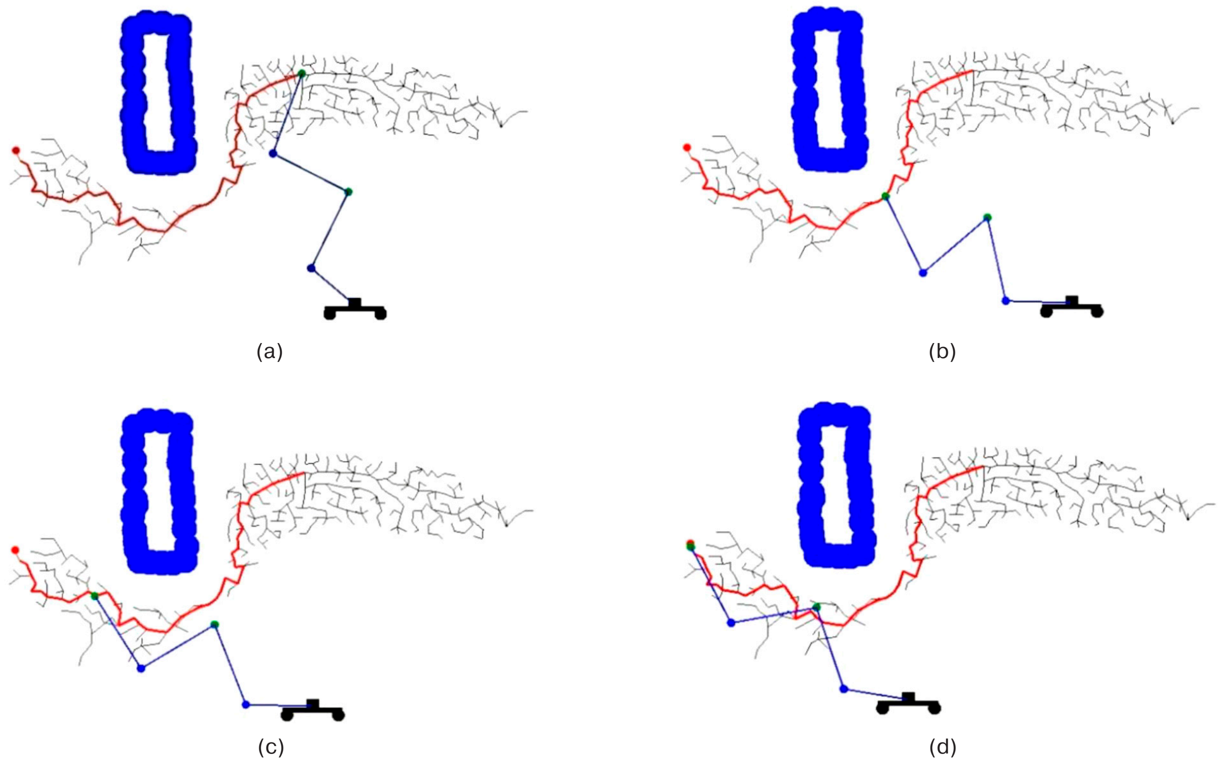


Fig. 10. Application of the RRT method for the purposeful motion planning for a manipulator on a mobile base

It is important to note that the size of the neighborhood in which the search is performed, which is determined according to the current number of tree nodes, decreases as the tree grows [8]:

$$r = \gamma(\log(n)/n)^{1/d+1},$$

where d is the dimensionality of the configuration space; n is the current number of the tree vertices; γ is a constant coefficient determined by the volume of the allowed configuration space [7].

The following steps are aimed at local optimization of the tree structure in the neighborhood selected earlier around the c_{new} vertex. As part of their execution, for each vertex $c \in C^*$ the possibility of re-forming the path leading to it through vertex c_{new} is analyzed, taking into account the actual change in the cost of the corresponding route. If the value of $cost(c_{\text{init}}, c)$ index decreases, a local restructuring of the tree is performed, where the considered vertex $c \in C^*$ becomes a child of c_{new}. As shown in Fig. 11, the application of the RRT* method to robotic manipulator motion planning problems provides the construction of much smoother trajectories compared to those formed on the basis of the original version of the RRT method.

Minor changes in the algorithmic implementation of the method ensure its applicability for solving robotic manipulator motion planning problems in the conditions of a priori unknown and dynamic scenes due to additional mechanisms of operative rearrangement of the synthesized tree [10–12]. Thus, Fig. 12 shows fragments of model experiments on mobile robotic manipulator motion planning in an a priori unknown scene, when the search tree is rebuilt as obstacles are detected directly in the process of movement.

Along with the classical version of the RRT method, its modification RRT-Connect, which is associated with a radical transformation of the order of route network formation to find the trajectory of purposeful manipulator motion in the space of possible configurations, has become widespread. According to the new scheme of its step-by-step reconstruction, the model of the discrete search space is represented by a set of two trees, the alternate growth towards each other of which reflects the allowable changes in the robotic manipulator's states, starting from both the initial c_{init} and the goal c_{goal}, respectively (Fig. 13).

Mutual integration of the synthesized structures is ensured by periodic attempts to include each emerging vertex of one tree into the composition of the other. As is commonly believed, the RRT method with a counter-growth and its modifications [13] have increased efficiency compared to the original prototype, which is fully confirmed by the data of experimental studies shown in Figs. 14 and 15. The capabilities, advantages, and distinctive features of the RRT-Connect method make it promising for use not only in tasks of planning purposeful motions by moving objects of various types in complex environments, but also for group control of autonomous robotic manipulators when performing mutual convergence and automatic jointing operations.

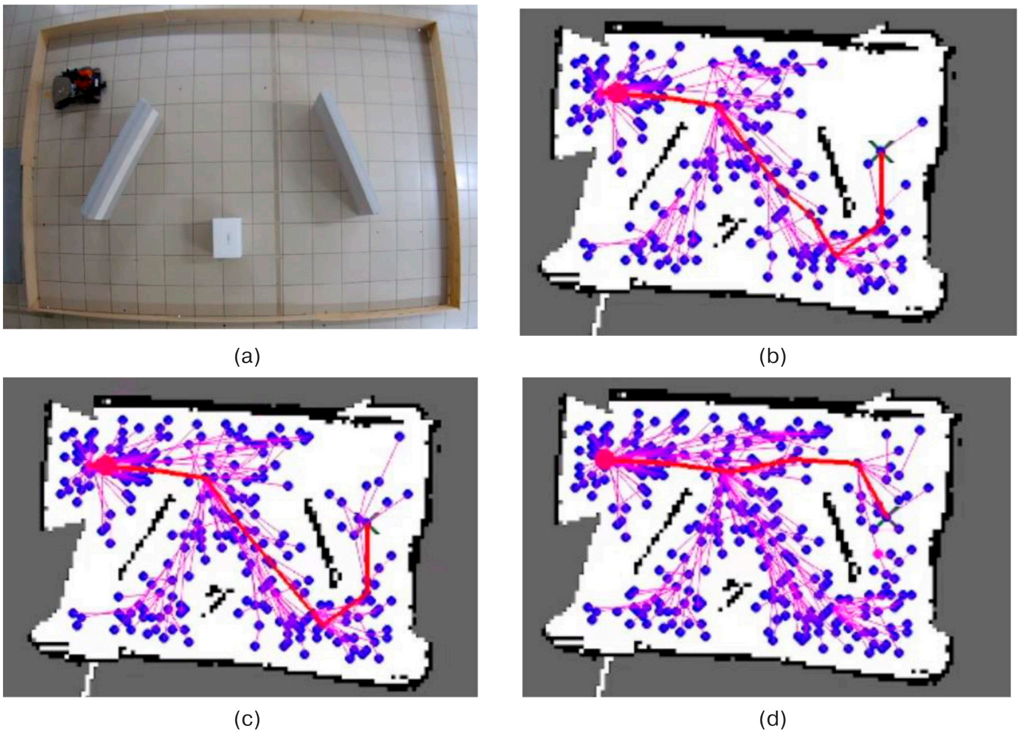


Fig. 11. Fragments of a complex experiment on motion planning of an autonomous mobile robotic manipulator using the RRT* method: configuration of a real scene (a); construction and adjustment of the desired route during the algorithm operation (b, c, d)

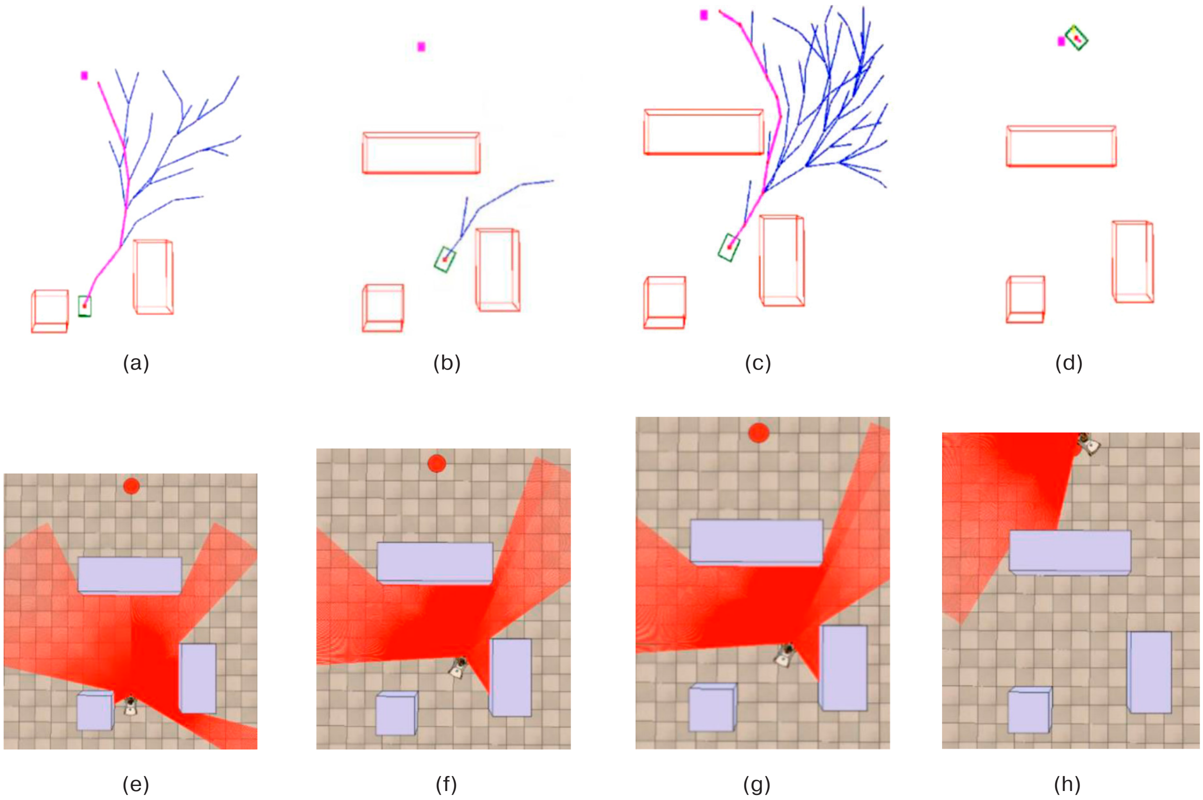


Fig. 12. Fragments of model experiments on using the RRT method for planning mobile robotic manipulator motions in the conditions of a priori unknown scene: rebuilding the search tree (a, c, e, g) as obstacles are detected in the process of manipulator motion (b, d, f, h)

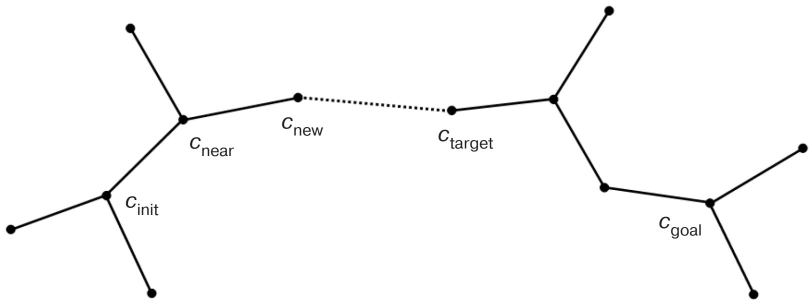


Fig. 13. Bidirectional exploration of configuration space according to the RRT method with counter-growth (RRT-Connect). c_{target} is the nearest vertex for c_{new}, for which the check on the possibility of combining two trees is performed

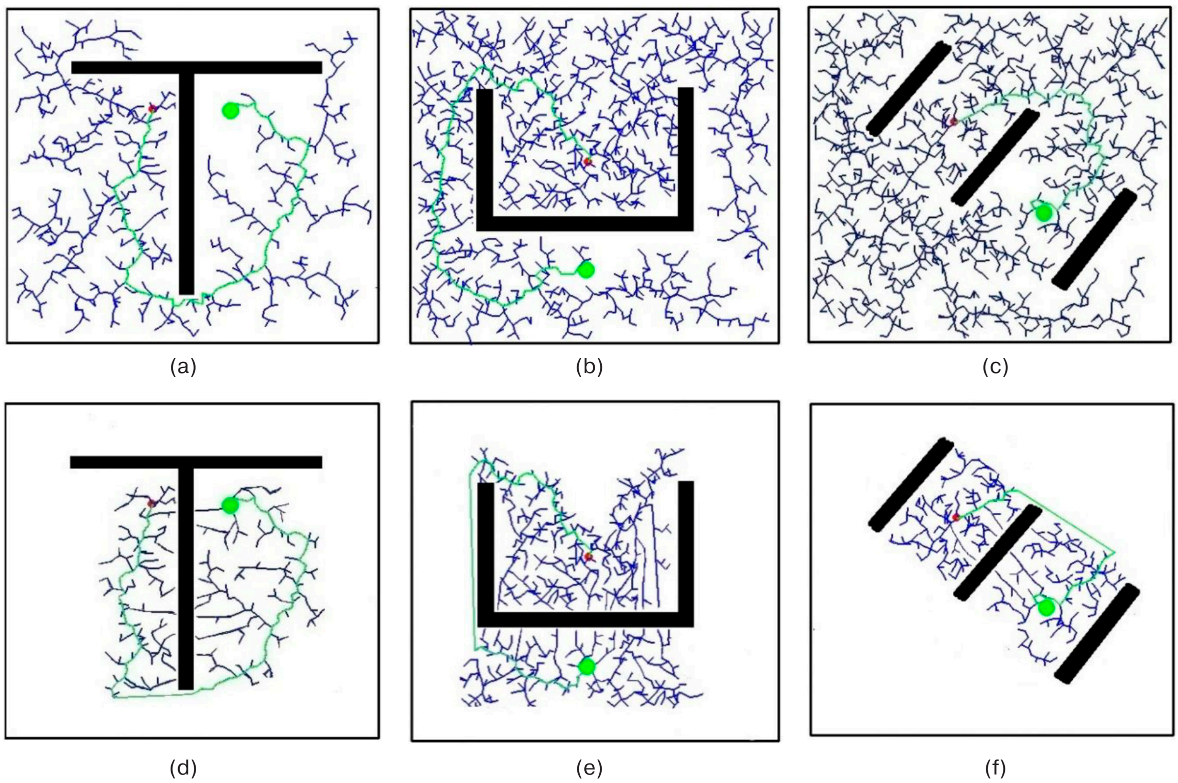


Fig. 14. Experimental results on motion planning of an autonomous mobile robotic manipulator in an obstacle-ridden environment based on RRT (a–c) and RRT-Connect (d–e) methods

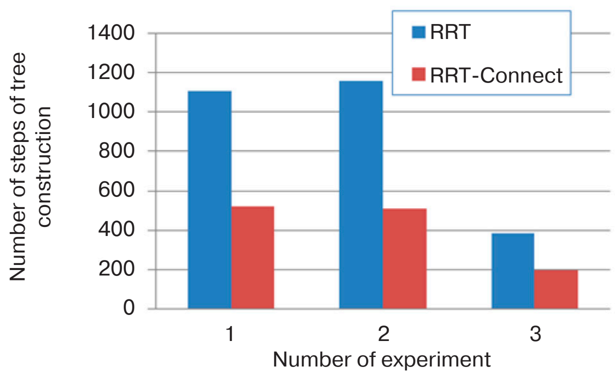


Fig. 15. Experimental results on evaluating the effectiveness of RRT and RRT-Connect methods for motion planning of an autonomous mobile robotic manipulator in an obstacle-ridden environment

CONCLUSIONS

Review of specialized literature and experimental studies have convincingly demonstrated the broad capabilities of the RRT method for providing solutions to motion planning problems for mobile and robotic manipulators of various types and layouts, including manipulators with redundant or reconfigurable structure, placed on a stationary or mobile base. Generalization of the obtained results opens up real prospects for using the RRT method as a constructive basis not only for creating universal means of motion planning for mobile robotic systems with on-board manipulator, but also for solving problems of automating the docking of autonomous mobile platforms.

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

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RESEARCH ARTICLE

Calculating permissible deviations of vibration accelerations of printed circuit assemblies by simulation modeling

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Abstract
Objectives. A variety of technical condition control methods are used in the production and operation of printed circuit assemblies (PCA) for radio-electronic means (REM). The main methods are optical, electrical, and thermal. However, not all possible defects can be detected using these methods. For example, a weakened PCA fastener in a block or the incorrect installation of an electric radioelement (ERE) on a printed circuit board (PCB) can be detected only by analyzing the mechanical characteristics of the REM. These factors, in particular, are the values of the vibration acceleration amplitudes on ERE or at selected PCB control points (hereinafter referred to as the PCA vibration acceleration amplitude). In order to draw a conclusion about the presence of a defect, the measured values of the vibration acceleration amplitudes obtained as a result of testing PCA for the effects of harmonic vibration are compared with the permissible values calculated during the simulation of mechanical processes in PCA. This takes into account the variations in the physical and mechanical parameters of materials and geometric parameters of the PCA design. The aim of this paper is to determine the permissible values of PCA vibration acceleration amplitudes to be compared with the measured values.
Methods. The Monte Carlo simulation method is used to calculate the permissible deviations of vibration accelerations. This consists in repeatedly calculating the values of the vibration acceleration amplitudes at random values of the physical and mechanical parameters of materials and geometric parameters of the PCA design within their tolerances.
Results. Experimental verification of this method was carried out using the *SolidWorks* software for modeling mechanical processes. This enabled the tolerance values for PCA vibration acceleration at the control point at the first resonant frequency to be established and experimental data to be obtained when introducing various defects. The results of comparing the measured values with the calculated tolerance enabled conclusions to be made with regard to the possibility of detecting PCA defects.
Conclusions. Using this method of calculating tolerances for the PCA vibration acceleration amplitude allows the presence of defects in REM that do not affect the electrical or thermal characteristics of REM to be determined, thus increasing the efficiency of technical condition control.

Keywords: non-destructive testing, simulation modeling, Monte Carlo method, printing circuit boards, electronic means, mechanical processes

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Резюме
Цели. При производстве и эксплуатации печатных узлов (ПУ) радиоэлектронных средств (РЭС) используются различные методы контроля технического состояния. Основные из них – это оптический, электрический и тепловой. Но не все возможные дефекты выявляются с использованием указанных методов. Например, ослабленное крепление ПУ в блоке или некорректная установка электрорадиоэлемента (ЭРЭ) на печатной плате выявляются только путем анализа механических характеристик РЭС, в частности значений амплитуд виброускорений на ЭРЭ или в выбранных контрольных точках печатной платы (далее – амплитуда виброускорения ПУ). Чтобы сделать вывод о наличии дефекта, измеренные значения амплитуд виброускорений, полученные в результате испытаний ПУ на воздействие гармонической вибрации, сравниваются с допустимыми значениями, рассчитанными при имитационном моделировании механических процессов в ПУ с учетом разбросов физико-механических параметров материалов и геометрических параметров конструкции ПУ. Цель работы состоит в определении допустимых значений амплитуд виброускорений ПУ, с которыми будут сравниваться измеренные значения.
Методы. Для расчета допустимых отклонений виброускорений предлагается использование метода имитационного моделирования Монте-Карло, заключающегося в многократном расчете значений амплитуд виброускорений при случайных значениях физико-механических параметров материалов и геометрических параметров конструкции ПУ в пределах своих допусков.
Результаты. В результате экспериментальной проверки описанного метода с помощью программы моделирования механических процессов *SolidWorks* определены значения допуска на виброускорения ПУ в контрольной точке на первой резонансной частоте и получены экспериментальные данные при внесении различных дефектов. Результаты сравнения измеренных значений с рассчитанным допуском позволяют сделать вывод о возможности обнаружения дефектов ПУ.
Выводы. Использование данного метода расчета допусков на амплитуду виброускорения ПУ позволяет определять наличие дефектов в РЭС, которые не влияют на электрические или тепловые характеристики РЭС, и таким образом повысить эффективность контроля технического состояния.

Ключевые слова: неразрушающий контроль, имитационное моделирование, метод Монте-Карло, печатный узел, радиоэлектронное средство, механические процессы

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INTRODUCTION

Modern radio-electronic means (REM) are complex devices, both in terms of electrical circuits and in terms of design. A wide variety of circuit and design solutions,[1] as well as materials used in REM production[2] can cause the presence of deviations in their characteristics from their nominal values. As a rule, the technical condition of REM can be diagnosed [1, 2] by electrical, thermal, and mechanical characteristics.[3] Methods for diagnosing electrical and thermal characteristics are fairly well developed and elaborated [3–6], while diagnostics by mechanical characteristics still remains relevant due to the difficulties in controlling mechanical characteristics and the variety of mechanical connections present in modern REM designs [7–9].

Despite the high requirements for the quality and reliability of products at the production stage, there is a probability of various defects such as: deformation of electro-radio elements (ERE); weakening of their fasteners or printed circuit board (PCB); formation of cracks in PCB, which to a certain extent would affect the mechanical mode of operation and may result in REM failure.

The production stage of printed circuit assemblies (PCA) is completed by testing, in order to confirm their reliability throughout their life cycle. Depending on the REM specifics, they are subjected to a large number of different *in situ* tests[4] [10]. The vast majority of REMs are tested for mechanical effects: primarily vibration [11–13]. In this case, the measured characteristics are compared with the maximum permissible, in order to assess the vibration resistance of REM [14]. However, a number of defects (e.g., PCA weakened mounting, ERE incorrect installation, etc.) may not lead to the measured value of the mechanical characteristic exceeding the maximum permissible value. They may, however, result in REM failures during operation. Therefore, the paper proposes that the measured values of mechanical characteristics be compared with the values of their tolerances due to the variation of physico-mechanical and geometric parameters of REM materials. This will enable a conclusion about REM technical condition based on the results of comparison to be drawn.

METHOD FOR CALCULATING PERMISSIBLE DEVIATIONS OF PCA VIBRATION ACCELERATIONS

One of the technical condition control methods necessary to ensure high reliability of REM involves non-destructive testing by mechanical characteristics. This is based on a comparison of values of the ERE vibration acceleration amplitudes and in PCB control points of the tested PCA and the PCA reference sample. The presence of defects in PCA results in the deviation of the ERE vibration acceleration amplitudes from their nominal values, both higher and lower.

The PCA vibration acceleration amplitude depends on the physico-mechanical parameters of PCA materials, geometric parameters of PCA structural elements, and PCA fastening points.

To control PCA by mechanical characteristics, a reference mechanical model needs to be created, the calculation results of which would be used for comparison with the measured values of vibration acceleration amplitudes of the studied PCA samples. In order to create the mechanical model, a variety of programs can be used to model the mechanical processes in REM. The accuracy of modeling PCA mechanical characteristics is determined by many factors. These include: correctness and completeness of describing the topological model of mechanical processes; precisely describing fastening conditions; as well as setting such values of physico-mechanical parameters of materials and geometrical dimensions of construction elements which correspond to real values as much as possible. Practice shows

[1] Muromtsev D.Yu., Tyurin I.V., Belousov O.A., Kurnosov R.Yu. *Design of functional units and modules of radioelectronic devices:* A textbook for universities. 2nd ed. St. Petersburg: Lan; 2021. 252 p. (in Russ.).

[2] Pokrovskaya M.V., Popova T.A. *Materials and structural elements of REM:* A textbook. Moscow: RTU MIREA; 2021. Part 1: Material science and structural materials. 200 p. (in Russ.).

[3] Davydov P.S. *Technical diagnostics of radioelectronic devices and systems*. Moscow: Radio and Communications; 1988. 256 p. (in Russ.).

[4] Baranov V.M., Karasevich A.M., Sarychev G.A. *Testing and quality control of materials and structures*: A textbook for universities. Moscow: Higher School; 2004. 359 p. (in Russ.).

that for the majority of engineering calculations the modeling error of mechanical characteristics is no more than 30% for preliminary calculations and about 5–10% for calculations with refined data.

Initial data on the values of physico-mechanical parameters of REM materials necessary for modeling mechanical processes, as indicated in a range of reference books, can be obtained as a rule from experimental studies and set in a certain range of values. The model of mechanical processes in PCA, analyzed by specified physico-mechanical parameters of materials and with experimentally investigated distribution of PCA ERE vibration acceleration amplitudes, can be taken as a reference model. This model can also be used for technical condition control during experimental tests of PCA samples.

When using the reference mechanical model of PCA, the tolerances for the values of ERE vibration acceleration amplitudes are calculated using the program for modeling mechanical processes. Based on the results, the maximum permissible value $a^{\max}$ and minimum permissible value $a^{\min}$ of vibration acceleration amplitudes for each ERE can be determined. These modeling results form the basis for comparison with experimentally obtained values, wherein the deviations beyond the tolerance limits are considered as various kinds of defects [2].

In order to determine the PCA suitability for operation, the tolerance interval $[a^{\min}_{\text{PCA }m}, a^{\max}_{\text{PCA }m}]$ needs to be calculated for each mth control point of the vector of vibration acceleration measured values $\overline{a_{\text{PCA }m}}$ PCA would be considered serviceable, if the following condition is met:

$$\overline{a_{\text{PCA }m}} \in \left[a^{\min}_{\text{PCA }m}, a^{\max}_{\text{PCA }m}\right].$$

When controlling PCA technical condition, the minimum permissible value $a^{\min}_{\text{PCA }m}$ and the maximum permissible value $a^{\max}_{\text{PCA }m}$ of PCA vibration acceleration amplitudes are used, while the maximum value $a^{\max}_{\text{PCA }m}$ can be used to calculate reliability factors.

After calculating the PCA reference mechanical model, vibration accelerations are measured in the control points of the studied PCA group using vibration detectors. The values of the PCA vibration acceleration amplitudes obtained as a result of measurements are compared with their maximum permissible values. Then a conclusion about the PCA technical condition is made on the basis of the comparison results. The values of vibration acceleration amplitude of elements for serviceable PCA samples should lie within the range of values obtained by calculating the reference mechanical model. A PCA sample with a deviation of PCA vibration acceleration amplitude beyond the calculated limits detected is considered defective.

The PCA reference mechanical model is obtained at parameter values of REM designs lying within their tolerances. However, the mechanical model can also be used to form a fault base which can form a reference book of the vibration acceleration amplitude distribution over the PCA surface in the presence of any defect. Such a reference book is formed in advance before PCA diagnostics. Applying this method allows defects related to the ERE installation, as well as defects related to PCB production.

Thus, the PCA reference mechanical model takes two factors into account: the spread of various parameters (physico-mechanical parameters of materials, geometric parameters of designs) within their tolerances when using the model to search for defective products; and the possible presence of typical defects in PCA when using the model to identify defects in the studied PCA.

In some cases, the existing models and methods for calculating the mechanical modes of REM designs do not allow the influence of physico-mechanical parameters of REM design materials and geometrical parameters of REM designs on the mechanical mode of the product to be analyzed in detail. The Monte Carlo method of statistical testing used for modeling various physical processes in REM, in particular, mechanical processes in PCA design and REM as a whole, is highly capable of resolving this problem [15, 16]. The advantages of the Monte Carlo method over other methods of studying physical processes offer a fairly simple mathematical apparatus of calculations, as well as a clear physical interpretation of the considered problem. These factors thus simplify the programming process and provide ease of control at the stage of program debugging.

When applying the Monte Carlo method, a special random number generator program is used. This program repeatedly outputs random values of a certain quantity distributed in accordance with the specified distribution law. For each random variable value, the values of REM mechanical characteristics are determined. This calculation is repeated a number of times as specified by the user. For each calculation, the values of the model parameters take random values lying within their tolerances. Based on modeling results, histograms showing the laws of distribution of mechanical characteristics are built. Then the mathematical expectation and standard deviation of the PCA vibration acceleration amplitudes are calculated from these.

The applied method does not require parametric sensitivity functions to be calculated. However, it requires a large amount of machine time depending on the complexity of the mechanical model and the number of iterations. At the same time, the error of the method is usually of the order of 10%.

Figure 1 shows the flow diagram of the method for calculating the maximum permissible values of the ERE vibration acceleration amplitude using simulation modeling of mechanical processes.

When modeling using this method, such factors as deviations physico-mechanical parameters of materials and geometrical parameters of REM design within their tolerances are taken into account. The use of simulation modeling allows a lot of statistical information to be collected. In this way the permissible variation of ERE vibration accelerations can be determined.

The input data for modeling is:

- the description of REM design;
- $q_{mi}^{min}, q_{mi}^{max}$ being minimum and maximum values of the ith physico-mechanical parameter of REM design, respectively;
- $q_{gj}^{min}, q_{gj}^{max}$ being minimum and maximum values of the jth geometric parameter of REM design, respectively.

Using the program for modeling the mechanical modes of REM operation, a multiple (N times) mechanical calculation of REM design containing PCA (the block, as a rule) is carried out at the first stage. This calculation is performed, in order to determine the spread in vibration acceleration amplitudes in PCA fastening points.

The parameter nominal value can be determined from the minimum and maximum limits of its actual value spread range, taking into account the normal law of parameter distribution according to the following equation:

$$q^{nom} = (q^{max} + q^{min})/2.$$

The relative tolerance value for the parameter value is determined by the following equation:

$$\delta = (q^{max} - q^{min})/q^{nom}.$$

The values of physico-mechanical parameters of materials (q_m) and geometric parameters of designs (q_g) for each implementation of the Monte Carlo method take random values within their tolerances. These take into account the value of random variable ξ_n in accordance with the following equations:

$$q_m = q_m^{nom}(1 + \xi_n \delta_m), \quad q_g = q_g^{nom}(1 + \xi_n \delta_g).$$

The random variable ξ_n values are generated according to the normal law of distribution of the random variable with zero mathematical expectation and standard deviation $\sigma = 0.33$. The truncated normal distribution of variable ξ_n on the interval $\pm 3\sigma$ is derived.

After performing N calculations of the mechanical mode of PCA design, N values of vibration acceleration amplitudes (a_f) in PCA fastening points are obtained. According to these values, the mathematical expectation of the vibration acceleration amplitude in each PCA fastening point $m(a_f)$ can be determined as follows:

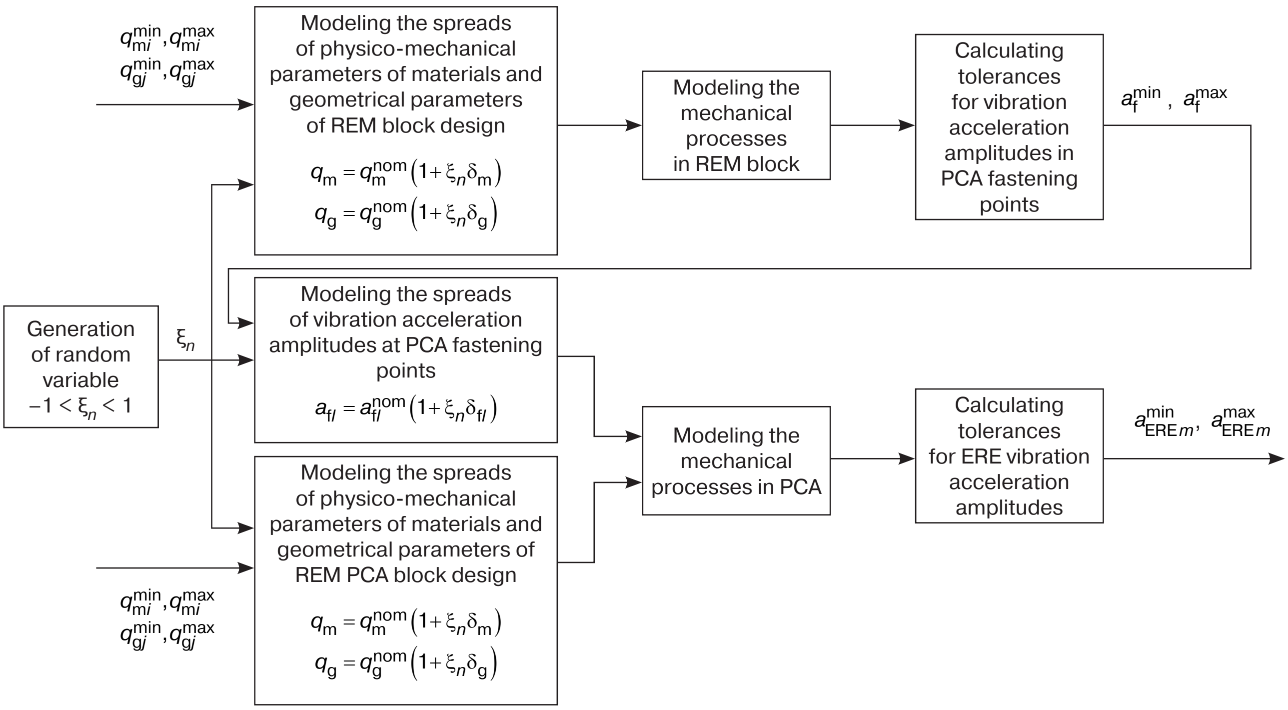


Fig. 1. Flow diagram of the method for calculating permissible deviations of PCA vibration accelerations. $a_{fl}^{nom} = (a_{fl}^{min} + a_{fl}^{max})/2$. $a_{ERE\,m}^{min}$, $a_{ERE\,m}^{max}$ are tolerances for ERE vibration acceleration amplitudes

$$m(a_f) = \frac{\sum_{n=1}^{N} a_f^n}{N},$$

where a_f^n is value of the vibration acceleration amplitude at the PCA fastening point on the nth implementation.

The dispersion of vibration acceleration $D(a_f)$ is determined by the following equations:

$$D(a_f) = \frac{\sum_{n=1}^{N} \left(a_f^n - m(a_f)\right)^2}{N-1}$$

or

$$D(a_f) = \left(\frac{\sum_{n=1}^{N} \left(a_f^n\right)^2}{N} - \left(m(a_f)\right)^2 \right) \frac{N}{N-1}.$$

The standard deviation $\sigma(a_f)$ of the vibration acceleration amplitude at the PCA fastening point is calculated by the following equation:

$$\sigma(a_f) = \sqrt{D(a_f)}.$$

In order to determine the range of permissible values of vibration acceleration amplitude $[a_f^{\min}, a_f^{\max}]$, confidence probability β should be specified as follows:

$$\beta = P\left(a_f^{\min} \le a_f \le a_f^{\max}\right),$$

with which the actual value of vibration acceleration amplitude may lie within this range. Taking into account the value of probability β, the value of coefficient χ is determined according to the reference data. For example, for a confidence probability value $\beta = 0.9973$, the value of coefficient χ is equal to 3.

The minimum value $a_f^{\min}$ and the maximum value $a_f^{\max}$ of the vibration acceleration amplitude taking into account the value coefficient χ for a given probability β are calculated according to the following equations:

$$a_f^{\min} = m(a_f) - \chi\sigma(a_f), \quad a_f^{\max} = m(a_f) + \chi\sigma(a_f).$$

As the result of calculating the mechanical mode of the block, the range $[a_f^{\min}, a_f^{\max}]$ within which the vibration acceleration amplitude values may lie at PCA fastening points can be determined.

Then the statistical modeling of mechanical processes in PCA is carried out in the same way. This involves randomly specifying the values of vibration acceleration amplitude at PCA fastening points from the range $[a_f^{\min}, a_f^{\max}]$, as well as the values of physico-mechanical parameters of PCB material and geometrical parameters of PCA design from the range of possible values. The modeling thus determines the range $[a_{\mathrm{PCA}\,m}^{\min}, a_{\mathrm{PCA}\,m}^{\max}]$ within which the values of ERE vibration acceleration amplitudes for serviceable PCAs lie.

The process of PCA control by mechanical characteristics imposes increased requirements to the reliability of modeling mechanical modes in PCA. When building a model of mechanical processes, certain assumptions also need to be taken into account when analyzing the modeling results.

The error Δ_a^{calc} of calculating the ERE vibration acceleration amplitudes is determined by the following equation:

$$\Delta_a^{\mathrm{calc}} = \sqrt{\Delta_m^2 + \Delta_g^2 + \Delta_s^2 + \Delta_\xi^2},$$

where Δ_m is the error at which physico-mechanical parameters of REM design materials are specified; Δ_g is the error at which geometrical parameters of REM design are specified; Δ_s is the error depending on the computational grid step; Δ_ξ is the error determined by the number of the Monte Carlo method implementations.

The error in determining the maximum permissible deviations of ERE vibration acceleration amplitudes is determined by the number of implementations N in the Monte Carlo method, in addition to error Δ_a^{calc} introduced by various assumptions when creating the mechanical model. The relative error related to the number of implementations can be determined by the following equation:

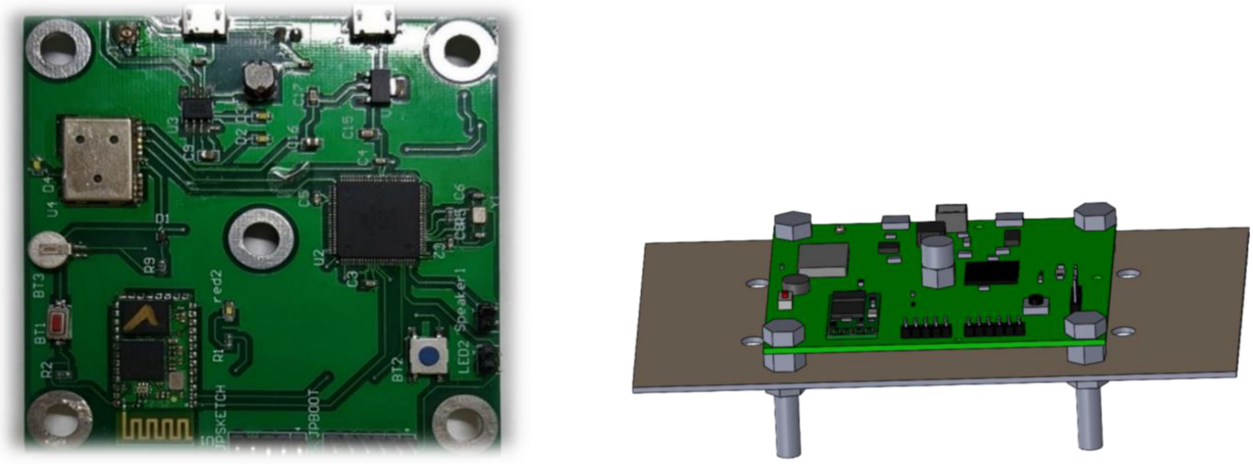
$$\Delta_\xi = 3\sqrt{\frac{D(\xi)}{N}}.$$

It is very important to ensure the accuracy of modeling mechanical processes, since the result of PCA control by mechanical characteristics depends on it. An incorrect result may lead to "rejecting" the serviceable product or to missing the product with a defect posing serious consequences in its operation.

In order to apply this method, a variety of programs for modeling mechanical processes in REM designs of different hierarchy levels, such as *ASONIKA-TM*[5], *SolidWorks*[6], etc., may be used [17, 18].

[5] https://asonika-online.ru/products/asonika-tm/ (in Russ.). Accessed June 15, 2023.

[6] https://www.solidworks.com/. Accessed June 15, 2023.



(a) (b)

Fig. 2. The PCA (a) and its model in *SolidWorks* software (b)

EXPERIMENTAL VERIFICATION OF THE METHOD FOR CALCULATING PCA VIBRATION ACCELERATION TOLERANCES

For the experimental verification of the method described, an onboard radio-electronic device for controlling run-up parameters is used. This device is a PCB with the following EREs installed upon it: Atmel ATmega2560 microcontroller (Atmel Corporation, USA); InvenSense MPU-6050 accelerometer (InvenSense Inc., USA); Global Navigation Satellite System receiver U-blox Neo 7M (U-blox, Switzerland), Bluetooth chip HC-05 (Core Electronics, China); and AMS1117-3.3 power supply (UMW, China).

In order to calculate tolerances for the vibration acceleration amplitude value, PCA mechanical processes are simulated using *SolidWorks* software. The PCA and its model are shown in Fig. 2.

During modeling, the spread of PCB material density 1500–1800 kg/m^3 and elastic modulus 22–26 GPa is set. The number of the Monte Carlo method implementation is 500. As a result of modeling, the spread of the PCA vibration acceleration amplitude is obtained at the PCA control point in a serviceable condition at the first resonant frequency whose value is 170 Hz. The control point is located in the center of PCB and is selected by the results of analyzing distribution of vibration acceleration values on PCB based on the maximum value. The spread of vibration acceleration amplitude values ranges from 4.8 m/s^2 to 5.2 m/s^2, respectively, while the tolerance value is equal to ±0.2 m/s^2. Then the modeling of mechanical processes in PCA is carried out with simulation of various defects such as: a weakened PCA fastening (defect No. 1); the absence of ERE (defect No. 2); a crack in PCB (defect No. 3); and a different PCB thickness (defect No. 4). As a result, the amplitude–frequency characteristics (AFC) of vibration acceleration at the PCA control point shown in Fig. 3 are obtained.

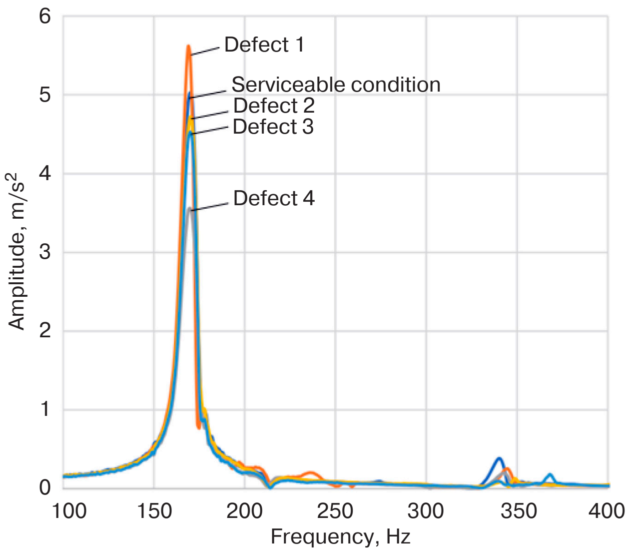


Fig. 3. Calculated values of AFC at the PCA control point in serviceable condition and under different defects

It can be seen from the graphs that each of the defects causes deviation of vibration acceleration AFC at the PCA control point from AFC for the serviceable condition. It is most effective to compare AFC at the first resonant frequency since at other frequencies, the result of comparison may be incorrect. This can be due to small differences in the values of vibration acceleration amplitudes, comparable to the calculation errors.

Further, experimental studies are carried out of the mechanical characteristics of serviceable PCA and PCA with single defects simulated by modeling. The experiment is conducted using a vibration test bench (Fig. 4) at the harmonic vibration frequency equal to the first resonance frequency (170 Hz) obtained as a result of modeling. As a result, the experimental values of vibration acceleration amplitudes at the PCA control point at the resonant frequency under different defects are obtained: for a weakened PCA fastening (defect No. 1), it is 5.6 m/s^2; for the absence of ERE (defect No. 2), it is 4.7 m/s^2; for a crack in PCB (defect No. 3), it is 4.5 m/s^2; and for a different thickness of PCB (defect No. 4), it is 3.5 m/s^2.

Fig. 4. Setup for experimental study of PCA under the impact of harmonic vibration

As seen from the experimental results, each of the defects causes deviation of vibration acceleration values at the PCA control point from the value for the serviceable condition beyond the calculated tolerance obtained as a modeling result. Moreover, a number of defects may cause approximately the same change in vibration acceleration at the PCA control point (for example, defects No. 2 and No. 3 in the experiment) compared to the measurement error. This indicates that it is not possible to determine the type of defect unambiguously (the presence of a particular type of defect can be stated only with a certain degree of probability determined on the basis of the analysis of possible types of defects in the studied REM sample). Consequently, only when comparing the measured values of vibration accelerations with the tolerance limits obtained as a result of simulation modeling, is it possible to draw a conclusion regarding the presence or absence of defects in PCA, and to determine the type of possible defects with a certain probability.

CONCLUSIONS

The method for calculating tolerances for the PCA vibration acceleration amplitude was developed using the Monte Carlo simulation of mechanical processes in REM PCA. This takes into account the spread of physico-mechanical and geometric parameters of REM design. Based on the experimental results, conclusions may be drawn about the legitimacy of applying the described method in calculating permissible values of PCA vibration accelerations in production practice, in order to control the technical condition of REM PCA and search for defects. This method allows the presence of single defects in PCA to be recognized effectively. Studies involving the possible detection of multiple defects (simultaneous presence of two or more defects in PCA) are currently being conducted by the authors of the paper.

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

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RESEARCH ARTICLE

Use of a spatially distributed in-phase antenna to increase the noise immunity of signal reception

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Abstract
Objectives. Radio-technical information transmission systems are widely used in various sectors of our life, not only for telecommunications and associated domestic needs, but also for the functioning of various special services, such as emergency response units, which increasingly use robotic complexes in the course of their work. In the event of an emergency, robot devices can be used to get in under rubble, in concrete pipes or other municipal facilities, which typically result in a sharp deterioration of the necessary conditions for the propagation of radio waves. In this regard, the problem of ensuring reliable communication with the robotic complex becomes rather acute. The aim of the present work is to reduce the effect of multipath propagation of radio waves in the communication channel under complex interference conditions.
Methods. The methods of statistical radio engineering and mathematical modeling are used according to optimal signal reception theory.
Results. The presented model for a multi-element, spatially-distributed, in-phase receiving antenna of various configurations, featuring an electronically adjustable radiation pattern, is designed to ameliorate the multipath nature of signal propagation. A simulation of a multipath communication channel was carried out in the presence of one main and three reflected beams of radio wave propagation, as well as with harmonic interference at two angles of its arrival and different frequency detuning relative to the frequency of the useful signal. The probability of a bit error when receiving discrete information using the proposed antenna is estimated.
Conclusions. The proposed signal processing algorithm on the receiving side can be used to partially compensate for the influence of the multipath effect. As a result, the noise immunity of information reception in comparison with reception on an omnidirectional antenna with one antenna element increases: for a bit error probability of 10^{-3}, the energy gain ranges from 2 dB for two beams to 7–10 dB for three or four beams. In the presence of concentrated harmonic interference in the radio channel, its simultaneous spatial (by the antenna) and spectral (by the demodulator) filtering is also observed, the effectiveness of which depends on the direction of arrival and the frequency detuning of the interference, which also leads to a significant decrease in the error probability.

Keywords: spatially distributed in-phase antenna, electronic beam control, multipath propagation of radio waves, harmonic interference, noise immunity, bit error rate

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НАУЧНАЯ СТАТЬЯ

Использование пространственно-распределенной синфазной антенны для повышения помехоустойчивости приема сигналов

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Резюме
Цели. Радиотехнические системы передачи информации находят широкое применение в различных отраслях нашей жизни не только для обеспечения телекоммуникаций и бытовых потребностей человека, но и для функционирования различных спецслужб, например, служб МЧС, которые в своей работе применяют роботизированные комплексы. В случае чрезвычайного происшествия возможно попадание такого робота под завал, в железобетонные трубы или другие коммунальные объекты, в результате чего условия распространения радиоволн резко ухудшаются. В этой связи остро стоит вопрос обеспечения надежной связи с роботизированным комплексом. Цель работы – снижение влияния эффекта многолучевого распространения радиоволн в канале связи в сложных помеховых условиях.
Методы. Использованы методы статистической радиотехники, теории оптимального приема сигналов и математического моделирования.
Результаты. Приведена модель приемной многоэлементной пространственно-распределенной синфазной антенны разных конфигураций с электронно-регулируемой диаграммой направленности, предназначенной для борьбы с многолучевым характером распространения сигнала. Проведено моделирование многолучевого канала связи при наличии одного основного и трех отраженных лучей распространения радиоволн, а также с гармонической помехой при двух углах ее прихода и разной частотной расстройкой относительно частоты полезного сигнала. Оценена вероятность битовой ошибки при приеме дискретной информации с применением предложенной антенны.
Выводы. Применение предложенного алгоритма обработки сигналов на приемной стороне позволяет частично скомпенсировать влияние эффекта многолучевости. В результате помехоустойчивость приема информации по сравнению с приемом на всенаправленную антенну с одним антенным элементом повышается: для вероятности битовой ошибки 10^{-3} энергетический выигрыш составляет от 2 дБ при 2 лучах до 7–10 дБ при 3–4 лучах. При наличии в радиоканале сосредоточенной гармонической помехи также наблюдается ее одновременная пространственная (с использованием антенны) и спектральная (с использованием демодулятора) фильтрация, эффективность которой зависит от направления прихода и частотной расстройки помехи, что также приводит к существенному снижению вероятности ошибки.

Ключевые слова: пространственно-распределенная синфазная антенна, электронное регулирование диаграммы направленности, многолучевое распространение радиоволн, гармоническая помеха, помехоустойчивость, вероятность битовой ошибки

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INTRODUCTION

Radio-technical information transmission systems are widely used in various sectors of our life, not only for telecommunications and associated domestic needs, but also for the functioning of various special services, such as emergency response units, which increasingly use robotic complexes in the course of their work. In the event of an emergency, robot devices can be used to get in under rubble, in concrete pipes or other municipal facilities, which typically result in a sharp deterioration of the necessary conditions for the propagation of radio waves. In this regard, the problem of ensuring reliable communication with the robotic complex becomes rather acute.

Radio signals are significantly affected by the radio propagation environment though which they pass. In addition to additive noise interference, concentrated interference from other radio facilities and retranslated interference caused by multipath propagation of radio waves in their reflection from obstacles and refraction are observed in the communication channel [1–3]. The formation of such a multipath communication channel causes distortion of the useful radio signal parameters; such changes to its amplitude, phase, and angle of arrival (AoA) result in the essential decrease of noise immunity of receiving information [4–10].

There are various methods for counteracting multipath propagation in the communication channel. These include the use of channel equalizers, radiation pattern (RP) control, increasing the intervals in the transmitted pulse sequence, and using the dispersed reception systems. One such approach is the Multiple-Input Multiple-Output (MIMO) [11] system widely used in wireless local area networks of different standards, as well as in wireless mobile communication systems.

Another effective way to counteract multipath in communication channels involves the use of beam antennas and antenna systems to spatially filter received signals. When using such antennas, RPs are formed either by design methods or by special methods of the received signals processing [12].

One complex beam antenna system is represented by an in-phase antenna array, comprising separate near-omnidirectional antennas, which are arranged in such a way that the phases of the signals induced in them are the same, allowing the signals from each antenna to be added up in phase.

This eventually results in the increasing signal level at the output of the antenna system, a narrowing of the RP, and, finally, increasing the gain factor as compared to that of a single antenna included in the array.

MODEL OF THE IN-PHASE ANTENNA WITH ELECTRONICALLY ADJUSTABLE RP

A spatially distributed antenna system containing N = 2 up to 8 antenna elements may be used under complex interference conditions for reducing the effect of multipath radio wave propagation in the communication channel with a robotic system [13].

Such an in-phase antenna system (Fig. 1) consists of resonator antenna elements *1–8*, electronically adjustable delay elements *9–16*, and am in-phase adder *17*. The resonator antenna elements are arranged uniformly with an angular step of $2\pi/N$ in a circle of diameter equal to half the wavelength of the received signal $\lambda/2$. The signals from antenna elements come through adjustable delay elements to the in-phase adder to form the resulting signal S_{out}. The purpose of the adjustable delay elements consists in ensuring the in-phase condition of the received oscillations and forming the summarized antenna pattern.

Time delays of the received oscillations from antenna elements to the in-phase adder with allowance for the required angle φ of the RP rotation are determined as follows:

$$\tau_i = \frac{T}{4}\left\{1+\sin\left[\left(\frac{\pi}{2}-\frac{i\pi}{4}\right)+\varphi\right]\right\}, \tag{1}$$

where $i=\overline{1,8}$ is the antenna element number of the system while T is the wave period of the received signal.

In [14, 15], RPs of the in-phase antenna under consideration are calculated for three cases: nominal frequency of the received signal, reduced frequency, or increased frequency. It is shown how the RP width and

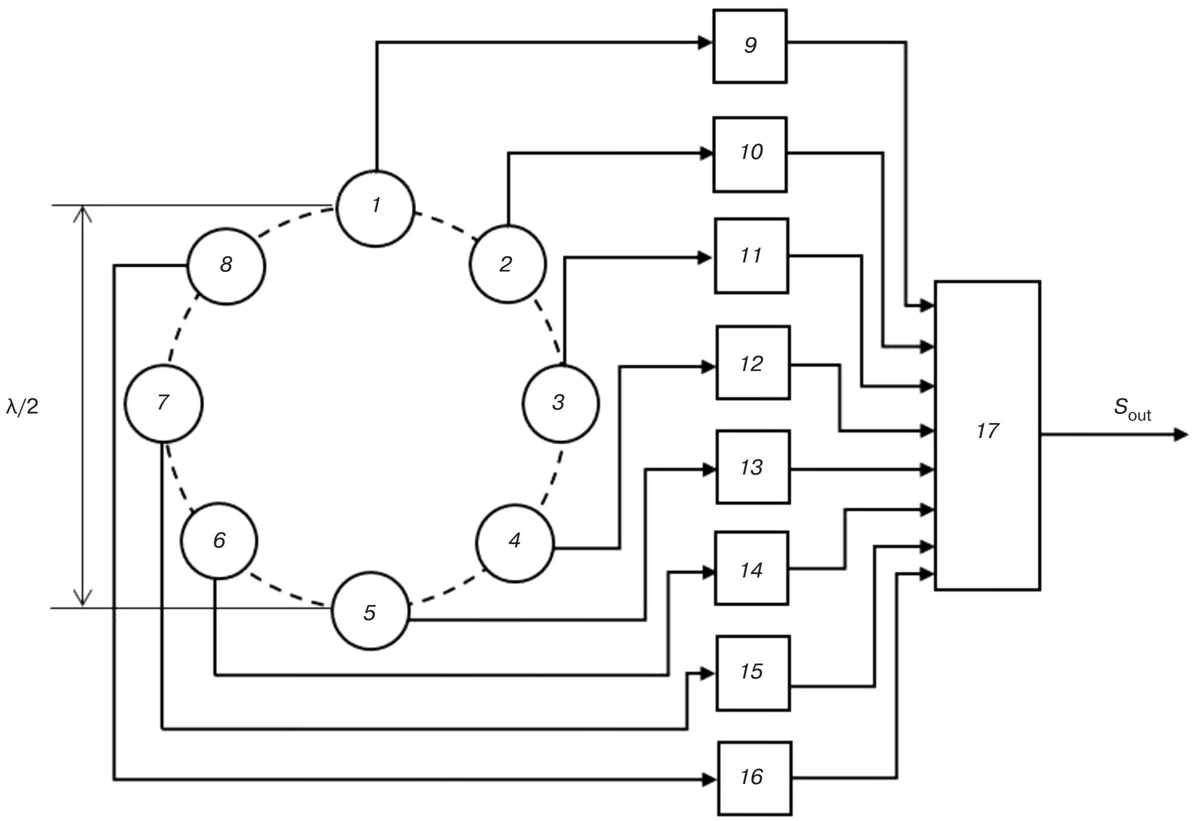

Fig. 1. Schematic diagram of the in-phase antenna array with electronically adjustable RP control

sidelobe level change with frequency. The plots show that structurally simple two-element antennas have quite wide RP and very high sidelobe levels. Four- and eight-element antennas, which have good, very close indices, can be used for spatial filtering in channels with multipath wave propagation. Here, it may be noted that the selective properties of these antennas remain normal when the signal frequency deviates from the nominal frequency even by as much as 10%.

The possibility of adjusting the antenna RP electronically is illustrated in Fig. 2 showing the directional characteristics at various angles φ set in delay elements (1). It is worth noting that at different angles of rotation, the pattern shape itself, and hence the selective properties, remain unchanged.

MODELING RESULTS

In order to assess immunity to interference of the communication system with the proposed in-phase antenna on the receiving side under difficult interference conditions, mathematical modeling was carried out.

A. Signal and disturbance models. A signal with binary phase-shift keying $s(t) = A_0\cos(\omega_0 + C_k\pi)$ is used

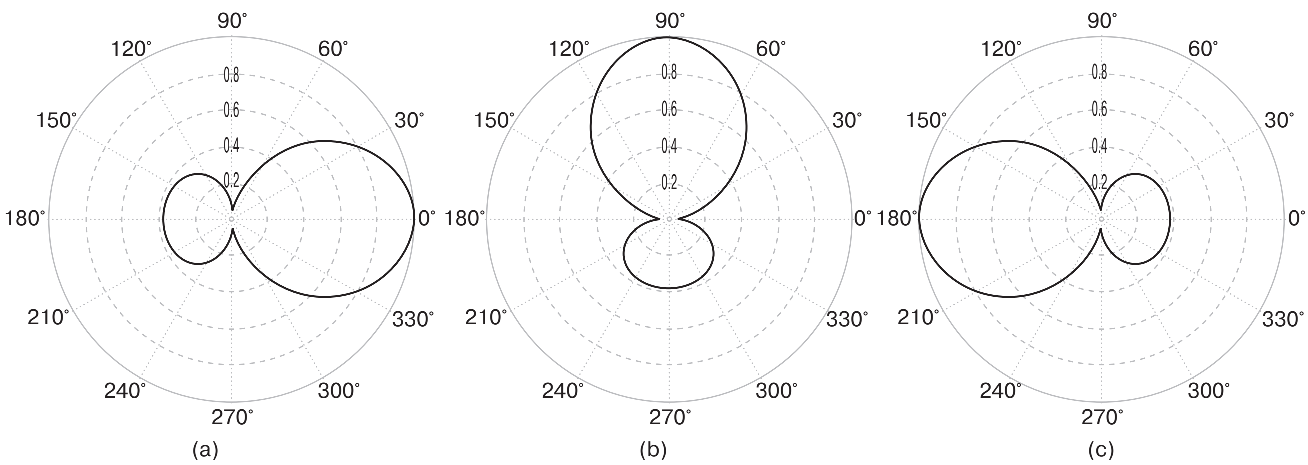

Fig. 2. RPs of the in-phase antenna: (a) φ = 0, (b) φ = π/2, and (c) φ = π

as a test signal. Here, $A_0 = \sqrt{2E / T_s}$ is its amplitude, ω_0 is carrier frequency, t is time, $C_k = \pm 1$ is information symbol, E is signal energy, and T_s is signal duration. A coherent demodulator is used. Gaussian noise with uniform spectral density N_0 is used as fluctuation noise. The communication channel has been assumed to be multipath with one main beam and several (M = 1, 2, 3) retransmitted beams

$$s_r(t) = \mu_r s(t - \tau_r)$$

with different relative intensity μ_r, time delay τ_r, and AoA θ_r.

In addition, harmonic oscillation $s_h(t) = \mu_h A_0 \cos(\omega_h t + \varphi_h)$ with random phase φ_h, relative intensity μ_h, frequency ω_h close to the useful signal frequency, and different AoAs θ_h have been used as a concentrated disturbance.

B. Multipath communication channel. For modeling the multipath communication channel, one main beam (AoA θ_r = 0) and three reflected beams are used: $\theta_r = \pi/4$, $\mu_r = 0.5$, and $\tau_r = 0.5T_s$ for the first reflected beam; $\theta_r = \pi/3$, $\mu_r = 0.3$, and $\tau_r = 0.1T_s$ for the second reflected beam; and $\theta_r = \pi/5$, $\mu_r = 0.4$, $\tau_r = 0.7T_s$ for the third reflected beam. The signal-to-noise ratio E/N_0 varies within the range from 1 to 13 dB.

Figure 3 shows the obtained dependencies of the bit error probability P_e on the signal-to-noise ratio (SNR) for different numbers of received beams including the main one. Curves *1* corresponds to the in-phase antenna with four antenna elements, curves *2* correspond to the one with eight antenna elements, curves *3* corresponds to the simple omnidirectional antenna with one antenna element, while curves *4* correspond to the simple omnidirectional antenna with one antenna element and one main received beam (the classical case is given for comparison). Although the presence of reflected beams during reception can be seen to significantly increase the bit error probability compared to the classical case, the proposed in-phase antenna can be used to partially compensate their influence. As a result, the noise immunity of receiving information is improved as compared to the omnidirectional antenna reception with a single antenna element. For error probability $P_e = 10^{-3}$, the energy gain ranges from 1.5–2 dB for 2 beams to 7–10 dB for 3–4 beams; it is noticeable that the difference for the 4-element and 8-element antennas is small, which indicates the possibility of simplifying its design.

C. Communication channel with harmonic interference. The following harmonic interference parameters are used in the communication channel modeling: relative intensity μ_h = 0.5; random initial phase φ_h is uniformly distributed on the interval $(-\pi, \pi]$; reduced frequency deviation $\Delta\omega T_s = (\omega_h - \omega_0)T_s$ is in the interval (−12, +12). The in-phase antenna contains 8 antenna elements.

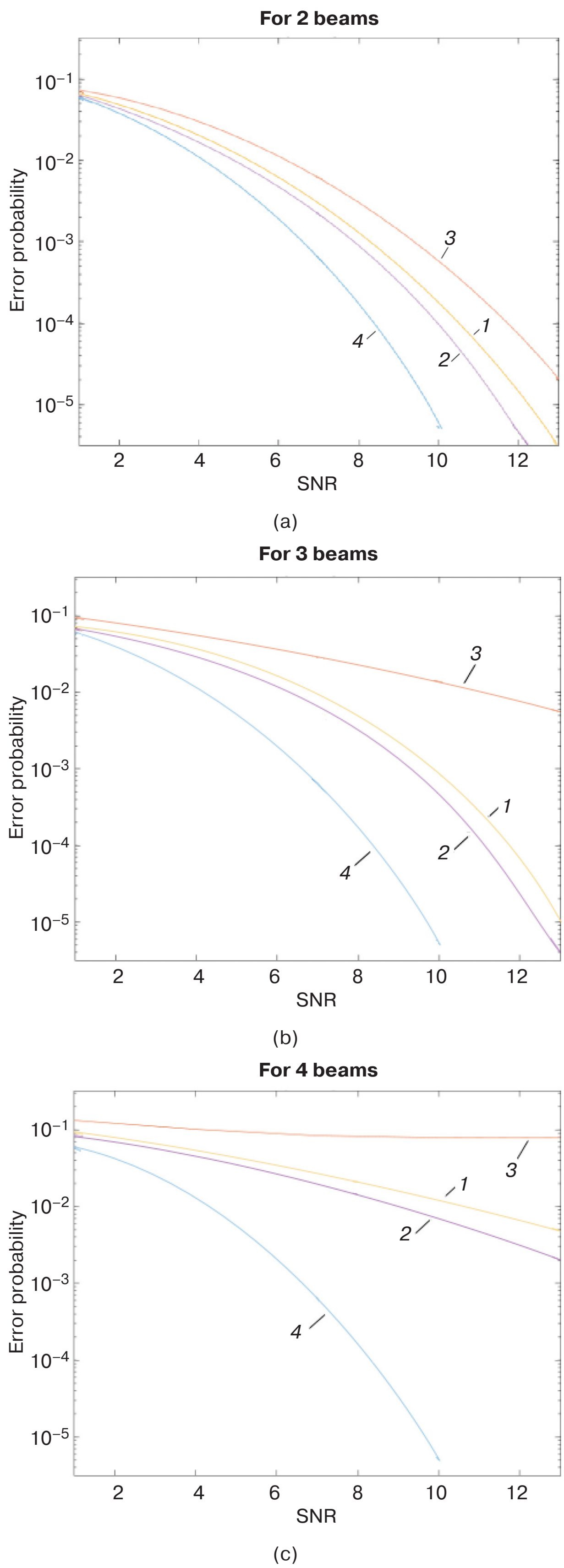

Fig. 3. Dependencies of bit error probability on SNR for: (a) two-beam communication channel, (b) three-beam communication channel, (c) four-beam communication channel

Figure 4 shows the dependencies of the bit error probability P_e on the interference detuning $\Delta\omega T_s$ at E/N_0 = 7 dB and at two AoAs: $\theta_h = 0$ (direction of the RP maximum) and $\pi/3$. A simultaneous spatial (using antenna) and spectral (using demodulator) filtering of interference is observed, resulting in a significant decrease in error probability, i.e., to be more ordered at $\theta_h = 0$. It may be assumed that the impact of such harmonic interference may be neglected at $\Delta\omega T_s \geq 5$.

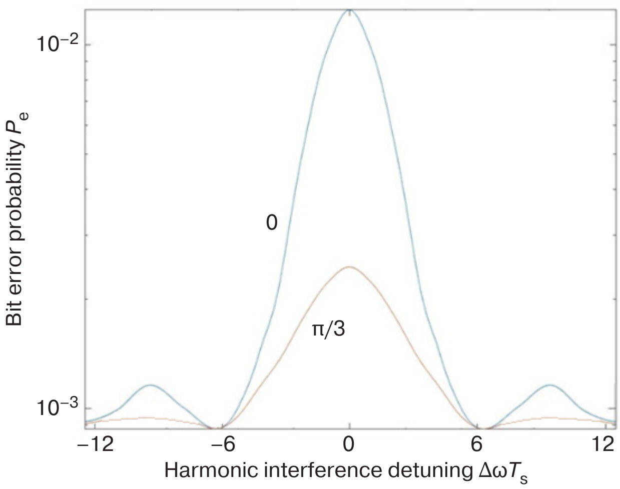

Fig. 4. Dependencies of bit error probability on harmonic interference detuning

CONCLUSIONS

In the present work, a mathematical model for a multi-element, spatially-distributed, in-phase antenna, whose design is aimed at counteracting the multipath nature of signal propagation, is constructed. The principal possibility of electronically adjusting the RP is demonstrated.

By applying the proposed signal processing algorithm on the receiving side, the impact of the multipath effect can be partially compensated. As a result, the noise immunity of receiving information is increased compared to the omnidirectional antenna reception with one antenna element; for error probability $P_e = 10^{-3}$, the energy gain ranges from 2 dB for 2 beams up to 7–10 dB for 3–4 beams.

When concentrated harmonic interference is present in the radio channel, there is also simultaneous spatial (using antenna) and spectral (using demodulator) filtering whose efficiency depends on the arrival direction and frequency detuning of the interference, which also results in a significant reduction in error probability.

Authors' contributions

G.V. Kulikov—the research idea, consultations on the issues of conducting all stages of the study.

Yu.A. Polevoda—computer simulation, processing of results.

M.S. Kostin—development of an antenna model.

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   [Original Russian Text: Kulikov G.V., Lelyukh A.A., Grachenko E.N. Noise immunity of coherent signal receiver with quadrature amplitude modulation in the presence of relayed interference. *Radiotekhnika i Elektronika*. 2020;65(8):804–808 (in Russ.). https://doi.org/10.31857/S0033849420070074]

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Mathematical modeling

Математическое моделирование

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RESEARCH ARTICLE

Mathematical modeling of velocity and accelerations fields of image motion in the optical equipment of the Earth remote sensing satellite

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Abstract

Objectives. The paper considers a satellite with an optoelectronic payload designed to take pictures of the Earth's surface. The work sets out to develop a mathematical model for determining the dependencies between the state vector of the satellite, the state vector of the point being imaged on the Earth's surface, and the distribution fields of the velocity vectors and accelerations of the motion of the image along the focal plane of the optoelectronic payload.

Methods. The method is based on double differentiation of the photogrammetry equation when applied to a survey of the Earth's surface from space. For modeling the orbital and angular motion of the satellite, differential equations with numerical integration were used. The motion parameters of the Earth's surface were calculated based on the Standards of fundamental astronomy software library.

Results. Differential equations of motion of the image were obtained. Verification of the developed mathematical model was carried out. The motion of the considered satellite was simulated in orbital orientation mode using an image velocity compensation model. The distribution fields of velocity vectors and accelerations of motion of the image of the Earth's surface were constructed. The residual motion of the field of image following compensation was investigated.

Conclusions. The proposed mathematical model can be used both with an optoelectronic payload when modeling shooting modes and estimating image displacements at the design stage of a satellite, as well as at the satellite operation stage when incorporating the presented model in the onboard satellite software. The presented dependencies can also be used to construct an image transformation matrix, both when restoring an image and when obtaining a super-resolution.

Keywords: remote sensing of the Earth, satellite, images of Earth's landscapes, mathematical model, image velocity field, image acceleration field, super-resolution

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НАУЧНАЯ СТАТЬЯ

Математическое моделирование полей скоростей и ускорений движения изображения в оптической аппаратуре спутника дистанционного зондирования Земли

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Резюме

Цели. В статье рассматривается спутник с оптико-электронной аппаратурой, предназначенной для съемки поверхности Земли. Цель статьи – разработка математической модели для определения зависимостей между вектором состояния спутника, вектором состояния снимаемой точки на земной поверхности и полями распределений векторов скоростей и ускорений движения изображения по фокальной плоскости оптико-электронной аппаратуры.

Методы. Используемый метод основан на двойном дифференцировании уравнения фотограмметрии при применении его к съемке поверхности Земли из космоса. Для построения модели орбитального и углового движений спутника применяются дифференциальные уравнения с численным интегрированием. Параметры вращения Земли и движения земной поверхности вычисляются на основе библиотеки программ Standards of fundamental astronomy.

Результаты. Получены дифференциальные уравнения движения изображения. Проведена верификация разработанной математической модели. Проведено моделирование движения спутника в режиме орбитальной ориентации и в режиме компенсации скорости движения изображения. Построены поля распределения векторов скоростей и ускорений движения изображения поверхности Земли. Исследовано остаточное поле движения изображения после компенсации.

Выводы. Предложенная математическая модель может найти применение как на этапе проектирования спутника с оптико-электронной аппаратурой при моделировании режимов съемки и оценках смещений изображения, так и на этапе эксплуатации спутника при применении представленной модели в бортовом программном обеспечении спутника. Представленные зависимости также можно использовать для построения матрицы сдвига изображения в задачах восстановления изображения и получения сверхразрешения.

Ключевые слова: дистанционное зондирование Земли, спутник, изображения ландшафтов Земли, математическая модель, поле скоростей движения изображения, поле ускорений движения изображения, сверхразрешение

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Автор заявляет об отсутствии конфликта интересов.

INTRODUCTION

The paper considers a satellite equipped with a high-resolution imaging optoelectronic payload (OEP) with charge-coupled photosensitive devices (CCPD) operating in a time delay and integration (TDI) mode. The TDI technology is based on multiple exposures of the same object, which significantly increases the signal-to-noise ratio and can thus be used for scanning low-light scenes, but imposes limitations on its application, since it becomes necessary to ensure the movement of the projected image of the object in accordance with the movement of charge packets on photodetectors.[1]

The accuracy at which the image motion velocity (IMV) is known sharply limits the use of TDI technology. In order to ensure that the accumulated shift during the exposure time does not exceed ~1/3 of a pixel, it is necessary to account for such IMV vector fields on a CCPD [1].

Among the main components of the superposition of the charge packet motion along CCPD during the exposure time are the orbital and angular motion of the satellite, the curvature of the Earth's surface and its rotation, as well as operational errors of the satellite attitude control and stabilization system (ACSS).

Many authors have dealt with issues of IMV calculation. The calculation of IMV fields is considered in [2–4]. In [2, 3, and 5], problems associated with calculating the velocity field of image motion when a satellite moves in a central gravitational field are also considered.

Compensation of IMV fields is considered in [6–9]. These works discuss the method of providing the required (reference) IMV by means of a satellite's rotational motion in accordance with the special program law of orientation and stabilization control.[2]

The present author assumes that, in the presence of compensation, there may be deviations of actual IMV from the required value, for example, due to unauthorized turns of the satellite due to errors in the ACSS operation, possible vibrations affecting the satellite structure, as well as scanning without considering terrain relief.

The present work aims to develop a general mathematical model for calculating IMV fields and image motion acceleration (IMA) vectors taking into account the main dynamic and kinematic factors of the imaging process, as well as to estimate the residual IMV and IMA fields in the presence of compensation. In the presented mathematical model of IMV calculation, unlike [2, 3, and 5], the main dynamic effects of external and internal forces and torques forcing on the satellite body may be taken into account.

The obtained results can be used in compiling an image field shift matrix for solving the super-resolution problem.

PROBLEM STATEMENT

We shall construct a mathematical model of scanning the Earth's surface from space based on the following assumptions:

1. The satellite model represents a completely solid body orbiting the Earth according to the EGM2008 gravitational field model [10].
2. The model of the onboard OEP represents a completely solid body with focal distance f and focal plane (FP) having dimensions a and b.
3. The Earth model is an ellipsoid with WGS84 parameters.[3]
4. Coordinate systems used: geocentric celestial inertial reference system (GCRS) [11]; international terrestrial reference system (ITRS) [11]; local-vertical-local-horizontal (LVLH) coordinate system or orbital frame (OF) [12]; satellite body frame (BF); and OEP focal plane frame (FPF). For writing down equations of the satellite motion, the inertial quasi-non-moving GCRS coordinate system is used. When writing differential equations of the satellite motion in the rotating ITRS coordinate system, it is necessary to consider the precession and nutation of the Earth in motion

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equations. Considering precession, nutation, and motion of the Earth's poles, as well as transition parameters between the International Atomic Time (TAI) and Coordinated Universal Time (UTC) scales are included in the corresponding matrices in the Earth rotation model using the software package provided by Standards of Fundamental Astronomy (SOFA) [13, 14].

5. The time scales used are TAI and UTC [11].

The following functional dependencies need to be defined:

$$\mathbf{v}_{x,y} = \dot{\mathbf{x}}_{x,y} = f(\mathbf{r}_{\text{sat}}, \mathbf{v}_{\text{sat}}, \mathbf{q}_{\text{sat}}, \mathbf{w}_{\text{sat}}, \mathbf{r}_{\text{e}}, \mathbf{v}_{\text{e}}, \mathbf{a}_{\text{e}});$$
$$\mathbf{a}_{x,y} = \ddot{\mathbf{x}}_{x,y} = f(\mathbf{r}_{\text{sat}}, \mathbf{v}_{\text{sat}}, \dot{\mathbf{v}}_{\text{sat}}, \mathbf{q}_{\text{sat}}, \mathbf{w}_{\text{sat}}, \dot{\mathbf{w}}_{\text{sat}}, \mathbf{r}_{\text{e}}, \mathbf{v}_{\text{e}}, \mathbf{a}_{\text{e}}), \quad (1)$$

where $\mathbf{v}_{x,y}$ is the vector of IMV at the point with x and y coordinates on the FP; $\mathbf{a}_{x,y}$ is the vector of IMA; $\mathbf{r}_{\text{sat}}, \mathbf{v}_{\text{sat}}, \dot{\mathbf{v}}_{\text{sat}}$ are position, velocity, and acceleration of the satellite in the GCRS, respectively; $\mathbf{q}_{\text{sat}}, \mathbf{w}_{\text{sat}}, \dot{\mathbf{w}}_{\text{sat}}$ are orientation quaternion, angular velocity, and angular acceleration of the satellite in the BF, respectively; $\mathbf{r}_{\text{e}}$, $\mathbf{v}_{\text{e}}$, $\mathbf{a}_{\text{e}}$ are position, velocity, and acceleration of the scanned point on the Earth's surface, respectively.

The schematic explaining the problem statement is shown in Fig. 1.

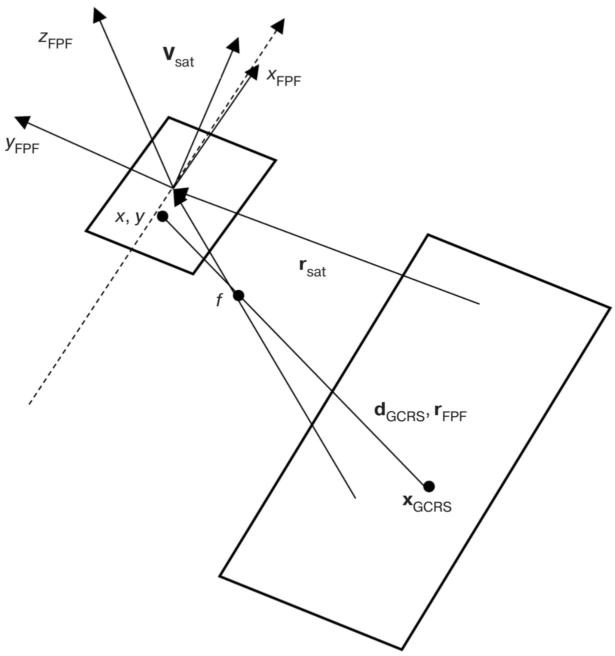

Fig. 1. Graphical representation of problem statement

MATHEMATICAL SURVEYING MODEL

According to the fundamental equation of space photogrammetry, the relationship between the FPF and the GCRS with respect to scale (in image space) is defined using a system of collinearity equations [15] expressed in projections on the FPF axis, as follows:

$$x = fXZ^{-1};\ y = fYZ^{-1}, \quad (2)$$

where x, y are the coordinates of the image point in the FPF (in image space).

We define the range vector $\mathbf{r}_{\text{FPF}}$ expressed in the FPF coordinate system (in object space), using the following relationship:

$$\mathbf{r}_{\text{FPF}} = \mathbf{M}_{\text{GCRS}}^{\text{FPF}} \mathbf{d}_{\text{GCRS}}, \quad (3)$$

where $\mathbf{d}_{\text{GCRS}}$ is the scanning range vector in the GCRS connecting the point on the FPF and the point to be imaged on the Earth's surface; $\mathbf{M}_{\text{GCRS}}^{\text{FPF}} = \mathbf{M}_{\text{BF}}^{\text{FPF}} \mathbf{M}_{\text{GCRS}}^{\text{BF}}$ is conversion matrix from the GCRS to the FPF; $\mathbf{M}_{\text{BF}}^{\text{FPF}}$ is conversion matrix from the BF to the FPF; $\mathbf{M}_{\text{GCRS}}^{\text{BF}}$ is conversion matrix from the GCRS to the BF (satellite orientation matrix).

Equations (2) and (3) describe the process when the imaging object and FP are stationary; x, y coordinates, $\mathbf{d}_{\text{GCRS}}$ vector, and $\mathbf{M}_{\text{GCRS}}^{\text{FPF}}$ matrix are unchanged. Since scanning of the Earth's surface from space takes place over time, all components in the above equations are functions of time.

MATHEMATICAL MODEL FOR IMAGE MOTION VELOCITY

In order to find the IMV vector at the point FP, we differentiate Eqs. (2) by time, as follows:

$$\dot{x} = \frac{d}{dt} fXZ^{-1} + f\frac{d}{dt}\left(XZ^{-1}\right);$$
$$\dot{y} = \frac{d}{dt} fYZ^{-1} + f\frac{d}{dt}\left(YZ^{-1}\right),$$

The first summand $\frac{d}{dt} fXZ^{-1} = 0,$ since the focal length is a constant value within the framework of the problem to be solved. Then:

$$\dot{x} = f\frac{d}{dt}\left(XZ^{-1}\right) = f\frac{V_x Z - XV_z}{Z^2} = \left(fV_x - xV_z\right)Z^{-1};$$
$$\dot{y} = f\frac{d}{dt}\left(YZ^{-1}\right) = f\frac{V_y Z - YV_z}{Z^2} = \left(fV_y - yV_z\right)Z^{-1}, \quad (4)$$

where $V_x = \frac{d}{dt}X$ и $V_y = \frac{d}{dt}Y$.

For defining vector $\mathbf{v}_{\text{FPF}} = \{O_{\text{FPF}}, V_x, V_y, V_z\}$, we differentiate Eq. (3), as follows:

$$\mathbf{v}_{\text{FPF}} = \frac{d}{dt}\mathbf{r}_{\text{FPF}} = \frac{d}{dt}\mathbf{M}_{\text{GCRS}}^{\text{FPF}}\mathbf{d}_{\text{GCRS}} + \\ + \mathbf{M}_{\text{GCRS}}^{\text{FPF}}\frac{d}{dt}\mathbf{d}_{\text{GCRS}}. \quad (5)$$

We define the derivative of the transformation matrix $\mathbf{M}_{\text{GCRS}}^{\text{FPF}}$, as follows:

$$\frac{d}{dt}\mathbf{M}_{\text{GCRS}}^{\text{FPF}} = \frac{d}{dt}\mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{M}_{\text{GCRS}}^{\text{BF}} + \mathbf{M}_{\text{BF}}^{\text{FPF}}\frac{d}{dt}\mathbf{M}_{\text{GCRS}}^{\text{BF}}.$$

In the resulting equation, since there is no rotation between FPF and BF (FP and satellite structure) according to the problem statement conditions, the first summand reverses to zero.

Then after substituting Poisson's equation $\frac{d}{dt}\mathbf{M}_{\text{GCRS}}^{\text{FPF}} = -\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{FPF}}$ [5], we obtain from (5) the following:

$$\mathbf{v}_{\text{FPF}} = \mathbf{M}_{\text{GCRS}}^{\text{FPF}}\frac{d}{dt}\mathbf{d}_{\text{GCRS}} - \\ - \mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\mathbf{d}_{\text{GCRS}}, \quad (6)$$

where $\mathbf{W}_\times = [\boldsymbol{\omega}\times] = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$ is the angular velocity matrix of the satellite in BF.

Equation (6) shows that the total IMV is composed of translational and angular motions of the OEP and the imaging object.

We proceed to finding functional dependencies for the IMA.

MATHEMATICAL MODEL FOR IMAGE MOTION ACCELERATION

For determining the IMA, we differentiate Eq. (4) for the second time, as follows:

$$\ddot{x} = \frac{d}{dt}\left(f\left(V_xZ - XV_z\right)Z^{-2}\right) = \\ = f\left[\left(A_xZ - XA_z\right)Z^{-2} - 2V_z\left(V_xZ - XV_z\right)Z^{-3}\right]; \\ \ddot{y} = \frac{d}{dt}\left(f\left(V_yZ - YV_z\right)Z^{-2}\right) = \\ = f\left[\left(A_yZ - YA_z\right)Z^{-2} - 2V_z\left(V_yZ - YV_z\right)Z^{-3}\right]. \quad (7)$$

For determining acceleration vector $\mathbf{a}_{\text{FPF}} = \{O_{\text{FPF}}, A_x, A_y, A_z\}$ in the FPF, we differentiate Eq. (5) for the second time, as follows:

$$\mathbf{a}_{\text{FPF}} = \frac{d}{dt}\left[\frac{d}{dt}\mathbf{M}\mathbf{d}_{\text{GCRS}} + \mathbf{M}\frac{d}{dt}\mathbf{d}_{\text{GCRS}}\right] = \\ = \frac{d^2}{dt^2}\mathbf{M}\mathbf{d}_{\text{GCRS}} + 2\frac{d}{dt}\mathbf{M}\frac{d}{dt}\mathbf{d}_{\text{GCRS}} + \mathbf{M}\frac{d^2}{dt^2}\mathbf{d}_{\text{GCRS}}. \quad (8)$$

We rewrite Eq. (8) in the following form:

$$\mathbf{a}_{\text{FPF}} = -\frac{d}{dt}\left[\mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\right]\mathbf{d}_{\text{GCRS}} - \\ - 2\mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\frac{d}{dt}\mathbf{d}_{\text{GCRS}} + \\ + \mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{M}_{\text{GCRS}}^{\text{BF}}\frac{d^2}{dt^2}\mathbf{d}_{\text{GCRS}}; \\ \mathbf{a}_{\text{FPF}} = -\left\{\left[\underbrace{\frac{d}{dt}\mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}}_{0} + \right.\right. \\ + \mathbf{M}_{\text{BF}}^{\text{FPF}}\frac{d}{dt}\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}} + \\ \left.\left. + \mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{W}_\times\frac{d}{dt}\mathbf{M}_{\text{GCRS}}^{\text{BF}}\right]\mathbf{d}_{\text{GCRS}}\right\} - \\ - 2\mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\frac{d}{dt}\mathbf{d}_{\text{GCRS}} + \\ + \mathbf{M}_{\text{BF}}^{\text{FPF}}\mathbf{M}_{\text{GCRS}}^{\text{BF}}\frac{d^2}{dt^2}\mathbf{d}_{\text{GCRS}}; \\ \mathbf{a}_{\text{FPF}} = \mathbf{M}_{\text{BF}}^{\text{FPF}}\left[-\mathbf{E}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\mathbf{d}_{\text{GCRS}} - \right. \\ - \mathbf{W}_\times\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\mathbf{d}_{\text{GCRS}} - \\ - 2\mathbf{W}_\times\mathbf{M}_{\text{GCRS}}^{\text{BF}}\frac{d}{dt}\mathbf{d}_{\text{GCRS}} + \\ \left. + \mathbf{M}_{\text{GCRS}}^{\text{BF}}\frac{d^2}{dt^2}\mathbf{d}_{\text{GCRS}}\right], \quad (9)$$

where $\mathbf{E}_\times = [\mathbf{e}\times] = \begin{bmatrix} 0 & -e_z & e_y \\ e_z & 0 & -e_x \\ -e_y & e_x & 0 \end{bmatrix}$ is the angular acceleration matrix of the satellite in the BF.

In the resulting equation, the first summand is the Euler acceleration, the second summand is the centripetal acceleration, while the third summand is the Coriolis acceleration. Next, we define the range vector $\mathbf{d}_{\text{GCRS}}$ and its derivatives.

MATHEMATICAL MODEL FOR THE POINT MOTION ON THE EARTH'S SURFACE

Equations of the point motion on the Earth's surface are written as follows:

$$\begin{gathered}\mathbf{x}_{\mathrm{GCRS}} = \mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}\mathbf{x}_{\mathrm{ITRS}};\\ \dot{\mathbf{x}}_{\mathrm{GCRS}} = \mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}\dot{\mathbf{x}}_{\mathrm{ITRS}} + \boldsymbol{\omega}_{\mathrm{GCRS}} \times \mathbf{x}_{\mathrm{GCRS}};\\ \ddot{\mathbf{x}}_{\mathrm{GCRS}} = \mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}\ddot{\mathbf{x}}_{\mathrm{ITRS}} - \boldsymbol{\omega}_{\mathrm{GCRS}} \times\\ \times (\boldsymbol{\omega}_{\mathrm{GCRS}} \times \mathbf{x}_{\mathrm{GCRS}}) + 2\boldsymbol{\omega}_{\mathrm{GCRS}} \times\\ \times \dot{\mathbf{x}}_{\mathrm{GCRS}} + \dot{\boldsymbol{\omega}}_{\mathrm{GCRS}} \times \mathbf{x}_{\mathrm{GCRS}},\end{gathered} \tag{10}$$

where $\mathbf{x}_{\mathrm{ITRS}}, \dot{\mathbf{x}}_{\mathrm{ITRS}}, \ddot{\mathbf{x}}_{\mathrm{ITRS}}$ are position, velocity, and acceleration of the point on the Earth's surface (in the ITRS), respectively; $\mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}$ is the rotation matrix between the ITRS and GCRS coordinate systems; $\boldsymbol{\omega}_{\mathrm{GCRS}}$ is the angular velocity vector of the Earth's rotation in the GCRS.

The angular acceleration vector of the Earth rotation can be neglected ($\dot{\boldsymbol{\omega}}_{\mathrm{GCRS}} \approx 0$).

Then the range, relative velocity, and relative acceleration vectors can be defined as follows:

$$\begin{gathered}\mathbf{d}_{\mathrm{GCRS}} = \mathbf{x}_{\mathrm{GCRS}} - \mathbf{x}_{\mathrm{sat}} = \mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}\mathbf{x}_{\mathrm{ITRS}} - \mathbf{x}_{\mathrm{sat}};\\ \dot{\mathbf{d}}_{\mathrm{GCRS}} = \dot{\mathbf{x}}_{\mathrm{GCRS}} - \dot{\mathbf{x}}_{\mathrm{sat}} = \mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}\dot{\mathbf{x}}_{\mathrm{ITRS}} +\\ + \omega_{\mathrm{GCRS}}\mathbf{x}_{\mathrm{GCRS}} - \dot{\mathbf{x}}_{\mathrm{sat}};\\ \ddot{\mathbf{d}}_{\mathrm{GCRS}} = \ddot{\mathbf{x}}_{\mathrm{GCRS}} - \ddot{\mathbf{x}}_{\mathrm{sat}} =\\ = \mathbf{M}_{\mathrm{ITRS}}^{\mathrm{GCRS}}\ddot{\mathbf{x}}_{\mathrm{ITRS}} - \boldsymbol{\omega}_{\mathrm{GCRS}} \times (\boldsymbol{\omega}_{\mathrm{GCRS}} \times \mathbf{x}_{\mathrm{GCRS}}) +\\ + 2\boldsymbol{\omega}_{\mathrm{GCRS}} \times \dot{\mathbf{x}}_{\mathrm{GCRS}} - \ddot{\mathbf{x}}_{\mathrm{sat}}.\end{gathered} \tag{11}$$

The vector field of velocities and accelerations along the FP are obtained by substituting the resulting Eqs. (11) into (9) and (6), calculating the IMV and IMA vectors in accordance with Eqs. (4) and (7) at each point of FP.

VERIFICATION

We compare the results obtained in the presented mathematical model with those obtained in [2] for the same initial data.

Based on calculations using the proposed mathematical model at the point with coordinates (0, 0), the following IMV values are obtained: 46.951 mm/s along the *x* axis and 2.592 mm/s along the *y* axis. In [2], values of 46.921 mm/s in the *x* axis and 2.591 mm/s in the *y* axis are obtained. Thus, the calculation relative error is no more than 0.1%, which indicates the reliability of the proposed model for calculating the IMV.

Table 1. Initial data for modeling

Parameter	Unit of measure (UoM)	Numerical value
Satellite inclination	degree	60.000
Orbit eccentricity	–	0.01
Semi-major axis of the orbit	km	6678.000
OEP focus distance, *f*	m	1.500
FP dimensions	mm	120 × 80

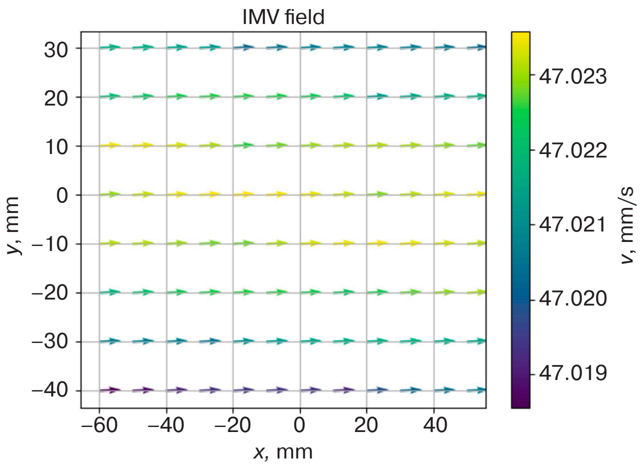

Fig. 2. Verification of the model

MODELING

The program is developed based on the mathematical model. The satellite dynamics are described by differential equations of the solid body motion [7, 12]. The satellite state vector is integrated using the fourth order Runge–Kutta method [12] in the TAI time scale [11]. In the linear perturbation part of the satellite motion, only the acceleration due to the effects of the Earth's gravitational field with a 20 × 20 decomposition according to the EGM2008 model [10] is considered, while in the angular perturbation part, only the control torques determined using a proportional derivative controller based on the mismatch between the actual angular motion and the reference motion are taken into account. When calculating the transition matrix from GCRS to ITRS and calculating the transition between TAI and UTC time scales, the program library provided by SOFA [14] is used.

Two cases are considered. In the first case, the satellite is in orbital orientation (the BF axes are co-directed with the LVLH axes), while in the second case, the satellite rotation parameters correspond to the reference angular motion at which the IMV compensation is provided [7].

Modeling is carried out for the three sets of initial data presented in Tables 2–4.

Table 2. Initial data for modeling

Parameter	UoM	Numerical value
Modeling start time	UTC	2020-01-01 00:00:00.000000
Modeling end time	UTC	2020-01-01 00:30:00.000000
Satellite inclination	degree	97.000
Orbit eccentricity	–	0.001
Semi-major axis of the orbit	km	6900.000
OEP focus distance, f	m	2.000
FP dimensions	mm	160 × 20
Reference IMV in the FP center	mm/s	20.000
Reference IMV at the FP right edge	mm/s	20.000

The results of the field modeling without compensation are shown in Figs. 3 and 4.

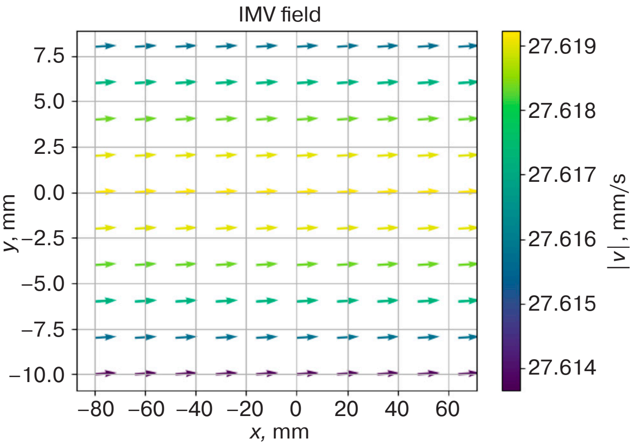

Fig. 3. Field of IMV vectors without compensation

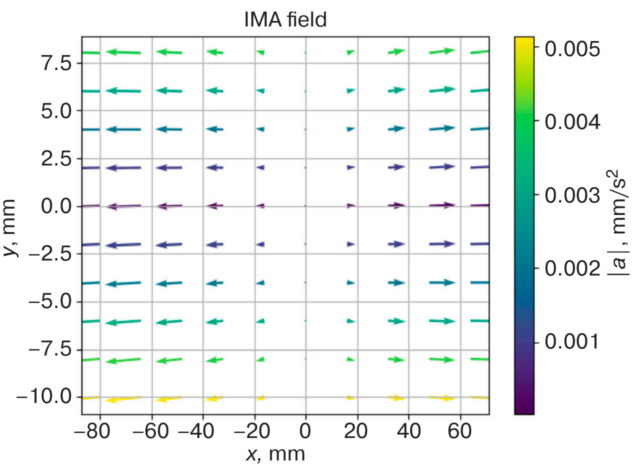

Fig. 4. Field of IMA vectors without compensation

The modeling results of the residual IMV and IMA fields with compensation (reference IMV along x = 20 mm/s, along y = 0 mm/s) are shown in Figs. 5 and 6.

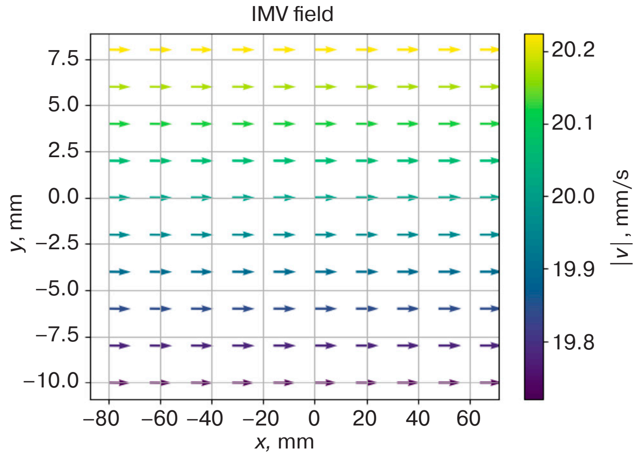

Fig. 5. Field of IMV vectors with compensation

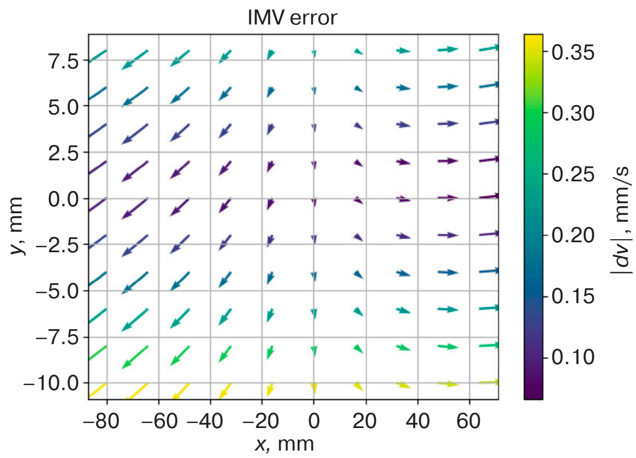

Fig. 6. Difference between the reference and actual fields of the IMV after compensation

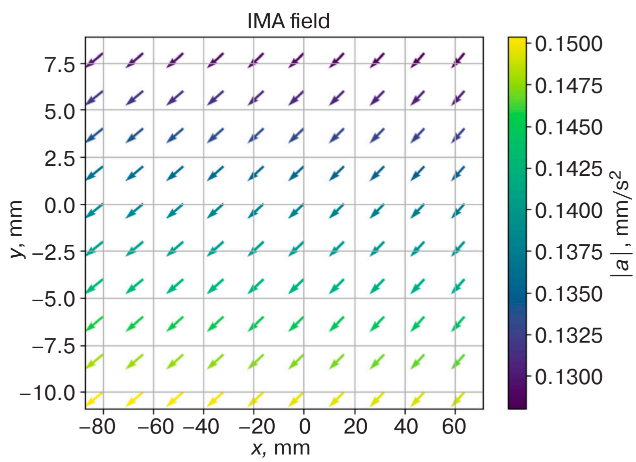

Fig. 7. Field of IMA vectors with compensation

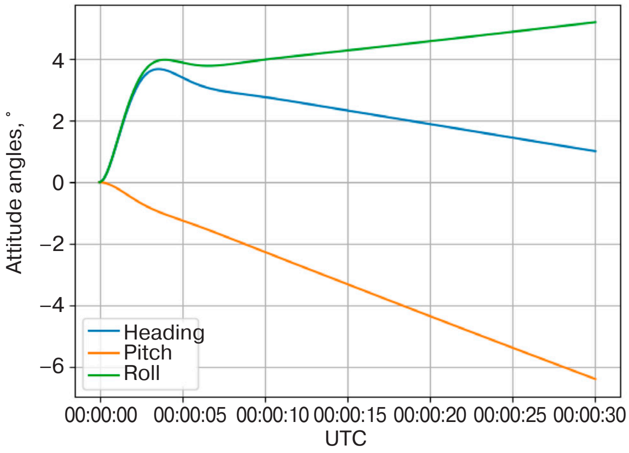

Fig. 8. Satellite attitude angles relative to LVLH

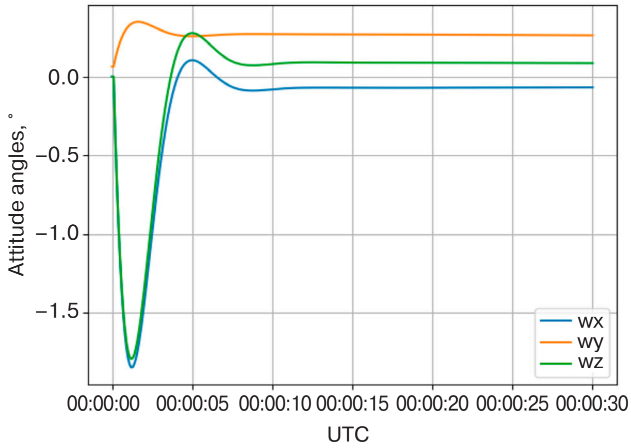

Fig. 9. Satellite angular rates relative to BF

The residual transverse velocity field of IMV (along the y-axis) can be seen in Fig. 6. This may be explained by the fact that when calculating the reference angular velocity using the algorithm described in [7], two points are taken as reference points: in the center of FP and at the right edge of FP (in the considered case, corresponding to the coordinates [0, 10]). It is at these points that the actual IMV is equal to the reference IMV.

Thus, the modeling shows that the residual field exists even when the compensation algorithm is used, allowing such coordinates of the FP to be selected in which the IMV reference vector is required.

The graphs of satellite attitude angles and satellite angular velocities in the IMV compensation mode are presented in Figs. 8 and 9.

The fields of IMV and IMA vectors without compensation are presented in Figs. 10 and 11.

Table 3. Initial data for modeling

Parameter	UoM	Numerical value
Modeling start time	UTC	2020-01-01 00:00:00.000000
Modeling end time	UTC	2020-01-01 00:30:00.000000
Satellite inclination	degree	97.000
Orbit eccentricity	–	0.001
Semi-major axis of the orbit	km	7000.000
OEP focus distance, f	m	2.000
FP dimensions	mm	160 × 20

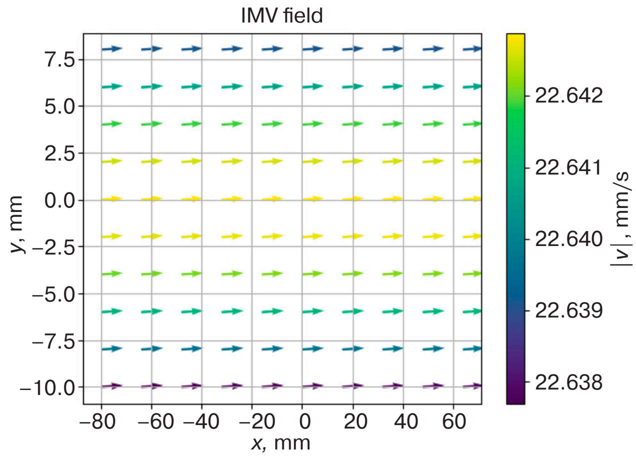

Fig. 10. Field of IMV vectors without compensation

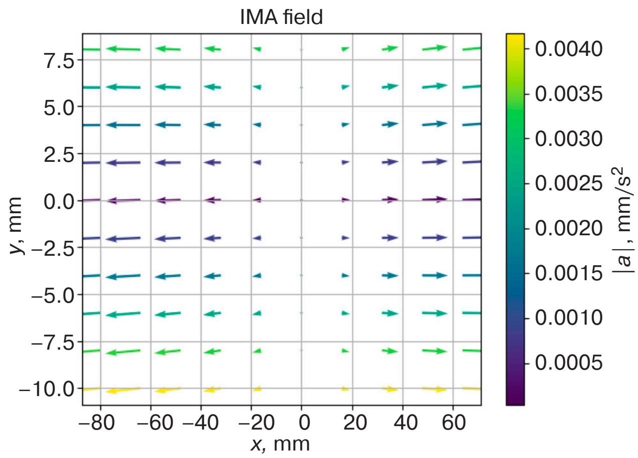

Fig. 11. Field of IMA vectors without compensation

Figure 12 shows the field of IMV with compensation. Figure 13 indicates the difference between the reference and actual fields of IMV after compensation.

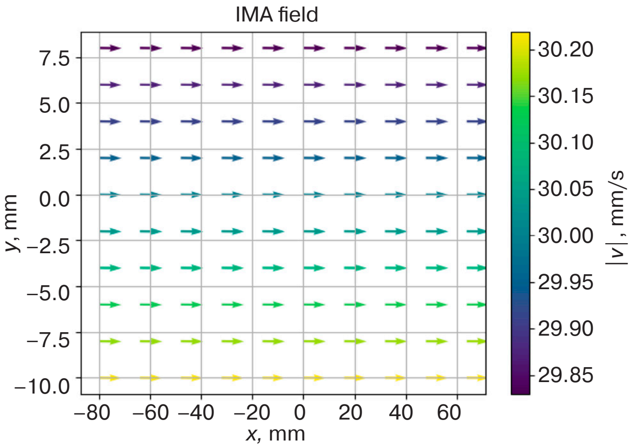

Fig. 12. Field of IMV vectors with compensation

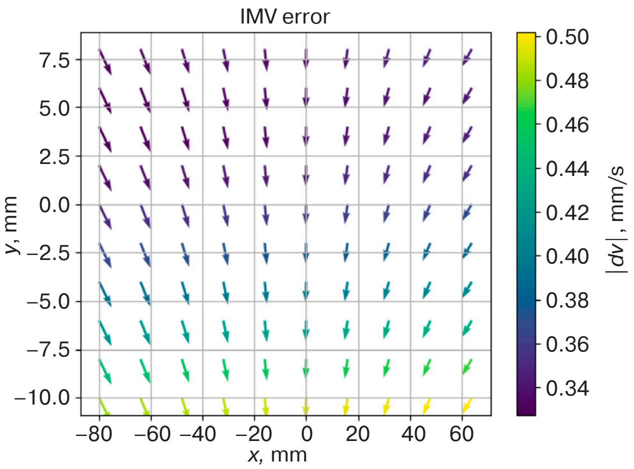

Fig. 13. Difference between the reference and actual fields of IMV after compensation

Table 4. Initial data for modeling

Parameter	UoM	Numerical value
Modeling start time	UTC	2020-01-01 00:00:00.000000
Modeling end time	UTC	2020-01-01 00:30:00.000000
Satellite inclination	degree	97.000
Orbit eccentricity	–	0.001
Semi-major axis of the orbit	km	7000.000
OEP focus distance, *f*	m	2.000
FP dimensions	mm	160 × 20
Reference IMV in the FP center	mm/s	30.000
Reference IMV at the FP right edge	mm/s	30.000

CONCLUSIONS

The obtained and presented mathematical dependencies can be used for calculating the vector fields of image motion velocities and accelerations on photodetectors of the optoelectronic payloads installed on the satellite.

The dependencies can also be used to estimate the accumulated image displacement during the exposure time at the ground stage and preventing shooting with inappropriate image motion velocities during satellite operation, i.e., preventing directional "blurring" of the image. As a result, they may find application in calculating the image shift matrix for super-resolution.

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RESEARCH ARTICLE

Investigation of influence of objective function valley ratio on the determination error of its minimum coordinates

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Abstract

Objectives. A valley is a region of an objective function landscape in which the function varies along one direction more slowly than along other directions. In order to determine the error of the objective function minimum location in such regions, it is necessary to analyze relations of valley parameters.

Methods. A special test function was used in numerical experiments to model valleys with variables across wide ranges of parameters. The position and other valley parameters were defined randomly. Valley dimensionality and ratio were estimated from eigenvalues of the approximated Hessian of objective function in the termination point of minimum search. The error was defined as the Euclidian distance between the known minimum position and the minimum search termination point. Linear regression analysis and approximation with an artificial neural network model were used for statistical processing of experimental data.

Results. A linear relation of logarithm of valley ratio to logarithm of minimum position error was obtained. Here, the determination coefficient R^2 was ~0.88. By additionally taking into account the Euclidian norm of the objective function gradient in the termination point, R^2 can be augmented to ~0.95. However, by using the artificial neural network model, an approximation R^2 ~ 0.97 was achieved.

Conclusions. The obtained relations may be used for estimating the expected error of extremum coordinates in optimization problems. The described method can be extended to functions having a valley dimensionality of more than one and to other types of hard-to-optimize algorithms regions of objective function landscapes.

Keywords: objective function landscape, valley landscape, valley ratio, valley dimensionality, Hessian eigenvalues, linear regression, approximation, artificial neural network

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НАУЧНАЯ СТАТЬЯ

Исследование влияния степени овражности целевой функции на погрешность определения координат ее минимума

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Резюме

Цели. Целью работы было исследование зависимостей, связывающих характеристики оврагов, т.е. участков рельефа минимизируемой функции, на которых ее изменение по одному из направлений значительно медленнее, чем по другим направлениям, с погрешностью определения координат ее минимума.

Методы. В экспериментах использовалась специально разработанная тестовая функция с изменяемыми в широких пределах параметрами овражности. В сериях опытов случайно задавались положение и параметры оврага и координаты стартовой точки поиска. Размерность и степень овражности оценивались по собственным числам аппроксимированного гессиана функции в точке окончания поиска минимума. Погрешность определялась как эвклидово расстояние между заданным положением минимума функции и конечной точкой поиска. Для статистической обработки результатов применены линейный регрессионный анализ и аппроксимация с помощью модели искусственной нейронной сети (ИНС).

Результаты. Установлено наличие линейной зависимости между логарифмами степени овражности и погрешности определения координат минимума функции. Коэффициент детерминации R^2 ~ 0.88. Дополнительный учет эвклидовой нормы градиента функции в точке окончания поиска позволил повысить коэффициент детерминации до R^2 ~ 0.95, а при использовании модели ИНС – до R^2 ~ 0.97.

Выводы. Найденные зависимости можно использовать для оценки ожидаемой погрешности определения координат экстремумов оптимизируемых функций. В дальнейшем необходимо расширить методику на функции с размерностью оврагов более единицы и на другие типы сложных для алгоритмов оптимизации участков рельефа.

Ключевые слова: рельеф целевой функции, овражность рельефа, степень овражности, размерность овражности, собственные значения гессиана, линейная регрессия, аппроксимация, искусственная нейронная сеть

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INTRODUCTION

The problem of searching for an optimal solution of $\mathbf{x}_{\mathrm{opt}}$ is formulated as follows:

$$\mathbf{x}_{\mathrm{opt}} = \arg\min_{\mathbf{x}\in X} f(\mathbf{x}), \quad (1)$$

where X is the search area, while $f(\mathbf{x})$ is the objective function (OF). Numerous methods for solving problem (1) are known, both those having a sufficiently rigorous mathematical justification and which are applicable in cases where OF satisfies certain conditions (convexity, smoothness, etc.) [1, 2], as well as heuristic methods that do not impose strict requirements on the OF properties, but also do not guarantee finding the optimal solution [3, 4].

The possibility and accuracy of solving problem (1) are determined by the properties of both the OF and the search algorithm. In this connection, considerable research attention is attracted to an analysis of the OF landscape where the landscape is understood as a set of pairs $\{\mathbf{x} \in X, f(\mathbf{x})\}$. In this case, since the analytical expression of the function $f(\mathbf{x})$ is absent, its values have to be found by modeling the optimized system (black-box optimization problems). This research direction is referred to as exploratory landscape analysis (ELA).

In [5] and other works by the same group of authors, the classification of high-level OF landscape properties, determined qualitatively by the method of expert evaluation, and low-level properties, evaluated quantitatively by processing the results of the OF calculations at sampling points and the results of searching for OF extrema from the starting points, is given. High-level properties include multimodality, i.e., the presence of many local extrema, regularity and uniformity of the OF landscape properties in the search area, the presence of plateaus, and others. Low-level properties include statistics of the OF values, curvature and convexity indices, correlation indices of differences between OF values and distances between sampling points, and many others. In [6], more than 300 low-level properties are considered; a list of publications on this subject is also provided. Machine learning technologies [5, 7] are used to search for statistical dependencies between low- and high-level properties, as well as between landscape properties and the performance of various optimization algorithms on this landscape.

However, the above mentioned and other works known to us almost do not consider such OF landscape objects as valleys, i.e., areas in which OF along one or more directions changes significantly slower than along other directions [8], and walls representing OF sharp changes along any direction [9]. Meanwhile, in the presence of such objects, the search may end not at the extremum, but at some other point at the bottom of the valley or at the foot of the wall. In such case, optimization algorithms would find incorrect solutions. The problems related to the detection of these objects in the OF landscape and estimation of their quantitative characteristics have been little investigated.

Theoretical aspects of the occurrence of valleys in the landscape and methods of solution search in their presence are considered in [8]. Of the several definitions of valley proposed in this study, we use the most convenient for use in applications, which we present below with some simplification (by omitting additional conditions).

Let D be some region of the n-dimensional space R^n; let $J(\mathbf{x}) \in C^2(D)$ be a functional with continuous second derivatives in D; let $\mathbf{H}(\mathbf{x})$ be the matrix of second derivatives (Hessian) of functional $J(\mathbf{x})$ at point $\mathbf{x}$; and let $\lambda_i[\mathbf{H}(\mathbf{x})]$, $i = \overline{1, n}$ be eigenvalues of Hessian $\mathbf{H}(\mathbf{x})$ at point $\mathbf{x}$ ordered by descending.

The functional is called valley, i.e., it contains a valley, if there is such number $\sigma \gg 1$ and set $Q \subset D$, that

$$\begin{aligned} \forall \mathbf{x} \in Q \;\; \lambda_1[\mathbf{H}(\mathbf{x})] \geq \ldots \geq \lambda_{n-r}[\mathbf{H}(\mathbf{x})] \geq \\ \geq \sigma\lambda_{n-r+1}[\mathbf{H}(\mathbf{x})] \geq \ldots \geq \sigma\lambda_n[\mathbf{H}(\mathbf{x})]. \end{aligned} \quad (2)$$

This means that the largest $(n - r)$ eigenvalues of the Hessian are significantly larger than the other r eigenvalues at all points $\mathbf{x}$ belonging to the valley region Q. The number r is called the valley dimensionality; the number σ is called the valley ratio. The valley ratio shows to what extent in a given valley the rate of change of the OF along its bottom is smaller than along the directions orthogonal to the bottom. These indicators can be generalized as characteristics or indicators of the landscape's valley.

The result of the presence of valleys in the OF landscape, as noted above, consists in the error in determining the coordinates of the OF extrema; therefore, this error can serve as an objective characteristic of the valley. In practice, it is impossible to estimate the error directly when searching for the OF minimum since the true position of the minimum is unknown. At the same time, the valley ratio can be estimated on the basis of definition (2). In this connection, it is of interest to investigate the dependence linking the above error with the valley ratio. This task is not considered in [8] or other relevant works known to us; a practical means for estimating the valley ratio when searching for the OF minimum is also absent.

We also note [10], which introduces the definition of a valley as a one-dimensional set using the notion of topological homeomorphism. It also presents a method for determining the position and direction of a valley based on selecting a subset of points with the lowest OF values from a set of sampling points and applying the principal component analysis method to this subset. Quantitative characteristics of the valley are not considered in this study. In [11], the OF landscape properties of the well-known combinatorial traveling salesman problem are studied; this landscape is shown to contain groups of closely spaced depressions, also called valleys; however, these results are not applicable to optimization problems for functions of continuous variables.

The present work aims to investigate the dependence of the error in determining the coordinates of the sought OF minimum on the valley characteristics in the neighborhood of the search end points.

Achieving this goal requires performing a series of experiments on searching from different starting points for the OF minimum with varied valley parameters including its position, orientation relative to the coordinate axes, slope steepness and curvature, etc.

At the end of each search, it is necessary to determine the OF Hessian eigenvalues, and according to them, the valley dimensionality and the valley ratio in accordance with definition (2). In addition, the error equal to the distance of the search end point to the true position of the OF minimum must be calculated in order to analyze the statistical relationships linking the valley characteristics and the error in determining the OF minimum coordinates.

MATERIALS AND METHODS

First of all, it is necessary to choose a method for finding the OF minimum. The error of the minimum coordinates in the presence of valleys may significantly differ for different optimization algorithms. After selecting an algorithm and performing experimental studies, it would be possible to construct the valley estimation scale against which the results of other algorithms could be compared.

In the paper, the quasi-Newton (QN) local search algorithm implemented in *MATLAB* software environment by the *fmincon*(..) function is used. This type of algorithm is recommended in [6] as an exemplary one for searching local extrema of test functions when evaluating OF landscape properties. In addition, in QN methods, the Hessian approximation is an integral part of the algorithm at each iteration and, therefore, is automatically obtained at the final search point [1].

The list of output variables of the *fmincon*(..) function includes the vector of coordinates of the search end point $\mathbf{x}_{fin}$, the OF value f_{fin} at point $\mathbf{x}_{fin}$, the reason indicator for the search end *ExitFlag*, the OF gradient vector, and the Hessian approximation at point $\mathbf{x}_{fin}$ in the form of the real numbers matrix. In the input variables, we set the boundaries of the search area

$$-5 \le x_i \le 5, \quad i = \overline{1, ND}, \tag{3}$$

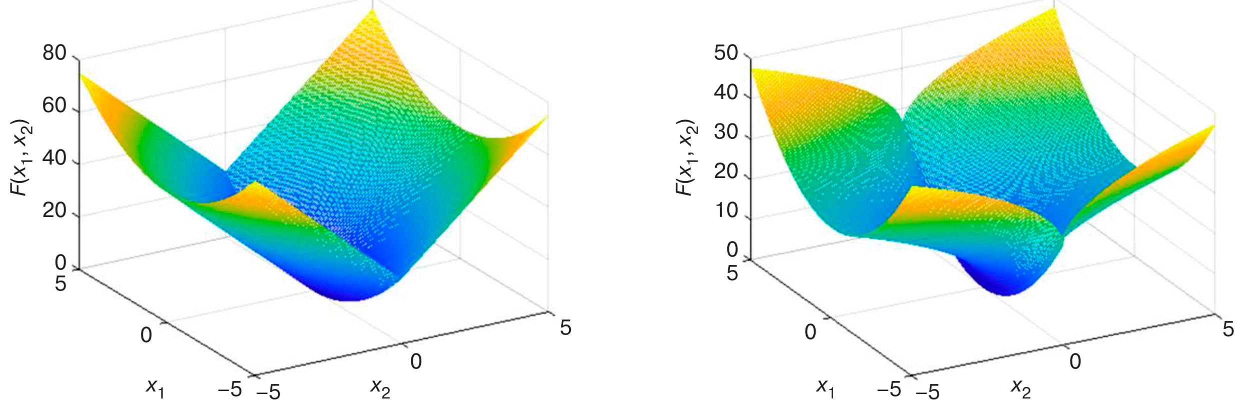
variant of the sequential quadratic programming (SQP) search algorithm, maximum number of iterations in each search is 1000, and other settings are default.

Next, we consider the OF used in the experiments. Sets of test functions [12, 13] are used for testing and comparing search algorithms for extrema. Although some of them possess the valley property, there is no function in which the valley parameters could be changed within wide limits. For this reason, the *TestValley*(..) function, whose text in *MATLAB* language is shown in Fig. 1, has been developed.

Here, $\mathbf{x}$ stands for coordinates of the point where the function value is calculated, $\mathbf{x}_{opt}$ and f_{opt} are specified coordinates of the minimum point and the function value in it, and $\mathbf{R}$ is the orthonormalized matrix specifying the rotation of coordinate axes. These parameters allow different positions and orientations of the valley to be obtained in the search space. Parameter N defines the valley dimensionality. Parameter W defines the curvature of the valley slopes. At W = 1, OF is quadratic, i.e., convex and smooth. At $1 < W < 0.5$, OF is convex, but not smooth. At $W = 0.5$, OF increases linearly. Finally, at $W < 0.5$, OF is concave. Parameter K sets a uniform scale

```
%%TestValley - Valley modeling with variable parameters
function f = TestValley(x,fopt,xopt,R,P,W,K,N)
%%P - Type of scaling on different coordinates
%%P=0 - Same acceleration rate for all x(i), i>N
%%P>0 - At j > i, the accretion rate along x(j) is faster than along x(i)
%%W - Type of dependence on the distance to the bottom of the valley
%%W=0.5 - Linear function
%%W<0.5 - Concave function; W>0.5 - convex function
%%K - Total scale factor in directions from the valley axis
%%N - Valley dimesionality
    n=length(x);
    z0=(x-xopt)*R;
    L=eye(n);
    for n1=1:n
        L(n1,n1)=10^(P*(n1-1)/2/(n-1));
    end
    z1=z0*L;
    z3=z1.^2;
    f =sum(z3(1:N),2)+K*(sum(z3(N+1:n),2))^W+fopt;
end
```

Fig. 1. Text of the program implementing the *TestValley*(..) function



(a) (b)

Fig. 2. Graphs of the *TestValley*(..) function: (a) $W = 0.5$; (b) $W = 0.25$

of the OF growth rate in all directions, while parameter P affects the OF anisotropy. At $P = 0$, OF grows at the same rate in all directions while at $P > 0$, the growth rate in different directions is different; these differences are greater the greater P is.

Examples of function graphs at the search space dimensionality $ND = 2$, parameters $P = 0$, $K = 10$, $N = 1$, and different values of parameter W are shown in Fig. 2.

Coordinates of starting points in the number of *NPnt* within the boundaries of the search area (3) are set using the Latin hypercube sampling algorithm implemented in *MATLAB* by the *lhsdesign*(..) function. The value of function f_{opt} in the minimum is set equal to 0. In the paper, only one-dimensional valleys at $N = 1$ are investigated. The values of other parameters are set by random numbers with uniform distributions in the following ranges:

$$\begin{aligned} &-3 \le x_{\text{opt}i} \le 3, \quad i = \overline{1, ND}; \\ &0 \le P \le 1; \quad 0.25 \le W \le 1.25; \\ &0 \le \lg K \le 4. \end{aligned} \tag{4}$$

The rotation matrix $\mathbf{R}$ is formed as a square matrix $ND \times ND$ of random numbers uniformly distributed in the interval (0, 1) with subsequent orthogonalization using the *MATLAB orth*(..) function. Setting the above parameters is possible both separately for each start, as well as once for the whole series of *NPnt* starts.

Calling the minimum search function and processing the results returned by it are explained by the program fragment in Fig. 3. In variables $\mathbf{X}_1$ and GF_1, the coordinates of the search end point $\mathbf{x}_{\text{fin}}$ and the OF value f_{fin} in it are returned, respectively. The arrays **grad** and **hess** contain the gradient vector and the approximated Hessian matrix, respectively. The @FEval pointer contains a reference to call the *TestValley*(..) function, which sets its input parameters as described above.

The program finds the eigenvalue vector of the **Ehess** Hessian and orders them by ascending absolute value in the **HessEV** array. Then the relations of adjacent values stored in the **S0hess** array are calculated. Finally, the estimation of the valley ratio *SValley* as the maximum of these relation values and the valley dimensionality *NValley* as the number of the maximum value in the array is determined. This definition of the valley ratio and dimensionality corresponds to the above definition (2), with the unprincipled difference that the ordering of the Hessian eigenvalues is performed in ascending rather than descending order. The error in determining the coordinates of the minimum DX_{opt} is calculated as the Euclidean distance between points $\mathbf{x}_{\text{opt}}$ and $\mathbf{x}_{\text{fin}}$.

The dependencies between variables are analyzed using two methods. The first one is linear regression analysis [14]. The *MATLAB fitlm*(..) function which approximates the linear model using the original data is used for implementing it. The second method is training the artificial neural network (ANN) model that approximates the desired dependence [15]. For this, the *fitnet*(..) function creating the ANN model with a given structure and the *train*(..) function performing the model training and testing are used.

```
[X1,GF1,ExitFlag,~,~,grad,hess]=fmincon(@FEval,Xin,[],[],[],[],Lb,Ub,[],MICoptions);
Ehess=eig(hess);
HessEV=sort(abs(Ehess));
S0hess=HessEV(2:end)./HessEV(1:end-1);
[SValley,NValley]=max(S0hess); % valley ratio and dimensionality
```

Fig. 3. Search function call and estimation of valley parameters at its end point

RESEARCH RESULTS

First, we consider the results of preliminary experiments presented in Fig. 4 giving insight into the influence of the valley ratio on the error of finding the minimum point of the *TestValley*(..) function. The dimensionality of problem $ND = 4$, the number of starts $NPnt = 40$, the position of the minimum, and the valley rotation are set once for the whole series. The input parameters of the function are shown above the diagrams showing the movement from the start point (red markers) to the end point $\mathbf{x}_{fin}$ (blue markers). One diagram shows the changes in all four coordinates, with circles marking coordinates x_1 and x_2 and triangles marking coordinates x_3 and x_4.

In the case of weak valley (Fig. 4a), the search from all starting points comes to the neighborhood of the minimum point of the test function. The average value of error DX_{opt} is 0.019 in this case. In the case of a strong valley (Fig. 4b), the searches starting from different points end in different points scattered along the valley bottom. In this case, the average DX_{opt} value reaches 9.2.

Then a series of experiments are performed to reveal the dependence between the estimation of the valley ratio *SValley* and the error of finding the minimum point of the test function DX_{opt}. The dimensionality of the *ND* space varies within the range from 2 to 12. Each experiment includes $12 \cdot 10^3$ starts, in each of which the random position of the search starting point, the position of the minimum $\mathbf{x}_{opt}$, and the rotation $\mathbf{R}$ of the *TestValley*(..) function, as well as the valley parameters *P*, *W*, and *K* in the ranges defined by inequalities (4), are set.

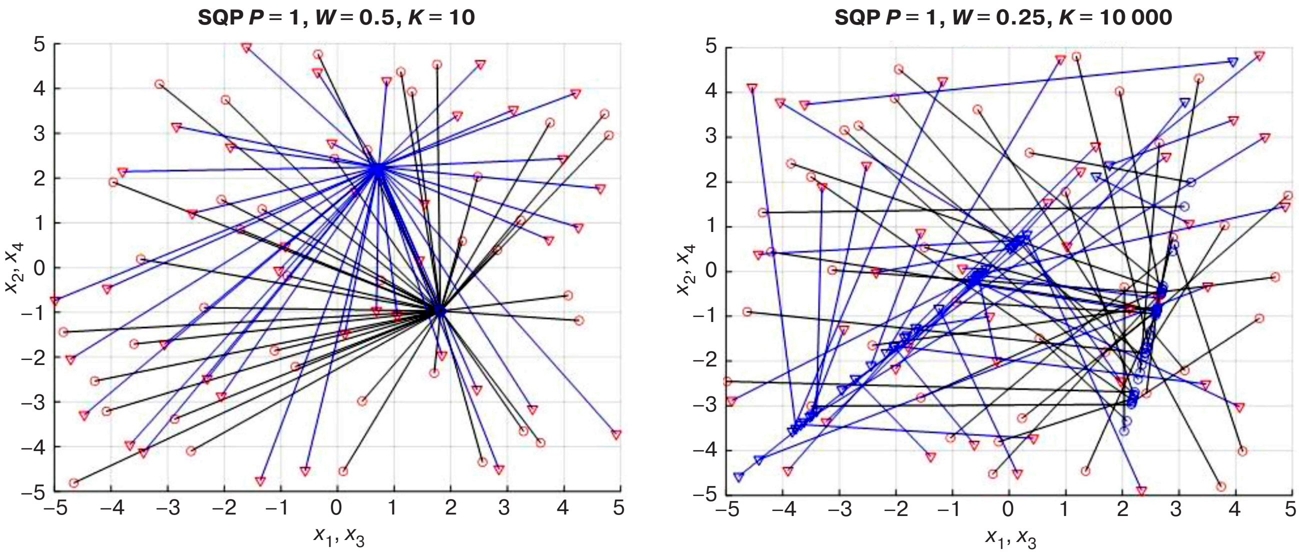
The experimental results for all *ND* values are similar. As an example, Fig. 5 shows histograms of the values of the experimental results for $ND = 4$. Due to the wide ranges of *SValley* and DX_{opt} values, their logarithms are analyzed and plotted. It can be concluded from the scatter plot of these variables shown in Fig. 6 that there is a stochastic dependence between them.

Notably, the value $ExitFlag = 1$ corresponds to the search end when the gradient modulus at the reached point does not exceed the specified *OptimalityTolerance* value (10^{-6} by default), while the value $ExitFlag = 2$ corresponds to the search end when the last movement during the search does not exceed the specified *StepTolerance* value (also 10^{-6} by default). In the second case, the modulus of the OF gradient at the search end point can be much larger than *OptimalityTolerance* since the OF smoothness conditions are violated on the valley axis (Fig. 2).

There is not a single case when the search ends due to exceeding the specified number of iterations ($MaxIteration = 1000$) or due to the algorithm being unable to find an acceptable point for further movement. Thus, all search starts end at points that the algorithm determines to be a local minimum. Similar results are recorded for all dimensionality values of the *ND* space.

Next, in most starts, the valley dimensionality is correctly determined at the search end point $NValley = 1$. At $ND = 4$, the valley dimensionality is determined incorrectly at 1092 points. These points (colored in black in Fig. 6) are all located in the region where the search error DX_{opt} is negligible and the valley ratio $SValley < 1000$. At $ND > 4$, estimations $NValley > 3$ are encountered, but also only in the region $\lg(DX_{opt}) < -4$. At $ND = 2$, values $NValley > 1$ are obviously impossible.

We proceed to the statistical processing of the data collected in the experiments. The influence of parameters



(a) (b)

Fig. 4. Results of *TestValley*(..) minimum search for weak (a) and strong (b) valley

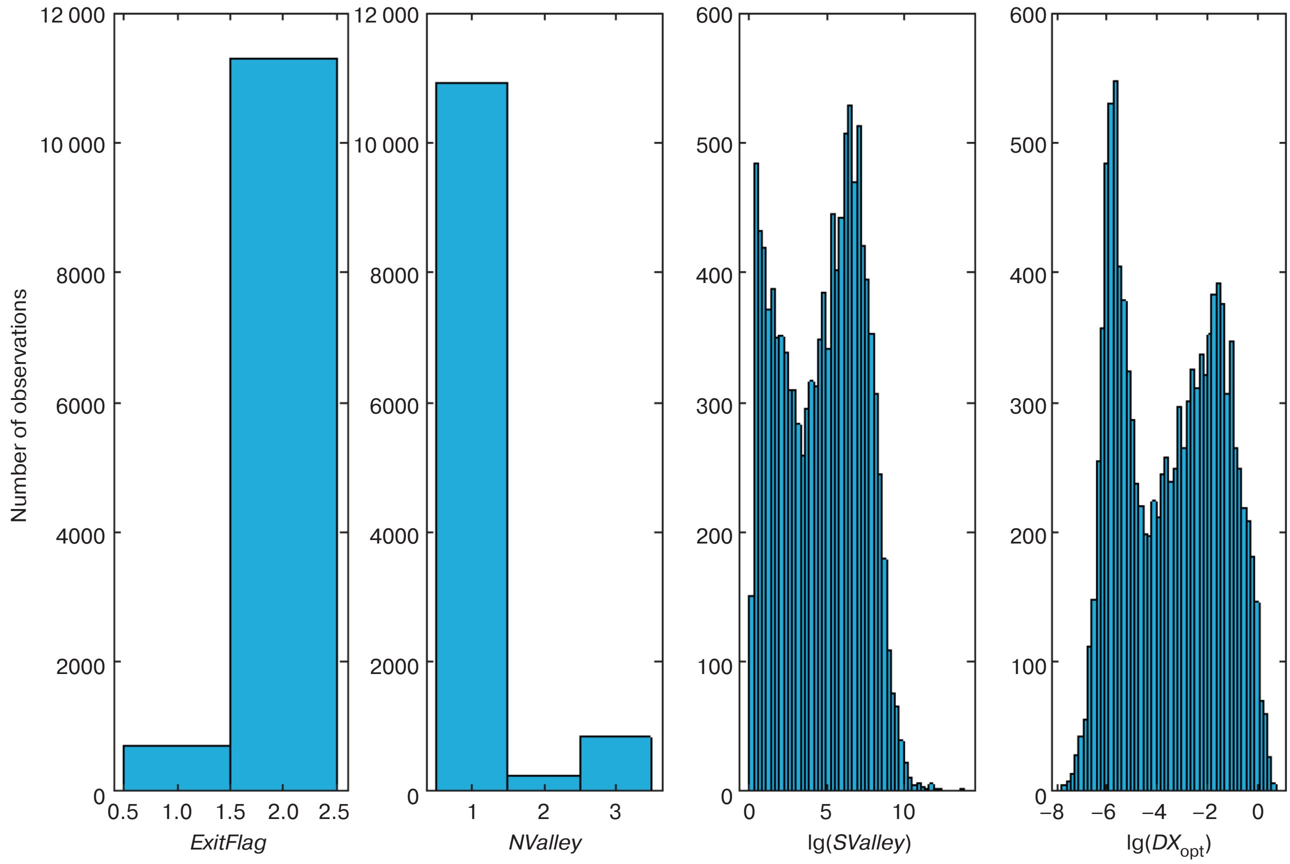


Fig. 5. Histograms of the main experiment results. *ExitFlag* is the reason indicator for search end; *NValley* is the estimation of valley dimensionality; *SValley* is the estimation of valley ratio; DX_{opt} is the error in determining the position of the OF minimum

P, *W*, and *K* of the *TestValley*(..) function on the valley ratio *SValley* is analyzed beforehand. The following linear model is studied:

$$\lg(SValley) = k_1 P + k_2 W + k_3 \lg(K) + b. \qquad (5)$$

The regression analysis of this model shows that the valley ratio is most strongly influenced by parameter *W* determining the curvature and convexity or concavity of the valley slopes. Parameter *K* is the next to contribute to the result, while the influence of parameter *P* is the least significant, although it cannot be neglected. The values of the coefficient of determination R^2, used for determining the adequacy of model [14], are within the range of 0.88–0.90 for different *ND*s.

Next, the linear model linking the error of finding the OF minimum point with the estimation of the valley ratio is considered:

$$\lg(DX_{opt}) = k\lg(SValley) + b. \qquad (6)$$

The regression analysis results are shown in Table 1, where the first group of columns corresponds to the accounting of all points while the second group excludes

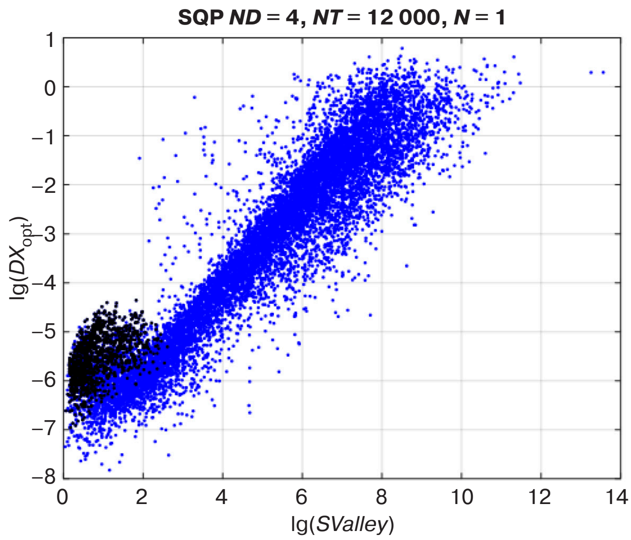


Fig. 6. Scatter plot of the logarithm values of the valley ratio *SValley* and the error in determining coordinates of the minimum DX_{opt}

points with *NValley* > 1. This data selection results in some improvement in the model accuracy expressed in increasing coefficient of determination R^2 and decreasing root-mean-square (RMS) error (residual) of regression *StdErr*.

Next, the possibility of improving the model accuracy by taking into account the Euclidean norm (length) of the OF gradient vector $\|\mathbf{grad}\|$ at the search end point is investigated. The following linear model is considered:

$$\lg\left(DX_{\mathrm{opt}}\right) = k_1 \lg\left(SValley\right) + k_2 \lg\left(\|\mathbf{grad}\|\right) + b. \quad (7)$$

The regression analysis results of this model are given in Table 2. As for the previous model, cases including all points and excluding points with *NValley* > 1 are distinguished. Notably, the correlation coefficient of values lg(||**grad**||) and lg(*SValley*) at different dimensions of *ND* space varies from 0.91 to 0.95, i.e., the correlation is significant. Nevertheless, taking the gradient norm into account provides additional

Table 1. Results of the regression analysis of model (6)

ND	All points				Points with *NValley* > 1 are excluded			
	b	*k*	R^2	*StdErr*	*b*	*k*	R^2	*StdErr*
2	−6.97	0.564	0.846	0.825	–	–	–	–
3	−6.81	0.675	0.855	0.755	−6.98	0.702	0.856	0.747
4	−6.80	0.714	0.881	0.686	−7.08	0.758	0.885	0.666
5	−6.82	0.744	0.882	0.685	−7.15	0.797	0.884	0.667
6	−6.79	0.756	0.884	0.674	−7.09	0.806	0.885	0.660
7	−6.72	0.757	0.883	0.673	−7.03	0.808	0.886	0.656
8	−6.69	0.766	0.876	0.700	−7.00	0.817	0.878	0.687
9	−6.63	0.764	0.874	0.700	−6.94	0.816	0.877	0.684
10	−6.60	0.772	0.868	0.712	−6.93	0.828	0.869	0.699
11	−6.59	0.777	0.865	0.716	−6.90	0.830	0.868	0.702
12	−6.54	0.779	0.857	0.740	−6.86	0.834	0.859	0.729

Table 2. Results of the regression analysis of model (7)

ND	All points					Points with *NValley* > 1 are excluded				
	b	k_1	k_2	R^2	*StdErr*	*b*	k_1	k_2	R^2	*StdErr*
2	−3.53	0.041	0.526	0.936	0.534	–	–	–	–	–
3	−3.84	0.125	0.464	0.929	0.529	−3.97	0.145	0.469	0.937	0.495
4	−3.91	0.163	0.453	0.935	0.507	−4.08	0.184	0.475	0.950	0.439
5	−4.01	0.196	0.438	0.936	0.502	−4.15	0.209	0.479	0.956	0.411
6	−3.98	0.198	0.442	0.937	0.495	−4.07	0.201	0.490	0.956	0.407
7	−3.95	0.199	0.444	0.938	0.490	−4.06	0.204	0.491	0.959	0.395
8	−3.86	0.184	0.460	0.939	0.492	−3.99	0.196	0.501	0.959	0.398
9	−3.89	0.195	0.451	0.937	0.493	−4.02	0.208	0.492	0.959	0.394
10	−3.84	0.190	0.456	0.937	0.492	−4.02	0.211	0.493	0.958	0.397
11	−3.84	0.194	0.458	0.936	0.494	−4.00	0.212	0.496	0.958	0.397
12	−3.84	0.195	0.454	0.934	0.501	−4.03	0.218	0.490	0.957	0.401

Table 3. Approximation results using ANN models

ND	Approximation along lg(*SValley*)				Along lg(*SValley*) and lg(‖**grad**‖)			
	All points		Without *NValley* > 1		All points		Without *NValley* > 1	
	R^2	*StdErr*	R^2	*StdErr*	R^2	*StdErr*	R^2	*StdErr*
2	0.863	0.777	–	–	0.954	0.451	–	–
3	0.881	0.685	0.877	0.691	0.952	0.437	0.953	0.425
4	0.906	0.609	0.904	0.608	0.959	0.404	0.963	0.378
5	0.904	0.617	0.900	0.618	0.960	0.399	0.966	0.360
6	0.907	0.602	0.904	0.603	0.959	0.402	0.965	0.364
7	0.908	0.598	0.906	0.595	0.961	0.388	0.969	0.341
8	0.903	0.621	0.900	0.622	0.961	0.391	0.970	0.340
9	0.903	0.613	0.901	0.613	0.964	0.376	0.972	0.329
10	0.895	0.634	0.891	0.640	0.960	0.391	0.969	0.339
11	0.891	0.644	0.888	0.648	0.961	0.384	0.970	0.336
12	0.883	0.668	0.879	0.676	0.959	0.398	0.970	0.337

information for estimating the error DX_{opt}. Compared to model (6), the coefficient of determination R^2 becomes closer to one while the RMS error *StdErr* decreases. At the same time, the exclusion of points with erroneously defined valley dimensionality improves the model performance, as in the previous case.

An alternative approach to the approximation of dependencies between data collected in experiments is based on training ANN models. It is known that ANNs with hidden layers and a sufficient number of neurons can be used to approximate any continuous function of several variables [15]. Here, the ANN model with one hidden layer containing 5 neurons is used. The same data used for regression analysis of models (6) and (7) is used as a training sample. All *MATLAB train*(..) function settings are default. The approximation results are presented in Table 3.

The comparison with the results from Tables 1 and 2 shows that ANN models provide a more accurate approximation of the required dependence on the same initial data than linear regression models. Notably, the results are not significantly improved by increasing the number of neurons up to 10.

CONCLUSIONS

An objective stochastic dependence between the valley ratio estimation of the OF landscape in the neighborhood of the minimum search end point and the error in determining the coordinates of the true position of the OF minimum has been demonstrated. When determining the coordinates of the minimum point, this dependence can be identified and recorded in the form of a linear regression equation or in the form of a trained ANN model, and then used to estimate the expected error.

ANN models were found to provide higher accuracy in predicting the magnitude of the error compared to linear regression models. Moreover, the accuracy of both types of models increases taking into account not only the estimate of the valley ratio, but also the Euclidean norm of the OF gradient at the search end point.

In the future, it is planned to expand the methodology to apply to functions with a valley dimensionality greater than one, as well as to other types of landscape areas presenting difficulties for optimization algorithms.

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RESEARCH ARTICLE

Properties of the Wrońskian determinant of a system of solutions to a linear homogeneous equation: The case when the number of solutions is less than the order of the equation

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Abstract
Objectives. The work sets out to study the properties of the Wrońskian determinant of the system of solutions to a linear homogeneous equation in cases when the number of solutions is less than the order of the equation, comparing them with the known properties of the same determinant when the number of solutions is equal to the order of the equation.
Methods. The work uses the methods of linear algebra according to the theory of ordinary differential equations, as well as mathematical and complex analysis.
Results. It is shown that the vanishing of a considered determinant on an arbitrarily small interval implies its vanishing on the entire domain of definition; the solutions turn out to be linearly dependent. A stronger result is obtained in three cases: (1) if the coefficients of the equation are analytic functions; (2) if the number of solutions is equal to one; (3) if the number of solutions is one less than the order of the equation. Namely, if the set of zeros of the considered Wrońskian has a limit point belonging to the domain of definition of solutions, then the determinant is identically equal to zero and the solutions are linearly dependent.
Conclusions. According to the obtained results, the Wrońskian of a system of solutions of a linear homogeneous equation can serve as an indicator of the linear dependence or independence of this system in cases where the number of solutions is lower than the order of the equation; here, the solutions are linearly dependent if and only if their Wrońskian is identically equal to zero. In this case, there is no need to check whether the determinant vanishes over the entire domain of definition, since it is sufficient to do this on an arbitrarily chosen interval or even (in the special cases listed above) on an arbitrarily chosen set having a limit point.

Keywords: linear homogeneous differential equation, Wrońskian, zeros of the Wrońskian, linear dependence, linear independence

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НАУЧНАЯ СТАТЬЯ

Свойства определителя Вронского системы решений линейного однородного уравнения: случай, когда число решений меньше порядка уравнения

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Резюме
Цели. Целью работы является изучение свойств определителя Вронского системы решений линейного однородного дифференциального уравнения в случае, когда число решений меньше порядка уравнения, и сравнение их с известными свойствами такого же определителя, но в случае равенства числа решений порядку уравнения.
Методы. В работе использованы методы линейной алгебры и теории обыкновенных дифференциальных уравнений, а также математического и комплексного анализа.
Результаты. Показано, что обращение в нуль рассматриваемого определителя на сколь угодно малом интервале влечет за собой обращение его в нуль на всей области определения, а решения при этом оказываются линейно зависимыми. В трех случаях: 1) если коэффициенты уравнения являются аналитическими функциями, 2) если число решений равно единице и 3) если число решений на единицу меньше порядка уравнения – получен более сильный результат. Именно, если множество нулей рассматриваемого определителя Вронского имеет предельную точку, принадлежащую области определения решений, то определитель тождественно равен нулю и решения линейно зависимы.
Выводы. Полученные результаты означают, что определитель Вронского системы решений линейного однородного уравнения в ситуации, когда число решений меньше порядка уравнения, служит индикатором линейной зависимости или независимости этой системы: решения линейно зависимы тогда и только тогда, когда их определитель Вронского тождественно равен нулю. При этом нет необходимости проверять обращение определителя в нуль на всей области определения, достаточно сделать это на произвольно выбранном интервале или даже (в перечисленных выше частных случаях) на произвольно выбранном множестве, имеющем предельную точку.

Ключевые слова: линейное однородное дифференциальное уравнение, определитель Вронского, нули определителя Вронского, линейная зависимость, линейная независимость

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INTRODUCTION

One of the main tools of mathematical modeling is ordinary differential equations, which serve as models for describing a wide variety of phenomena and processes [1–5]. In turn, an important tool for studying differential equations, primarily in terms of checking the linear dependence or independence of their solutions, is the Wrońskian.

It should be recalled that the Wrońskian of the system of functions $y_1(x)$, $y_2(x)$, …, $y_k(x)$, $x \in (a, b)$ consists in the following function:

$$W(x) = W_{y_1,y_2,\ldots,y_k}(x) = \\ = \begin{vmatrix} y_1(x) & y_2(x) & \ldots & y_k(x) \\ y_1'(x) & y_2'(x) & \ldots & y_k'(x) \\ \ldots & \ldots & \ldots & \ldots \\ y_1^{(k-1)}(x) & y_2^{(k-1)}(x) & \ldots & y_k^{(k-1)}(x) \end{vmatrix}. \quad (1)$$

The Wrońskian determinant theory is presented in practically every textbook on ordinary differential equations [6–12]; with few exceptions, such determinants are based on n solutions to the nth-order linear homogeneous equation. The remarkable properties of such determinants permit their use as indicators of linear dependence or independence of the considered system of solutions. State more precisely, a system of n solutions to the nth-order linear homogeneous equation is linearly dependent if and only if the Wrońskian of this system is identically equal to zero, and is linearly independent if and only if its Wrońskian is not equal to zero at any point in the definition domain of the considered solutions. It is also well-understood (see the corresponding examples in [6, 9, and 12]) that the situation is quite different for a Wrońskian of a system of functions not presenting solutions to a linear homogeneous equation; the determinant can be zero, even identically, if the functions are linearly independent. Otherwise stated, if the Wrońskian of some system of functions turns out to be identically equal to zero, no answer to the question about the linear dependence or independence of this system could be obtained by this means.

Here, a natural question arises: would the "good" properties of the Wrońskian of a system of solutions to the nth-order linear homogeneous equation be preserved if we take $k < n$ instead of n solutions? If so, could the Wrońskian of such a system be used just as effectively to find out its linear dependence or independence? This question is formulated, for example, in [9]; here however, the study of this question is limited to an example showing that the Wrońskian of a linearly independent system of $k < n$ solutions (in the example, $k = 2$ and $n = 3$), unlike that of a linearly independent system of n solutions, can go to zero at some points of its definition domain.

It is not difficult to provide an example for arbitrary n and $k < n$, when the Wrońskian of a linearly independent system of solutions goes to zero even in an infinite set of points. In what follows, we shall consider equation $y^{(n)} + y^{(n-2)} = 0$, whose fundamental system of solutions consists of the functions $1, x, x^2, \ldots, x^{n-3}$, $\sin x$, $\cos x$. For arbitrary $k \le n - 1$, we take the set of k solutions $1, x, x^2, \ldots, x^{k-2}$, $\sin x$ (for $k = 1$, we take one solution $\sin x$), whose Wrońskian coincides either with $\sin x$ or with $\cos x$ to the nearest numerical factor and consequently has an infinite number of zeros on the numerical axis.

The Wrońskian of a system from the $(n - 1)$th solution to the nth-order linear homogeneous equation is studied in [13], where, in particular, it is shown that, in the case of linear independence of such system, its Wrońskian cannot have an infinite number of zeros on any finite segment. In the cited work, the case of arbitrary number of solutions less than the order of the equation n is considered. The main result is contained in Theorem 1 stating that the equality to zero of the Wrońskian of such system of solutions on any interval implies its linear dependence. Thus, in the case of linear independence of solutions, the Wrońskian cannot be zero on any interval, even an arbitrarily small one.

Theorem 2 shows that this result can be strengthened in a number of special cases, including the above-mentioned case $k = n - 1$. Precisely stated, the set of zeros of the Wrońskian of a linearly independent system of solutions cannot have limit points in its definition domain, and, hence, cannot have an infinite number of zeros on any finite segment. For the case $k = n - 1$, a proof different from that given in [13], which allows weakening the conditions on the coefficients of the equation, is provided.

Thus, it can be said that the Wrońskian of a system of $k < n$ solutions to the nth-order linear homogeneous equation by its properties occupies an intermediate position between the Wrońskian determinant of an arbitrary system of functions and that of a system of n solutions, according to which properties such a determinant can be used to find out whether the considered system of solutions is linearly dependent or independent.

MAIN RESULT

We shall consider the following nth-order linear homogeneous equation:

$$y^{(n)} + a_{n-1}(x)y^{(n-1)} + \ldots + a_0(x)y = 0, \quad (2)$$

whose coefficients are $a_{n-1}(x), \ldots, a_0(x) \in C(a, b)$, $-\infty \le a < b \le +\infty$.

As is known, any solution to such equation continues over the entire interval (a, b). In the following, only solutions defined on (a, b) are considered.

Let $y_1(x), y_2(x), \ldots, y_k(x)$ be solutions to Eq. (2), $k \le n - 1$, $W_{y_1,y_2,\ldots,y_k}(x)$ be their Wrońskian (1). We shall also consider determinants of the following form:

$$W^{\alpha_1,\alpha_2,\ldots,\alpha_k}_{y_1,y_2,\ldots,y_k}(x) = \begin{vmatrix} y_1^{(\alpha_1)}(x) & y_2^{(\alpha_1)}(x) & \ldots & y_k^{(\alpha_1)}(x) \\ y_1^{(\alpha_2)}(x) & y_2^{(\alpha_2)}(x) & \ldots & y_k^{(\alpha_2)}(x) \\ \ldots & \ldots & \ldots & \ldots \\ y_1^{(\alpha_k)}(x) & y_2^{(\alpha_k)}(x) & \ldots & y_k^{(\alpha_k)}(x) \end{vmatrix},$$

where $0 \le \alpha_1, \alpha_2, \ldots, \alpha_k \le n$.

It is clear that if among the numbers $\alpha_1, \ldots, \alpha_k$ there are coincident ones, then $W^{\alpha_1,\alpha_2,\ldots,\alpha_k}_{y_1,y_2,\ldots,y_k}(x) \equiv 0$. The determinants $W^{\alpha_1,\alpha_2,\ldots,\alpha_k}_{y_1,y_2,\ldots,y_k}$ with $0 \le \alpha_1 < \alpha_2 < \ldots < \alpha_k \le n-1$ will be called *generalized Wrońskians*. Obviously, there are exactly C_n^k of different generalized Wrońskians of the system of k solutions including the Wrońskian $W_{y_1,y_2,\ldots,y_k} = W^{0,1,\ldots,k-1}_{y_1,y_2,\ldots,y_k}$ itself. It should be noted that in the case of linear dependence of the system of solutions $y_1, y_2, \ldots, y_k$ on some interval $(\alpha, \beta) \subset (a, b)$ (and hence, due to the uniqueness theorem of the solution to the Cauchy problem, on the entire interval (a, b)), all its generalized Wrońskians are identically zero on (a, b).

LEMMA 1. Let $y_1, y_2, \ldots, y_k$, $k \le n-1$ be solutions to Eq. (2), and let determinant $W_{y_1,y_2,\ldots,y_k}(x)$ be identically zero on some interval $(\alpha, \beta) \subset (a, b)$. Then for an arbitrary solution y_{k+1} all generalized Wrońskians of the system of solutions $y_1, y_2, \ldots, y_{k+1}$ are identically zero on (a, b).

The PROOF is carried out by induction on k. For $k = 1$, the statement is true due to the uniqueness theorem of the solution to the Cauchy problem. Let us assume it is true for some $k \le n-2$, and prove its validity for $k+1$.

Let $y_1, y_2, \ldots, y_{k+1}$ be solutions to Eq. (2) and

$$W_{y_1,\ldots,y_{k+1}}(x) = 0 \quad \forall x \in (\alpha,\beta) \subset (a,b). \tag{3}$$

We shall take the one less order determinant $W_{y_1,\ldots,y_k}(x)$. There are two possible cases: either $W_{y_1,\ldots,y_k}(x) \equiv 0$ on the interval (α, β) or $x_0 \in (\alpha, \beta)$ $W_{y_1,\ldots,y_k}(x_0) \ne 0$ at some point. We shall consider these cases.

1. Let $W_{y_1,\ldots,y_k}(x) = 0$ $\forall x \in (\alpha,\beta)$. Then by inductive assumption, all generalized Wrońskians of solutions $y_1, y_2, \ldots, y_{k+1}$ are identically zero on (a, b). Take an arbitrary solution y_{k+2} and consider the generalized Wrońskian $W^{\alpha_1,\ldots,\alpha_{k+2}}_{y_1,\ldots,y_{k+2}}$. Decomposing it by the last column, we obtain:

$$W^{\alpha_1,\ldots,\alpha_{k+2}}_{y_1,\ldots,y_{k+2}}(x) = \begin{vmatrix} y_1^{(\alpha_1)}(x) & y_2^{(\alpha_1)}(x) & \ldots & y_{k+2}^{(\alpha_1)}(x) \\ y_1^{(\alpha_2)}(x) & y_2^{(\alpha_2)}(x) & \ldots & y_{k+2}^{(\alpha_2)}(x) \\ \ldots & \ldots & \ldots & \ldots \\ y_1^{(\alpha_{k+2})}(x) & y_2^{(\alpha_{k+2})}(x) & \ldots & y_{k+2}^{(\alpha_{k+2})}(x) \end{vmatrix} =$$

$$= (-1)^{k+3} y_{k+2}^{(\alpha_1)}(x) W^{\alpha_2,\ldots,\alpha_{k+2}}_{y_1,\ldots,y_{k+1}}(x) +$$

$$+ (-1)^{k+4} y_{k+2}^{(\alpha_2)}(x) W^{\alpha_1,\alpha_3,\ldots,\alpha_{k+2}}_{y_1,\ldots,y_{k+1}}(x) + \ldots +$$

$$+ y_{k+2}^{(\alpha_{k+2})}(x) W^{\alpha_1,\ldots,\alpha_{k+1}}_{y_1,\ldots,y_{k+1}}(x) = 0 \quad \forall x \in (a,b),$$

and thus, the statement of the lemma is proved.

2. Now let $W_{y_1,\ldots,y_k}(x_0) \ne 0$ at point $x_0 \in (\alpha, \beta)$. Then due to continuity, $W_{y_1,\ldots,y_k}(x) \ne 0$ on some interval (α_1, β_1) containing point x_0. We shall show that the functions $y_1, y_2, \ldots, y_{k+1}$ are linearly dependent on this interval.

Due to (3), the columns of determinant $W_{y_1,\ldots,y_{k+1}}(x)$ are linearly dependent at each point $x \in (\alpha, \beta)$, i.e., there exist constants $\lambda_1(x), \lambda_2(x), \ldots, \lambda_{k+1}(x)$ being not equal to zero simultaneously (in general, different for each point x), such that

$$\begin{cases} \lambda_1(x) y_1(x) + \ldots + \lambda_{k+1}(x) y_{k+1}(x) = 0, \\ \ldots \\ \lambda_1(x) y_1^{(k)}(x) + \ldots + \lambda_{k+1}(x) y_{k+1}^{(k)}(x) = 0. \end{cases} \tag{4}$$

It should be noted that at $x \in (\alpha_1, \beta_1)$ $\lambda_{k+1}(x) \ne 0$. Indeed, otherwise, the following is obtained from the first k equalities (4):

$$\begin{cases} \lambda_1(x) y_1(x) + \ldots + \lambda_k(x) y_k(x) = 0, \\ \ldots \\ \lambda_1(x) y_1^{(k-1)}(x) + \ldots + \lambda_k(x) y_k^{(k-1)}(x) = 0, \end{cases} \tag{5}$$

from which $\lambda_1(x) = \lambda_2(x) = \ldots = \lambda_k(x) = 0$, since the determinant of system (5) is determinant $W_{y_1,\ldots,y_k}(x)$ not equal to zero on the interval (α_1, β_1).

For each $x \in (\alpha_1, \beta_1)$, we shall solve the equations of system (4) with respect to the function y_{k+1} and its derivatives, as follows:

$$\begin{cases} y_{k+1}(x) = \mu_1(x) y_1(x) + \ldots + \mu_k(x) y_k(x), \\ y'_{k+1}(x) = \mu_1(x) y'_1(x) + \ldots + \mu_k(x) y'_k(x), \\ \ldots \\ y_{k+1}^{(k)}(x) = \mu_1(x) y_1^{(k)}(x) + \ldots + \mu_k(x) y_k^{(k)}(x), \end{cases} \tag{6}$$

where $\mu_i(x) = -\lambda_i(x) / \lambda_{k+1}(x),\ i = \overline{1,k}$.

Considering the first k equalities in (6) as a system of linear algebraic equations with respect to unknowns $\mu_1(x), \ldots, \mu_k(x)$, and with the same nonzero determinant, the following is obtained:

$$\mu_i(x) = \frac{W_{y_1,\ldots,y_{i-1},y_{k+1},y_{i+1},\ldots,y_k}(x)}{W_{y_1,\ldots,y_k}(x)},\ i = \overline{1,k},$$

from which, in particular, it follows that $\mu_i(x) \in C^1(\alpha_1, \beta_1)$.

Next, we proceed as follows. We differentiate both parts of the first equation from (6) and subtract the second equation from the resulting equality:

$0=\mu_1'(x)y_1(x)+\ldots+\mu_k'(x)y_k(x)$, $x\in(\alpha_1,\ \beta_1)$. The same is done with the second and third equation, the third and fourth equation, etc. As a result, the following homogeneous system of equations with respect to derivatives $\mu_1'(x), ..., \mu_k'(x)$ is obtained:

$$\begin{cases}0=\mu_1'(x)y_1(x)+\ldots+\mu_k'(x)y_k(x),\\ 0=\mu_1'(x)y_1'(x)+\ldots+\mu_k'(x)y_k'(x),\\ \ldots\\ 0=\mu_1'(x)y_1^{(k-1)}(x)+\ldots+\mu_k'(x)y_k^{(k-1)}(x),\end{cases}$$

the determinant of which is $W_{y_1,\ldots,y_k}(x)\neq 0$ again. Hence, it may be concluded that $\mu_1'(x)=\ldots=\mu_k'(x)=0$ $\forall x\in(\alpha_1,\beta_1)$, and therefore $\mu_1(x), \ldots, \mu_k(x)$ are constants. Thus, due to the first equality in (6), solutions $y_1, y_2, \ldots, y_{k+1}$ are linearly dependent on the interval (α_1, β_1) and hence on (a, b). If an arbitrary solution y_{k+2} is taken now, then all generalized Wrońskians of the linearly dependent system $y_1, \ldots, y_{k+1}, y_{k+2}$ would be identically zero on (a, b). The lemma is proved.

Now, the main result of the work can be easily established.

THEOREM 1. Let $y_1(x), y_2(x), \ldots, y_k(x)$, $k\le n-1$ be solutions to Eq. (2), and let $W_{y_1,\ldots,y_k}(x)=0$ $\forall x\in(\alpha,\beta)\subset(a,b)$. Then functions $y_1, y_2, \ldots, y_k$ are linearly dependent on the interval (a, b).

PROOF. Suppose that solutions $y_1, y_2, \ldots, y_k$ are linearly independent. We supplement the system $y_1, y_2, \ldots, y_k$ to the fundamental system of solutions $y_1, y_2, \ldots, y_k, y_{k+1}, \ldots, y_n$ of Eq. (2). Applying Lemma 1 sequentially, it may be concluded that $W_{y_1,\ldots,y_{k+1}}(x)\equiv 0$, $W_{y_1,\ldots,y_{k+2}}(x)\equiv 0, \ldots, W_{y_1,\ldots,y_n}(x)\equiv 0$ on (a, b). But the equality to zero of the Wrońskian of the system of n solutions even at one point means their linear dependence. The obtained contradiction proves the theorem.

SPECIAL CASES

The following result shows that in some cases for linear dependence of solutions $y_1, y_2, \ldots, y_k$, it is sufficient to zeroize the Wrońskian $W_{y_1,\ldots,y_k}(x)$ on the set having a limit point.

THEOREM 2. Let the set of zeros of the Wrońskian $W_{y_1,\ldots,y_k}(x)$ of solutions $y_1(x), y_2(x), \ldots, y_k(x)$, $k\le n-1$ to Eq. (2) have the limit point $x_0\in(a, b)$. Let, further, one of the following conditions be satisfied: (a) the coefficients of Eq. (2) are analytic functions (in particular, constant values) on the interval (a, b); (b) $k=1$; (c) $k=n-1$, and the coefficients of Eq. (2) satisfy the following smoothness conditions:

$$a_0(x)\in C(a,b),\ a_l(x)\in C^{l-1}(a,b),\ l=1,2,\ldots,n-2,\quad a_{n-1}(x)\in C^{n-3}(a,b).$$

Then solutions $y_1, y_2, \ldots, y_k$ are linearly dependent on (a, b).

PROOF. If condition (a) is satisfied, all solutions to Eq. (2) are analytic functions on the interval (a, b) ([14], Ch. 1, § 6), and hence the Wrońskian $W_{y_1,\ldots,y_k}(x)$ is analytic on (a, b). By the uniqueness theorem for analytic functions ([15], Ch. I, § 5, p. 20), $W_{y_1,\ldots,y_k}(x)\equiv 0$ on the interval (a, b), and it remains to refer to Theorem 1.

Let condition (b) be satisfied, i.e., $k=1$. The Wrońskian of one solution is the solution itself, so our statement is an obvious consequence of the uniqueness theorem of the solution to the Cauchy problem.

We shall finally consider case (c). It should be noted that the result of differentiation of any generalized Wrońskian $W^{\alpha_1,\ldots,\alpha_k}_{y_1,\ldots,y_k}$ is a linear combination of some set of generalized Wrońskians of the same solutions $y_1, y_2, \ldots, y_k$. Indeed, if $\alpha_k<n-1$ in our determinant, then

$$\frac{d}{dx}W^{\alpha_1,\alpha_2,\ldots,\alpha_k}_{y_1,y_2,\ldots,y_k}=W^{\alpha_1+1,\alpha_2,\ldots,\alpha_k}_{y_1,y_2,\ldots,y_k}+ +W^{\alpha_1,\alpha_2+1,\ldots,\alpha_k}_{y_1,y_2,\ldots,y_k}+\ldots+W^{\alpha_1,\alpha_2,\ldots,\alpha_k+1}_{y_1,y_2,\ldots,y_k},\qquad(7)$$

where some of the obtained determinants may be equal to zero due to the presence of coincident lines in them.

If $\alpha_k=n-1$, then the last line of the last determinant in (7) will contain the nth derivatives of functions $y_1, y_2, \ldots, y_k$. Replacing the nth derivative of each solution by a linear combination of lower order derivatives due to Eq. (2), the following is obtained:

$$W^{\alpha_1,\ldots,\alpha_{k-1},n}_{y_1,y_2,\ldots,y_k}=-a_{n-1}W^{\alpha_1,\ldots,\alpha_{k-1},n-1}_{y_1,y_2,\ldots,y_k}- -a_{n-2}W^{\alpha_1,\ldots,\alpha_{k-1},n-2}_{y_1,y_2,\ldots,y_k}-\ldots-a_0W^{\alpha_1,\ldots,\alpha_{k-1},0}_{y_1,y_2,\ldots,y_k}.\qquad(8)$$

Each of the determinants in the right-hand side of (8) is either zero or coincides with one of the generalized Wrońskians of solutions $y_1, \ldots, y_k$.

We shall apply these observations to the case of $k=n-1$. It should be noted that there are exactly n different generalized Wrońskians of solutions $y_1, \ldots, y_{n-1}$ to Eq. (2): the Wrońskian $W_{y_1,\ldots,y_{n-1}}=W^{0,1,\ldots,n-2}_{y_1,\ldots,y_{n-1}}$ itself, determinants of the $W^{0,1,\ldots,l-1,l+1,\ldots,n-1}_{y_1,\ldots,y_{n-1}}$ form, and, finally, $W^{1,2,\ldots,n-1}_{y_1,\ldots,y_{n-1}}$. We simplify the notations assuming $W_{y_1,\ldots,y_{n-1}}=W$, $W^{0,1,\ldots,l-1,l+1,\ldots,n-1}_{y_1,\ldots,y_{n-1}}=W_l$, and $W^{1,2,\ldots,n-1}_{y_1,\ldots,y_{n-1}}=W_0$. Differentiating the determinants W and W_l according to

Eqs. (7) and (8) and discarding the resulting determinants equal to zero, the following is obtained:

$$W' = W_{n-2}, \tag{9}$$

$$W_l' = W_{l-1} - a_{n-1}W_l - (-1)^{n-l}a_l W,\quad l = \overline{n-2, 1}. \tag{10}$$

We show that the Wrońskian derivatives W of order 2 to $n-1$ are expressed through the generalized Wrońskians using the following formulas:

$$W^{(j)} = W_{n-j-1} + \sum_{l=n-j}^{n-2} \alpha_{jl}(x)W_l + \beta_j(x)W,\quad j = \overline{2, n-1}, \tag{11}$$

where functions $\alpha_{jl}(x), \beta_j(x) \in C^{n-j-1}(a,b)$ (we already have Eq. (9) as the expression for the first derivative).

Indeed, we obtain the formula for W'' by differentiating (9) and substituting W'_{n-2} according to (10): $W'' = W_{n-3} - a_{n-1}W_{n-2} - a_{n-2}W$, which corresponds to (11), and the coefficients at the determinants in the right-hand side are functions of the $C^{n-3}(a,b)$ class due to the condition of the theorem. Further, assuming that formula (11) is true for some j, $2 \le j \le n-2$, then, differentiating both parts of it and using (10), the following is obtained:

$$W^{(j+1)} = W_{n-j-2} - a_{n-1}W_{n-j-1} - (-1)^{j+1}a_{n-j-1}W + \sum_{l=n-j}^{n-2}[\alpha'_{jl}W_l + \alpha_{jl}(W_{l-1} - a_{n-1}W_l - (-1)^{n-l}a_l W)] + \beta'_j W + \beta_j W_{n-2} = W_{n-j-2} + \sum_{l=n-j-1}^{n-2}\alpha_{j+1,l}W_l + \beta_{j+1}W,$$

where $\alpha_{j+1,n-j-1} = -a_{n-1} + \alpha_{j,n-j}$,
$\alpha_{j+1,l} = \alpha'_{jl} - \alpha_{jl}a_{n-1} + \alpha_{j,l+1}$,
$l = n-j, n-j+1, \ldots, n-3$ (for $j \ge 3$),
$\alpha_{j+1,n-2} = \alpha'_{j,n-2} - \alpha_{j,n-2}a_{n-1} + \beta_j$,
$\beta_{j+1} = (-1)^j a_{n-j-1} - \sum_{l=n-j}^{n-2}(-1)^{n-l}\alpha_{jl}a_l + \beta'_j$.

It can be easily seen that due to the inductive assumption and the conditions of the theorem concerning the smoothness of the coefficients of equation $\alpha_{j+1,l}, \beta_{j+1} \in C^{n-j-2}(a,b)$, and thus (11) is proved.

Now let $x = x_0$ in (9) and (11). The point x_0, being the limit point for zeros of function $W(x)$, is such due to Rolle's theorem, and also for zeros of its derivatives $W'(x), \ldots, W^{(n-1)}(x)$. Hence, due to continuity, $W(x_0) = W'(x_0) = \ldots = W^{(n-1)}(x_0) = 0$. We obtain a linear homogeneous system of algebraic equations with respect to the unknowns $W_{n-2}(x_0)$, $W_{n-3}(x_0)$, …, $W_0(x_0)$ with triangular determinant different from zero:

$$0 = W_{n-2}(x_0),$$
$$0 = W_{n-j-1}(x_0) + \sum_{l=n-j}^{n-2}\alpha_{jl}(x_0)W_l(x_0),\quad j = \overline{2, n-1},$$

from which $W_{n-2}(x_0) = W_{n-3}(x_0) = \ldots = W_0(x_0) = 0$.

Then we use the already familiar technique: assuming that solutions $y_1, \ldots, y_{n-1}$ are linearly independent, we add one more solution to them to obtain the fundamental system of solutions $y_1, \ldots, y_{n-1}, y_n$ and, decomposing determinant $W_{y_1,\ldots,y_n}$ by the last column, we obtain $W_{y_1,\ldots,y_n}(x_0) = 0$, which means linear dependence $y_1, \ldots, y_n$. The obtained contradiction proves the linear dependence of solutions $y_1, \ldots, y_{n-1}$. The theorem is proved.

COROLLARY. Let $y_1(x), y_2(x), \ldots, y_k(x), x \in (a, b)$ be linearly independent solutions to Eq. (2). Then their Wrońskian cannot be identically zero on any interval $(\alpha, \beta) \subset (a, b)$. If one of conditions (a), (b) or (c) of Theorem 2 is satisfied, then the set of zeros of the determinant $W(x)$ cannot have limit points on the interval (a, b), or, equivalently, $W(x)$ cannot have an infinite number of zeros on any interval $[\alpha, \beta] \subset (a, b)$.

CONCLUSIONS

It follows from the above results that, in cases where the number of solutions is less than the order of the equation, the Wrońskian of a system of solutions to a linear homogeneous equation can be used to check whether the system is linearly dependent or independent; the solutions are linearly dependent if and only if their Wrońskian is identically equal to zero, and independent if the determinant is different from zero in at least one point. In this case, as Theorems 1 and 2 show, the verification of the identical equality to zero of the Wrońskian over the entire definition domain can be replaced by the verification of its equality to zero on a significantly smaller set, which facilitates the practical application of the results obtained.

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RESEARCH ARTICLE

Assessment of the effects of production system development projects: Case study of Lytkarino Optical Glass Factory

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Abstract
Objectives. Effective import substitution can be achieved only through the creation and use of efficient domestic production capacities. The aim of this study is to develop and justify a method for the integrated assessment of the effects of projects aimed at the introduction of new equipment, including import substitution projects.
Methods. The research was based on systemic and dialectical approaches, as well as systemic, comparative, economic and mathematical methods, and statistical analysis.
Results. The paper proposes a method for the integrated assessment of production system development projects. In order to obtain a synthetic assessment, a system of indicators was developed to study the effects of production system development projects, i.e., projects for the introduction of new equipment. The effects of the introduction of new equipment can be divided into internal and external: potential development, socioeconomic, import independence, public, and environmental. The indicators are not current values, but changes in dynamics. A comprehensive consideration of the effects allows the existing criteria for decision-making to be expanded when implementing projects to develop the production system. It also allows the impact on both the enterprise and society to be assessed. The authors define both the quantitative and qualitative indicators for each group of effects. On the basis of the author's system of indicators, a methodology for comparative comparison of indicators using normalized indices was developed and the calculation of a generalized indicator substantiated. The proposed system of indicators was successfully tested at the Lytkarino Optical Glass Factory science-intensive enterprise when assessing a new domestic device for the development of the production system.
Conclusions. The results of the approved method for integrated assessment enabled the use of diverse indicators for the quantitative and qualitative assessment of the effects of the introduction of science-intensive projects. This included projects for import substitution of machinery and equipment. A combination of various effects will be relevant to any socioeconomic system, so the proposed integrated assessment method for evaluating the effects is universal to a certain extent. It can thus be adapted for scientific, technical and technological projects on import substitution of any industrial enterprise.

Keywords: effect, development, import substitution, project, system of indicators, integral index

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НАУЧНАЯ СТАТЬЯ

Оценка эффектов реализации проектов развития производственной системы (на примере АО «Лыткаринский завод оптического стекла»)

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Резюме
Цели. Результативное импортозамещение возможно только за счет создания и использования эффективных отечественных производственных мощностей. Цель исследования состоит в разработке и обосновании методики интегральной оценки эффектов, полученных от проектов по внедрению нового оборудования, включая проекты по импортозамещению.
Методы. Основой исследования явились системный и диалектический подходы, а также методы системного, компаративного, экономико-математического и статистического анализа.
Результаты. В работе предложена методика интегральной оценки эффектов реализации проектов развития производственной системы. С целью получения синтетической оценки разработана система показателей для исследования эффектов проектов развития производственной системы – проектов по внедрению нового оборудования. Эффекты от внедрения нового оборудования подразделяются на внутренние и внешние эффекты различной природы: эффект развития потенциала, социально-экономические, эффект импортонезависимости, общественные, экологические. При этом индикаторами эффектов являются не текущие значения показателей, а их изменения в динамике. Комплексное рассмотрение эффектов позволяет расширить существующие критерии принятия решений при реализации проектов по развитию производственной системы, что позволяет оценить воздействие и на предприятие, и на общество в целом. Авторы определяют количественные и качественные показатели для каждой группы эффектов. На базе авторской системы показателей разработана методика компаративного сопоставления показателей с использованием нормированных индексов и обоснован расчет обобщенного показателя. Предложенная система показателей была успешно апробирована на наукоемком предприятии АО «Лыткаринский завод оптического стекла» при оценке эффектов от внедрения нового отечественного прибора для развития производственной системы.
Выводы. Результаты апробации методики позволили обосновать применение разноплановых показателей для количественной и качественной оценки эффектов от внедрения наукоемких проектов, включая проекты по импортозамещению техники и оборудования. Совокупность различных эффектов будет проявляться для любой социально-экономической системы, поэтому предлагаемая методика для оценки эффектов является в определенной мере универсальной и может быть адаптирована для научно-технических и технологических проектов по импортозамещению любого промышленного предприятия.

Ключевые слова: эффект, развитие, импортозамещение, проект, система показателей, интегральный индекс

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INTRODUCTION

Although the introduction of new technological solutions is aimed at the practical resolution of socio-economic and political objectives [1], such innovations do not always produce the expected consequences. A reasoned analysis of factors and economic calculations allow us to justify the various effects or results of new technologies and equipment after their introduction. In order to properly justify the need for technological innovations, non-economic factors need to be taken into consideration along with economic factors. Only a comprehensive consideration of all interrelated factors will allow a real picture of the economic feasibility and technical feasibility to be established in specific conditions of new machinery or equipment which as a rule require large capital investments.

At the current stage of development of domestic industry, the objective of replacing imported components and equipment is of particular relevance [2–5]. The legal regulation of industrial policy is based on the State Program "Development of Industry and Increasing its Competitiveness" (approved by the Decree of the Government of the Russian Federation No. 328 dated April 15, 2014)[1] and the Federal Law "On Industrial Policy in the Russian Federation" (No. 488-FZ dated December 31, 2014)[2]. At the same time, these documents provide not just for the replacement of imported components and equipment with domestic ones in the domestic market, but for the improvement of the quality of these components and equipment, in order to increase competitiveness in foreign markets.

In the current realities, the approach to import substitution has changed significantly. Starting from the spring of 2022, an impressive list of new legislative bills and a number of amendments to existing regulatory documents have been adopted with the objective of stimulating the domestic market. These include:

1. Decree of the Government of the Russian Federation of December 28, 2022, No. 2461 "On Amending Decree of the Government of the Russian Federation of November 16, 2015, No. 1236 and Annulling Certain Provisions of Certain Acts of the Government of the Russian Federation"[3];
2. New edition of the Decree of the Government of the Russian Federation of December 03, 2020 No. 2014 (ed. of February 28, 2023) "On the minimum mandatory share of purchases of Russian goods and its achievement by the customer"[4];
3. Amendments to the Decree of the Government of the Russian Federation of December 03, 2020 No. 2014 "On the minimum mandatory share of purchases of Russian goods and its achievement by the customer"[5];
4. Decree of the Government of the Russian Federation No. 522 dated December 31, 2022 "On Amendments to the Rules for Granting Subsidies from the Federal Budget to the Autonomous Non-Profit Organization "Agency for Technological Development" to Support Projects Involving the Development of Design Documentation for Component Products Required for Industries"[6], etc.

[1] State Program "Industry Development and Competitiveness Enhancement" (approved by Decree of the Government of the Russian Federation No. 328 dated April 15, 2014). http://government.ru/docs/all/91634/. Accessed March 31, 2023 (in Russ.).

[2] Federal Law "On Industrial Policy in the Russian Federation" No. 488-FZ dated December 31, 2014 (latest version). http://publication.pravo.gov.ru/document/0001201412310017. Accessed March 31, 2023 (in Russ.).

[3] Decree of the Government of the Russian Federation dated December 28, 2022 No. 2461 "On Amending Decree of the Government of the Russian Federation No. 1236 dated November 16, 2015 and Annulling Certain Provisions of Certain Acts of the Government of the Russian Federation." http://publication.pravo.gov.ru/Document/View/0001202212300083. Accessed March 31, 2023 (in Russ.).

[4] Decree of the Government of the Russian Federation No. 2014 dated December 03, 2020 "On the minimum mandatory share of purchases of Russian goods and its achievement by the customer" (as amended as of February 28, 2023). https://docs.cntd.ru/document/573031324. Accessed March 31, 2023 (in Russ.).

[5] Decree of the Government of the Russian Federation No. 2014 dated December 03, 2020 "On the minimum mandatory share of purchases of Russian goods and its achievement by the customer" (as amended and supplemented). https://base.garant.ru/75016819/. Accessed March 31, 2023 (in Russ.).

[6] Decree of the Government of the Russian Federation No. 522 dated March 31, 2022 "Concerning the Introduction of Amendments to the Rules for Granting Subsidies from the Federal Budget to the Autonomous Non-Profit Organization "Agency for Technological Development" for the Support of Projects Involving the Development of Design Documentation for Component Products Necessary for Industries." http://publication.pravo.gov.ru/Document/View/0001202204040037. Accessed March 31, 2023 (in Russ.).

The regulatory and legal documents referred to above indicate the need to produce domestic products, particularly in industries with a high share of imports (mechanical engineering, medicine, etc.).

In the current geopolitical situation, the issue of import substitution of components and equipment are of particular relevance for such a unique Russian industrial enterprise as the Lytkarino Optical Glass Factory (LZOS in Russian abbreviation).

At present, LZOS produces optical glass and glass fiber, large-size astronomical and space mirrors, space lenses, various optical parts and devices. The enterprise has its own scientific and technical center which is constantly developing new types of products and relevant technologies. At present, the development of the enterprise is based on the projects for the modernization and technical re-equipment of glass-making and optical-mechanical production facilities.

Since 2014, in order to obviate the purchase of imported components, spare parts, equipment and services, a number of projects have been implemented in LZOS:

1. Technical re-equipping with the establishment of a competence center for the development of technology for the production of special glasses and optical parts;
2. R&D work "Technology development and manufacturing of the precision matrices made of astrositall CO-115M for the panels of the main mirror of the Millimetron Observatory";
3. R&D work "Development of automated technologies for manufacturing blanks from optical colorless and colored glass by hot and cold processing methods";
4. R&D work "Development of technology for automation of optical glassmaking production";
5. R&D work "Development and production of a set of lens mirrors for the Zorkii optical station".

The active implementation of in-house designs, as well as the acquisition and implementation of domestically manufactured equipment has enabled LZOS to expand the product range and launch new products. The following objectives were set: development and production of competitive products with a higher potential for growth of own production; efficient use of limited resources; and cheaper production with optimal product quality.

METHODS

The study uses the example of the development project "Design and manufacture of a set of mirrors of the lens of the Zorkii optical station" implemented at LZOS to substantiate the possible effects of the introduction of the KP-119 interferometer (developer LZOS, Russia) for the control of off-axis aspherical surfaces.

The main results (effects) of the incorporation of the KP-119 device in production activities, both internal and external (Fig. 1), is highlighted here. This branching is due to the fact that the measurement of phenomena pertinent to economic relations simultaneously constitutes the subject of research of economic sciences, while also representing the object of metrology measurements [6].

The internal effects are related to the functioning of the plant and are aimed at increasing its potential. They can reasonably be divided into the following areas: development of the plant's potential and socioeconomic effects.

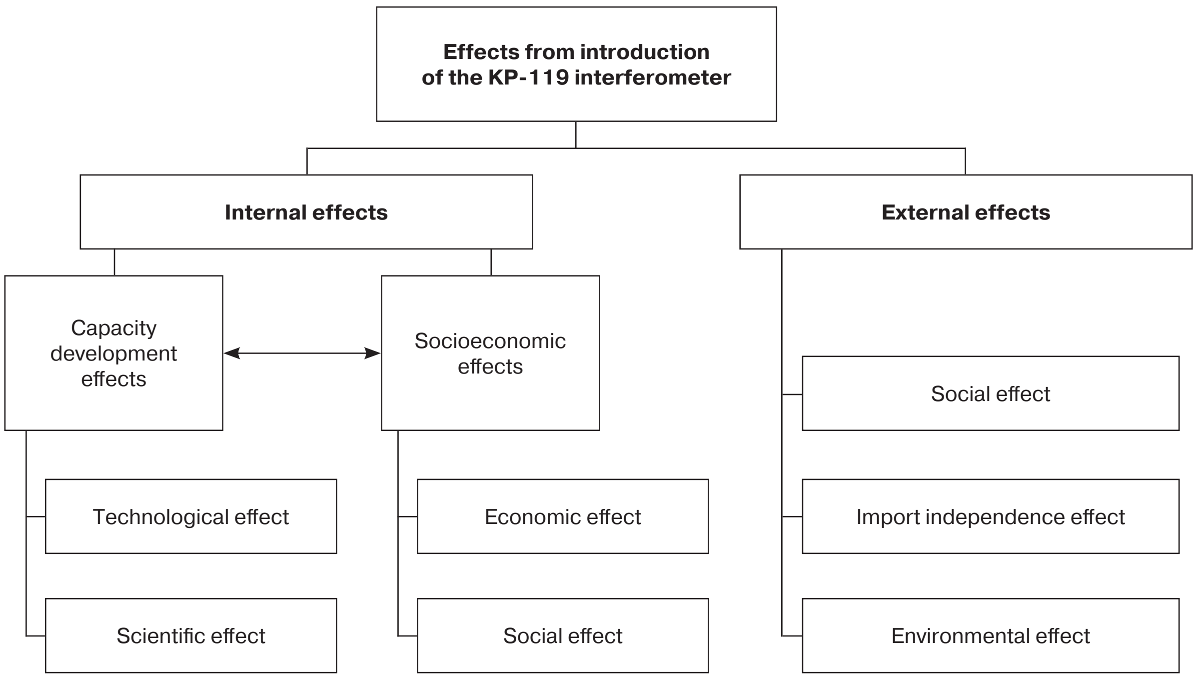

Fig. 1. Effects manifested by the introduction of the KP-119 interferometer

In turn, the effects of plant capacity development can be divided into two types: technological and scientific. The technological effects are conditioned by the availability of new machinery or equipment with better characteristics when compared to existing means of production (resource saving, including energy saving, productivity and reliability). The scientific effects consist in the accumulation of new knowledge and are conditioned by the scale of novelty of the newly introduced device, patentability and prospects of the idea.

Acceleration of the production cycle, reduction of production costs and increased investment will undoubtedly lead to an increase in the financial and economic performance of the enterprise, and to positive economic effects. The increasing value of intangible assets will indicate not only the innovative nature of the project, but also provide economic security and technological sovereignty of the organization. In turn, the social effect from the introduction of new technology will also lead to an improvement in the working conditions of employees and economic conditions.

The internal effects of enterprise potential development and socioeconomic effects are diverse, yet interrelated.

The external effects can be seen in the positive benefits for third parties not involved in the process of introduction and operation of new techniques and equipment, as well as for society as a whole. The public effect from the incorporation of the KP-119 device into production activities can be seen in the impact on social processes, increased capacity of related industries, as well as in the creation of prerequisites for secondary innovations. The effect of import-independence can also be seen in the strengthening of national security and national interests. This can be summed up as the localization of production of machinery and equipment in the territory of the Russian Federation, reduction of the share of imported components and materials in the production of own products. The environmental effect is associated with the improvement of the environment, for example, saving the use of natural resources, reducing the negative impact on the environment.

The external effects are characterized by interconnectedness and are aimed at a long-term perspective, including in related industries.

In terms of composition, the indicators of various effects can vary depending on the nature of technology and equipment introduced. In order to assess the effects of the introduction of the KP-119 interferometer for the control of off-axis aspherical surfaces, an original system of indicators needs to be developed. This system needs to include both quantitative and qualitative indicators. Quantitative indicators are used to establish measurable results and are used for quantitative evaluation. Qualitative indicators allow qualitative parameters to be evaluated on the basis of expert methods.

The selection of indicators was carried out on the basis of the scientific principles set out in the works of R. Kaplan and D. Norton [7–9]: visibility, tree structure of the system and reliability of information. Following these principles, the system of indicators is further divided into projections characterizing various aspects of the development of the research object. The number of indicators in the system should not exceed 30–35, and their number in one projection should be 3–7. At the same time, the indicators of effects are not the current values of indicators, but their changes (the values of indicators before and after the introduction of the interferometer are studied).

Analysis of the effects of the introduction of the KP-119 device was based on a comparison of indicators before and after its introduction. The approach to the comparative analysis of key indicators used to measure the effect of the introduction of the KP-119 device was based on the use of normalized indicators. These are relative indicators which reflect the changes in the values of indicators before and after the incorporation of the KP-119 device in the production activities of the enterprise.

The choice of such an approach is conditioned by the following considerations. First, the use of such indicators allows us to assess the change of complex phenomena in dynamics. Second, the use of indicators enables various types of comparative analysis (temporal, spatial, comparison with a benchmark, forecast, etc.) to be conducted. Third, the use of relative values allows us to analyze indicators in the same axes in a single graph (for example, using bar histograms or petal charts). It also enables integral indicators to be calculated for the study of generalized effects or synthesized indicators of the system state, Thus, this paper proposes to apply the normalization of the initial system indicators on a single dimensionless scale.

One result of the effects of the implementation of the KP-119 device is that the indicators characterizing these effects can be divided into positive and negative as per tradition. In order to increase the effects of the project, positive indicators should be maximized, and negative minimized.

In order to translate the initial data into dimensionless indicators, we will use the following formalized expression [10]:

$$y_{ij} = \begin{cases} 2^{-\frac{K_{ij0}}{K_{ij1}}} \text{ – for positive indicator,} \\ 2^{-\frac{K_{ij1}}{K_{ij0}}} \text{ – for negative indicator,} \end{cases} \quad (1)$$

where i is the number of the projection of the system of indicators; j is the index of the indicator within the projection; K_{ij0} and K_{ij1} are the values of the jth indicator of the effect of the ith projection before and after the introduction of the device KP-119. After calculation of the normalized index, all indicators become positive and change within the interval [0; 1].

Thus, the value of the normalized indicator y_{ij} is interpreted as follows. If $y_{ij} = 0.5$ ($K_{ij0} = K_{ij1}$), there is no growth in this indicator. If $y_{ij} > 0.5$, then growth in this indicator can be recorded. Finally, if $y_{ij} < 0.5$, there was a decrease in the value of the indicator.

After the procedure to calculate the normalized indices, an integrated indicator for assessing the effects of the introduction of the KP-119 device can be calculated. The use of generalized indicators also allows for key aggregated trends to be studied both in individual projections of the project and for the entire set of characteristics under study. In this case, a variety of approaches to the calculation of the generalized characteristic and the choice of weighting coefficients when performing the convolution [11–13] can be applied. In this study, the approach used was based on the calculation of the integrated indicator as the sum of normalized indices taking into account their weighting coefficients according to the following formula:

$$\begin{cases} \Omega = \sum_{i=1}^{n} \left(\sum_{j}^{m_i} y_{ij} w_j \right) w_i, \\ \sum_{j=1}^{m_i} w_j = \sum_{i=1}^{n} w_i = 1, \end{cases} \quad (2)$$

where n is the number of projections in the system of indicators; m_i is the number of indicators in the ith projection; w_j is the weight coefficient of the indicator significance in the system; w_i is the weight coefficient of the projection significance. The integrated indicator, as well as normalized indices, can vary from 0 to 1. The value of 0.5 is also accepted as a threshold (criterion) value for the integrated indicator separating the positive effect from the negative one. This is justified by the fact that with $\Omega < 0.5$ there is a generally negative dynamics of indicators, and with $\Omega > 0.5$ there is a positive one.

The principles of analysis, synthesis, decomposition and integration, which are known and successfully used in theory and practice, lie at the root of the effects assessment tool presented in this article [14]. The use of normalized indices and generalized indicators allows conclusions to be drawn about both individual effects in the development of the system and the integral effect of the project implementation as a whole.

RESULTS

According to the methodology described herein for selecting indicators, the entire system of indicators for assessing the effects of the introduction of the KP-119 interferometer for the control of off-axis aspherical surfaces can be divided into two projections. These two projections reflect the internal and external effects of the incorporation of the project into the production activities of the enterprise. In turn, the "Internal effects" can be divided into subsystems of indicators related to technological, scientific and socioeconomic effects. Further by analogy, each subsystem can be detailed by indicators which characterize the individual effects from the implementation of the KP-119 device.

When calculating the qualitative indicators, individual assessment of indicators was performed by individual experts each acting independently [15]. The expert group consisted of qualified representatives of LZOS (managers of the enterprise, employees of the "Optical Systems and Technologies" department of RTU MIREA, engineers and project managers). The experts established the statistical characteristics of the indicators according to a ten-point system (0 – no effect, 10 – maximum effect from the implementation of the device KP-119). Subsequently, the sum of the scores assigned by the experts and the arithmetic mean of the indicators were calculated. Thus, qualitative indicators were translated into quantitative ones.

The following table shows the composition of the system of indicators for assessing the effects from the implementation of the KP-119 device. The indicators take into account the specifics of the project and modern realities, calculation formulas and economic content of each indicator. Here, it is not the indicators per se which are of scientific interest, but their combination. Of interest also is the methodology of establishing a generalized index to determine the integrated assessment of the effect of the project implementation.

Table. System of indicators for assessing the effects of the introduction of the KP-119 interferometer

Indicator	Calculation formula	Methodological explanations
Internal effects		
1. Technological effect		
1.1. Resource saving indicators		
1.1.1. Energy capacity	$K_{111} = W/Q$, W is the total volume of consumed energy sources (electricity, heat energy, process fuel, etc.) for the product production; Q is the amount of products produced during the calculation period	Indicates the expenditure of energy (energy resources and energy carriers) on the production of a unit of the product
1.1.2. Resource capacity	$K_{112} = TC/Q$, TC is the total production costs	Indicates the cost of resources (in monetary terms) to produce a unit of the product
1.1.3. Duration of operations performance by the production workers when producing a unit of the product	$K_{113} = \sum_{i=1}^{n} t_i \, / \, n$, t_i is the duration of the ith operation, set according to timekeeping observations; n is the total amount of operations	Indicates the time spent on individual production processes in the production of a unit of the product
1.1.4. Yield of usable products	$K_{114} = QG/SR$, QG is the quantity of the used products produced during the calculation period; SR is the scope of the actually consumed raw materials	Indicates how efficiently raw materials are used, as well as characterizes the technical and organizational level of the technical process
1.2. Performance indicators		
1.2.1. Equipment performance	$K_{121} = Q/T$, Q is the scope of the produced products; T is the total operating time of the equipment	Indicates the scope of a product (work) produced per unit of time
1.2.2. Labor efficiency	$K_{122} = QS/R$, QS is the scope of the produced output in financial (value) terms; R is the number of workers producing products	Indicates how efficiently a worker (or group of workers) has invested his or her labor to create a unit of the product
1.2.3. Resource utilization factor	$K_{123} = FQ/TC$, FQ is the actual amount of resources; TC is the total capacity (maximum amount of utilized resources)	Indicates the degree (intensity) of the resource utilization
1.3. Reliability indicators		
1.3.1. Mean time between failures (failure-free operation)	$K_{131} = \sum_{i=1}^{m} t_i \, / \, m$, t_i are the time intervals of the equipment failure-free operation; m is the number of the equipment failures that occurred during the calendar period under consideration	Is a statistical measure and is used to predict behavior as the probability of equipment failure-free operation in a given period of time
1.3.2. Technical service life (durability)	$K_{132} = T_{resource}$, $T_{resource}$ is the technical resource of equipment (reserve)	Characterizes the reserve of a possible operating time of the equipment (time) from the beginning of its operation or resumption of its operation after repair to the onset of its limit state or overhaul to ensure its serviceability within a certain period of time

Table. Continued

Indicator	Calculation formula	Methodological explanations
1.3.3. Average restoration time (maintainability)	$$K_{133} = \frac{1}{n}\sum_{i=1}^{n} t_i,$$ n is the number of restorations; t_i is the time spent on restoration (detection, search for the cause and elimination of failure)	Characterizes the mathematical expectation of the time of restoration of the operable state of the object after failure
1.3.4. Price of reliability	$$K_{134} = Z_{pr} \cdot \left(\frac{NA}{NA_o}\right)^{\alpha},$$ Z_{pr} is the price of reliability of the prototype (analog); NA and NA_o are the mean time between failures or average service life of the equipment and the prototype; α is the empirical indicator characterizing the level of production, usually $\alpha \approx 0.5–1.5$	Indicates how many times the cost to the plant due to unreliable equipment exceeds the cost of production or how much of the cost of production is due to unreliable equipment or how much of the cost of operation is due to unreliable equipment
2. Scientific effect		
2.1. Prospects for further development	$$K_{21} = \sum_{i=1}^{N} K_{21i} / N,$$ K_{21i} is the score (from 1 to 10) of the *i*th expert; N is the number of experts participating in the survey	Indicates the potential of the underlying idea for further development at the plant. It is calculated according to expert assessments
2.2. Novelty	$$K_{22} = \sum_{i=1}^{N} K_{22i} / N,$$ K_{22i} is the score (from 1 to 10) of the *i*th expert; N is the number of experts participating in the survey	Indicates the level and scale of novelty of the installation, its components; as well as superiority over analogs. It is calculated according to expert assessments
2.3. Patentability	$$K_{23} = \sum_{i=1}^{N} K_{23i} / N,$$ K_{23i} is the score (from 1 to 10) of the *i*th expert; N is the number of experts participating in the survey	Indicates the protectability and prospects for patenting. It is calculated according to expert assessments
3. Economic effect		
3.1. Production cost	$$K_{31} = \sum_{i=1}^{n} Z_i,$$ n is the number of cost items; Z_i is the sum of a specific cost	It is formed taking into account the costs associated with the production and output of a unit of the product
3.2. Carrying value of the equipment	$$K_{32} = S - A - Ob,$$ S is the carrying value of the equipment, including acquisition, delivery, installation, cost of new units; A is the amortization; Ob is the depreciation	Indicates the carrying value of the equipment. After modernization, the carrying amount of the equipment is to be recalculated
3.3. Cost of intangible assets	$$K_{33} = NA,$$ NA is the carrying value of intangible assets	Indicates the value of objects that have no tangible, physical form and are intended for use in the production process

Table. Continued

Indicator	Calculation formula	Methodological explanations
	4. Social effect	
4.1. Number of jobs reconstructed/created	$K_{41} = Rm$, *Rm* is the number of jobs reconstructed/created as a result of equipment implementation	Indicates the number of reconstructed/created jobs where the new/modernized equipment is used
4.2. Index of salary level at reconstructed/created jobs	$K_{42} = a/a_{av}$, *a* is the average salary level of at the jobs being reconstructed/created; a_{av} is the average salary level in the region	Indicates the ratio of the average salary level of the jobs being reconstructed/created to the average salary level in the region
4.3. Employees satisfaction with working conditions	$K_{43} = \sum_{i=1}^{N} K_{43i} / N$, K_{43i} is the score (from 1 to 10) of the *i*th expert; *N* is the number of experts participating in the survey	Indicates employee satisfaction with working conditions. It is calculated according to expert assessments
4.4. Development/ optimization of the production and organizational processes	$K_{44} = \sum_{i=1}^{N} K_{44i} / N$, K_{44i} is the score (from 1 to 10) of the *i*th expert; *N* is the number of experts participating in the survey	Indicates how efficiently production and organizational processes function during equipment operation. It is calculated according to expert assessments
	External effects	
	5. Social effect	
5.1. Potential for development of the related industries	$K_{51} = \sum_{i=1}^{N} K_{51i} / N$, K_{51i} is the score (from 1 to 10) of the *i*th expert; *N* is the number of experts participating in the survey	Indicates the prospects for the development of related industries as a result of the development of the idea, novelty of the installation, its components. It is calculated according to expert assessments
5.2. Prerequisites for secondary innovations	$K_{52} = \sum_{i=1}^{N} K_{52i} / N$, K_{52i} is the score (from 1 to 10) of the *i*th expert; *N* is the number of experts participating in the survey	Indicates the prospects for further development of the idea/equipment and its components. It is calculated according to expert assessments
	6. Import independence effect	
6.1. Import dependence level	$K_{61} = \frac{Q_{subst}}{Q_{total}}$, Q_{subst} is the scope of imported products/equipment/technologies; Q_{total} is the total current scope of consumption or use of products/equipment/technologies in the process of functioning enterprises	Indicates the proportion of imported products/equipment/technology in the total volume of products/equipment/technology
6.2. Production localization ratio	$K_{62} = (P_{selling} - P_{imp})/P_{imp}$, $P_{selling}$ is the selling price of the product; P_{imp} is the price of the imported components, parts, and materials	Indicates the ratio of the difference between the selling price of the product and the price of the imported components, parts and materials to the selling price of the final product

Table. Continued

Indicator	Calculation formula	Methodological explanations
7. Environmental effect		
7.1. Index of environmental innovations introduction	K_{71} is derived from the Form 4-Innovation (Section 16)[7] and is defined as the sum of code "1" in lines 1101–1110 divided by 10	The index varies from 0 to 1 (0, no environmental innovation; 1, maximum level of its effectiveness)
7.2. Environmental legislation compliance index	K_{72} is derived from Form 4-Innovation (Section 16)[8] and is determined as the sum of code "1" in lines 1111–1117 divided by 7	The index varies from 0 to 1 (0, no environmental regulatory compliance; 1, maximum level of compliance)

Source: developed by authors.

[7] Order of the Federal State Statistics Service No. 538 dated July 29, 2022 "On Approval of Federal Statistical Observation Forms for Organization of Federal Statistical Observation of Activities in the Sphere of Education, Science, Innovation and Information Technology." Form No. 4-innovation "Information on innovation activity of the organization." https://docs.cntd.ru/document/351745217. Accessed March 31, 2023 (in Russ.).

[8] Ibidem.

Figure 2 shows the values of normalized indexes of the effects from the introduction of the KP-119 device, obtained by formula (1) by comparative comparison of data on the indicators presented in the table before and after the introduction of the device. The calculation period of indicators amounted to one year. Price indicators were calculated taking into account the discount rate.

The last line of the figure shows the result of calculation of the generalized indicator of the effect from the introduction of the KP-119 interferometer. Weighting coefficients in calculations of the integral indicator were chosen by experts.

Analysis of the values of normalized indicators allows the following conclusions to be drawn:

1. The values of most indices exceeded the value $y = 0.5$, which indicates positive effects from the introduction of the KP-119 interferometer for the control of off-axis aspherical surfaces.
2. Some indices were below the reference level $y = 0.5$. These include the indices of resource intensity, environmental innovation and production costs.
3. The value of the generalized index calculated by formula (2) turned out to be equal to $\Omega = 0.57$, indicating a positive integral effect obtained from the introduction of the interferometer.

CONCLUSIONS

The article presents the author's methodology for the integrated assessment of a production system development project. A system of indicators for the integrated study of the effects obtained from the project of implementation of a new device within the framework of the import substitution policy was developed, in

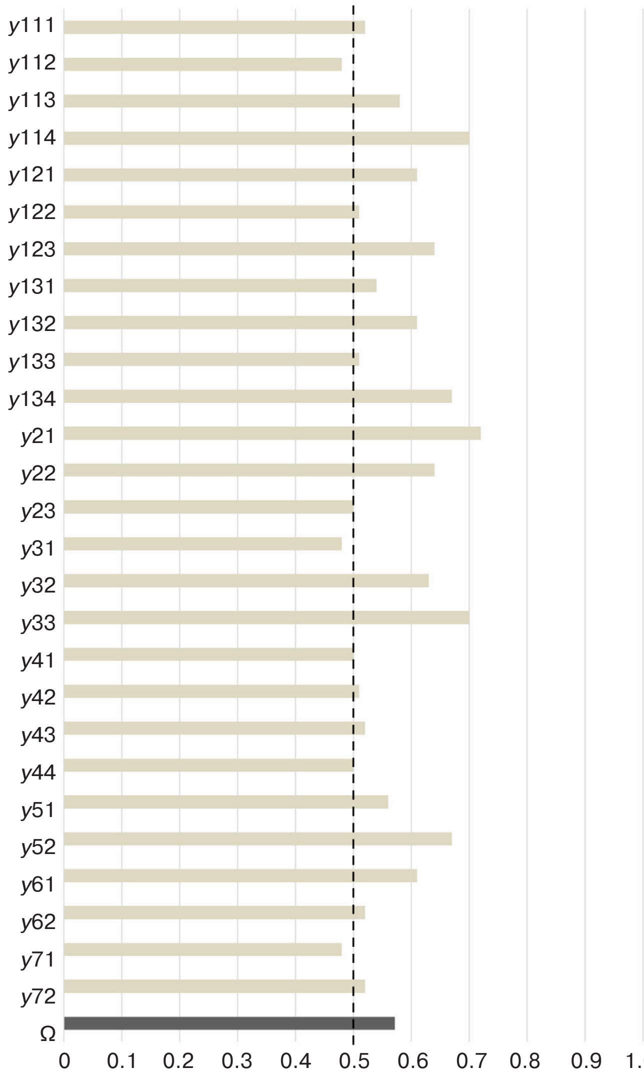

Fig. 2. Normalized indices of estimation of effects from the introduction of the KP-119 interferometer

order to obtain a synthetic assessment. The system of indicators is characterized by the various effects of the introduction of machinery and equipment (internal and external effects of different nature: capacity development, socioeconomic, import-independence, social, environmental). It also involves a comparison of quantitative values of indicators calculated before and after the incorporation of the project into the production system.

Confirmation of the results was based on the example of the "Development and manufacture of a set of lens mirrors of the Zorkii optical station". This project was undertaken at LZOS, consisting of the introduction of the KP-119 interferometer for the control of off-axis aspherical surfaces, and demonstrated a positive integrated effect.

The proposed methodology of integrated assessment of the effects of the introduction of a new device is to a certain extent universal and can be adapted to the scientific, technical and technological projects of any industrial enterprise. However, in order to assess the feasibility of the import substitution project, the rationality of integrating a new device into the production and technological value chain also needs to be analyzed. Thus, further development of the system of indicators needs to be associated with the addition of indicators to enable assessment of the impact of the project on the development of the production system as a whole, the reduction of dependence on imported equipment, the quality of manufactured products, total costs and the cost of manufactured products. These indicators will make it possible for the effects obtained from the import substitution project to be assessed.

Authors' contributions

M.A. Abdulkadyrov—presentation of data for calculations, scientific editing.

A.N. Ignatov—presentation of data for calculations, scientific editing.

N.N. Kulikova—the idea of the study, literature analysis, development of a system of indicators, writing and editing the text of the article.

E.S. Mityakov—literature analysis, development of calculation methods, research, preparation of graphic materials, writing and editing the text of the article.

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RESEARCH ARTICLE

Semantic features of complex technosocial systems: On the taxonomy of artificial intelligence technological packages

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Abstract
Objectives. The aim of this work is to enhance the scientific and methodological apparatus of artificial intelligence (AI) sciences by enriching their conceptual framework. The current conceptual framework of AI sciences does not reflect the intricate nature of this technological and socioeconomic phenomenon as possessing the diverse range of capabilities and the interconnectedness that allows for the imitation of human cognitive functions and comparable results. The author of the article structures the concept of the technological package of AI, describing its system properties, connections and functional elements based on the various types of human cognitive and operational activities.
Methods. The research is based on the concept (method) of technological packages—genetically and functionally connected sets of technologies with system properties.
Results. For the first time in Russian and international practice, the basic (general) taxonomy of the AI technological package has been specified and structured. A taxonomy of the AI metatechnological package (a package of metatechnologies) has been proposed. General taxonomy can serve as a tool for improving strategies, methodological documents and state programs to define the development of AI systems at state or industry level.
Conclusions. The suggested basic (general) taxonomy of technological package and taxonomy of metatechnologies package allows research to move away from the limited view of AI. It increases semantic and methodological clarity in relation to AI as a complex technosocial phenomenon and contributes to the harmonized integration of AI systems into the sphere of socioeconomic activities of the state. It can thus serve as a foundation for further improvement of state economic and legal regulation of AI development.

Keywords: artificial intelligence, information and communication technologies, technosocial systems, technological packages, meta-technological packages

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НАУЧНАЯ СТАТЬЯ

Семантические особенности сложных техносоциальных систем: к вопросу о таксономии технологического пакета искусственного интеллекта

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Резюме

Цель. Целью работы является совершенствование научно-методологического аппарата наук об искусственном интеллекте (ИИ) за счет обогащения их понятийного аппарата. Применяемый в настоящее время понятийный аппарат наук об ИИ не отражает сложной специфики данного технологического и социально-экономического феномена, как обладающего комплексом возможностей и соответствующих им взаимосвязей, позволяющих имитировать когнитивные функции человека и получать сопоставимые с ними результаты. С этой целью автор статьи структурирует понятие технологического пакета ИИ, описывая его системные свойства, связи и функциональные элементы сообразно видам мыслительной и деятельностной активности человека.

Методы. Исследование основано на концепции (методе) технологических пакетов – генетически и функционально связанных совокупностей технологий, обладающих системными свойствами.

Результаты. Впервые в отечественной и зарубежной практике уточнена и структурирована базовая (общая) таксономия технологического пакета ИИ, а также предложена таксономия метатехнологического пакета (пакета метатехнологий) ИИ. Общая таксономия может служить в качестве инструмента совершенствования стратегий, методологических документов и государственных программ, определяющих развитие систем ИИ на государственном или отраслевом уровне.

Выводы. Предложенные базовая (общая) таксономия технологического пакета и таксономия пакета метатехнологий позволяют отойти от редуцированного представления об ИИ, повышают семантическую и методологическую ясность в отношении ИИ как сложного техносоциального феномена и способствуют гармонизации интеграции систем ИИ в сфере социально-экономической деятельности государства, могут стать основой для дальнейшего совершенствования государственного экономического и правового регулирования развития ИИ.

Ключевые слова: искусственный интеллект, информационно-коммуникационные технологии, технологические пакеты, техносоциальные системы, метатехнологические пакеты

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Автор заявляет об отсутствии конфликта интересов.

GLOSSARY

Artificial Intelligence—the property of intelligent technological systems to perform creative functions that have traditionally been considered the prerogative of humans.

Taxonomy of technological package—systematized representation of key functional elements of technological package.

Technological independence—a set of measures aimed at the provision, development, and retention within the Russian Federation of human, financial, technological, and material potential aimed at the development of Russian industry, including through the predominant use of Russian industrial products, materials, raw materials, and technologies.

Technology package—a genetically and functionally related set of technologies that possess system properties. The technologies included in the package are interdependent, develop together and modify each other in the process of development.

Meta-technology package—a genetically and functionally related set of technologies that are influenced by the external environment. These technologies work together to transform the environment from its initial state to its final state.

INTRODUCTION

Artificial intelligence (AI) technologies at their current stage of development are becoming increasingly important in almost all areas of human activity. Not limited only to new products and services, AI has a transformative impact on established systems of economic, labor, social, and cultural relations [1].

Particularly in the economy, the introduction of AI systems can help to improve labor productivity, increase the efficiency of business processes and reduce costs. This, in turn, can lead to the creation of new markets and opportunities for accelerating economic growth. However, the introduction of AI can also significantly increase the risks of increased turbulence in the labor market by replacing professions that are by no means hard and unpopular, but are considered quite prestigious in society. Such an example can be seen in the capabilities of the ChatGPT-4 neural network in programming, technical writing, copywriting, and data analysis [2].

In the social sphere, the introduction of AI can lead to both the reduction of inequality, providing equal access to education, healthcare and other essential services, or, on the contrary, to an even greater exacerbation of social inequalities [1]. In modern socioeconomic conditions, AI technologies are a scarce resource due to their complexity and relatively low prevalence. However, their importance and demand are expected to increase. This circumstance can lead to a drastic escalation of social inequality, not only in terms of access to AI technologies and services, but also in terms of other essential resources, such as electricity and Internet communication, etc.

Thus, AI as a transformative technology creates technological tension: a misalignment of technological imperatives and social practices accepted in society [3]. Since these practices are deeply rooted, their forced change may result in innovative resistance in society [4]. This contradictory aspect of the adoption of new digital technologies indicates that the development of AI requires a comprehensive approach. This will involve analyzing and forecasting of potential social, economic, and cultural outcomes, risks and threats. It will also involve development of strategies and state programs to ensure the harmonious integration of AI systems into society. In this regard, it must be recognized that the current dominant view of AI in socioeconomic sciences and public administration lacks integrity at both the explanatory (concepts, principles, and semantic models) and impact (practices, methods, organizational, and activity models) levels.

The National Strategy for the Development of Artificial Intelligence until 2030 defines artificial intelligence as a set of technological solutions that enable the imitation of human cognitive functions, including self-learning and problem-solving without a predetermined algorithm. These solutions aim to achieve results that are at least comparable to those of human intellectual activity when performing specific tasks.[1] Nevertheless, in the practical sphere, AI is often understood either in a fragmentary way, i.e., as a set of unrelated ready-to-use “smart things” (tools) [5], or simplistically, as a universal and side-effect-free technological, economic, and managerial panacea [6]. Both examples of the reductionist approach to the understanding of AI contradict its nature as a complex multidimensional phenomenon that is constantly expanding its presence in more and more spheres of human activity at the individual and societal levels.

Reductionism, when applied to complex scientific and technological phenomena, greatly hinders accurate forecasting and planning for their development in order to promote economic growth and technological progress. Ultimately, it does not contribute to the harmonious adaptation of related innovations. Overcoming this circumstance requires a more effective methodological approach guided by the multidimensionality of AI. It is a complex scientific-technical, socioeconomic, and legal phenomenon that cannot be reduced to familiar examples of its applied use.

[1] Decree of the President of the Russian Federation dated October 10, 2019 No. 490 “On the development of artificial intelligence in the Russian Federation” (in Russ.). http://static.kremlin.ru/media/events/files/ru/AH4x6HgKWANwVtMOfPDhcbRpvd1HCCsv.pdf. Accessed May 23, 2023.

In this regard, this article refers to the concept (method) of technology package (TP) and applies it to AI by proposing a basic (general) taxonomy of AI TP. The methodological view of the AI TP as a package of technologies formulated in the article will allow the following actions to be performed:

- to structure the systems-relevant areas of integration of AI with humans at the individual and societal levels;
- to summarize the composition of the acts and systems of influences that AI has on these areas of systemic significance;
- to facilitate the harmonization of the concept of AI as a complex, multidimensional, and holistic phenomenon in both methodological and legal domains.

Previously, in Russian and international practice, the approach of considering AI as TP was not applied. This led to the aforementioned diminished understanding of AI, hindering the attainment of semantic clarity with respect to this phenomenon. The novelty of this article is based on the first attempt in Russian and international practice to structure the concept of AI TP. It describes the system properties, connections, and functional elements as a set of technological solutions that enable the imitation of human cognitive functions.

METHODS

In Russian scientific literature, TP is considered a genetically and functionally interconnected set of technologies and scientific and technical solutions with systemic properties [7]. The technologies included in the package are interdependent, developed together, and mutually modify each other during the development process. It is argued that TP, as a rule, fulfills one of the socially important needs [8]. In the context of AI, this requirement can be defined as the transfer of creative tasks, typically performed by humans, to intelligent systems. The aim is to lower labor expenses and enhance the effectiveness of carrying out these tasks by leveraging the capabilities of intelligent systems. This circumstance puts forward special requirements for the configuration of AI TP, emphasizing its human dimensionality (proportionality to a person). It also requires that the content and functionality of AI TP align with the values of individuals and society as both individual and collective subjects [9]. The human dimensionality in relation to AI necessitates the development of technological and humanitarian support to ensure consistent and harmonious interaction between AI and humans in all aspects of human life. Ultimately, this will lead to the convergence of human and AI capabilities within a single sociotechnological environment.

Let us try to structure the components of AI TP. As noted earlier, TP is a genetically and functionally related set of technologies with systemic properties. At the same time, TP elements should have interdependence and develop together, with the potential for mutual modification during the development process. TP has the following key structural elements: basic technology; basic ontologeme; closing technology; basic infrastructure; basic institutions (Fig. 1) [10, 11]. Let us consider them in more details.

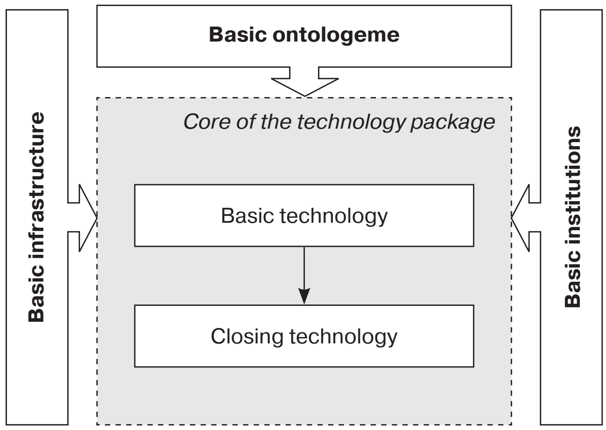

Fig. 1. TP key structural elements

Basic technology refers to the technology that enables the implementation of TP, which is the result of its development. With respect to AI, the underlying technology is machine learning, particularly deep learning [12, 13]. These technologies utilize sophisticated algorithms and neural networks to train AI systems and detect patterns in vast amounts of data. Machine learning and deep learning have now become the foundation for the advancement of various AI domains, including computer vision, natural language processing, and predictive analytics systems.

The basic ontologeme is a theoretical concept underlying TP. In other words, it is an idea that underlies the package notions. The basic ontologeme of AI is the ability to assign creative functions, which have traditionally been associated with humans, to intelligent systems. The same ontologeme determines the human dimensionality of AI.

Closing technology is a physical or humanitarian technology that combines a set of loosely related technologies into a systematically organized package. With respect to AI, a closing technology may be the development of what is known as "general artificial intelligence." This may be a thinking system capable of having multiple specific goals, switching between them, changing and updating them, including in an arbitrary order [14]. Modern AI systems can outperform humans in specific tasks, but the ability to freely switch between goals and update them is still exclusive to humans.

Table 1. Taxonomy of the AI TP key structural elements

Pos. No.	Key structural elements	Characteristics	Content
1	Basic technology	Realizes the possibility of TP implementation	Machine learning, deep learning
2	Basic ontologeme	Theoretical idea behind TP and the perceptions of it	Possibilities for delegating the creative functions traditionally inherent to human beings to intelligent systems
3	Closing technology	Completes a set of initially loosely coupled technologies into a systematically organized TP	Artificial General Intelligence: a system that is capable of having multiple specific goals, with the ability to switch between them, change and update them, and do so in an arbitrary order
4	Basic infrastructure	Critical infrastructure for TP development, the ultimate form of its implementation	Cloud computing, supercomputing, integrated data storage and analysis systems, specialized hardware
5	Basic institutions	Institutional solutions behind TP	Scientific and educational organizations, technology companies, startups, independent teams, authorities, communication platforms, regulations, standards

Basic infrastructure is a crucial infrastructure for the development of technology at a specific stage of technological and societal progress. The basic infrastructure is, in many respects, the ultimate realization of the TP. For example, in the case of nuclear energy TP, these are nuclear reactors capable of producing energy and generating new fissile materials. For AI, the underlying infrastructure includes cloud computing, supercomputers, integrated data storage and analysis systems, and specialized hardware such as graphics processing units and tensor processing units, all connected through networks and containers. These infrastructure elements provide the capability to process and analyze the enormous volumes of data needed to train AI models and offer scalability for the development and deployment of associated intelligent systems. The ultimate realization of this infrastructure can be achieved through Artificial Global Superintelligence [15]. This concept involves the creation of an integrated network of self-learning algorithms and super-powerful computing systems that span the entire world and are accessible for universal use. This hypothetical structure will be capable of processing and managing complex tasks in real time, predicting and solving global problems, and supporting the self-development and scalability of continuously improving AI systems [16].

Basic institutions are the foundational decisions that underlie TP. Basic AI institutions take into account the human dimensionality of this technology and, in many respects, mirror the structure of almost all significant social institutions. Their list includes:

- scientific research organizations (universities, laboratories, R&D centers, etc.), technology companies and startups;
- open source innovations and creative communities (open source projects and independent development teams);
- government authorities and international organizations which develop and support AI development programs and standards. This list also includes institutional mechanisms and standards for data protection, which regulate the use of AI and ensuring the safety, security and transparency of AI technologies;
- educational institutions and programs to ensure the development of skills and competencies required to work with AI technologies, and to keep knowledge up-to-date to adapt to the rapid development of this field;
- institutions and platforms that foster public discourse on ethical, legal and social issues associated with AI and ensure the participation of diverse groups in a collaborative engagement with AI.

The above listed structural elements of the AI TP are presented in Table 1.

RESULTS

The concept of AI as a TP allows us to consider this complex scientific and technological phenomenon in its entirety, including its technological, infrastructural, institutional, and social interactions. In this case, AI develops a comprehensive understanding of semantics within the methodological and regulatory framework. According to its functionality and the nature of connections within the framework of the TP concept, AI is a *technosocial system* comparable to a human being, *demonstrating tendencies towards dynamic and* *nonlinear self-expansion*. The latter circumstance is due to the unique ability of AI as a technological object and non-trivial machine [17] to connect its own internal state in response to an external influence. First of all, this is expressed in the AI's ability for self-learning, such as machine learning and deep learning. It is this specificity of AI which requires further elaboration of its TP taxonomy. As noted earlier, AI is not a closed, isolated system. As a result of its self-learning nature which determines its dynamic development, AI is forced to be in a *state of reverse afferentation* [18]. It can adjust its behavior based on the information received from the surrounding technological and social environment. Receiving initial data from outside, AI, as a functional system, compares them with target settings (internal programs laid down by a human). Then, after analyzing them, it performs corrections to its activity (computational) acts. At the same time, a human being, in all of their interactions with AI and its service applications, functions as *a recipient of the outcomes generated by AI* [18]. In this capacity, *they do not act as an autonomous entity*, but rather *as a component within the functional system of AI*.

In this regard, it seems relevant to supplement the methodology of the AI TP by introducing the concept of metatechnology. Metatechnology is a technology that undergoes the effects of the external environment, transforming it from the initial state to the final state. In this case, the initial state is understood as our modern fragmented concept of AI, which consists of a collection of unrelated digital tools (things) with limited functionality. The final state is understood as AI that is equivalent to a human being, encompassing a wide range of human thought and activities. In other words, the ultimate goal of AI meta-technology is to create a cohesive system that includes various components such as systems, processes, and decision-making abilities. This system interacts with humans and has the power to significantly impact their lifestyle, thoughts, and actions. Furthermore, it has the potential to transform the way humans interact with both the social and technological environment (see Fig. 2).

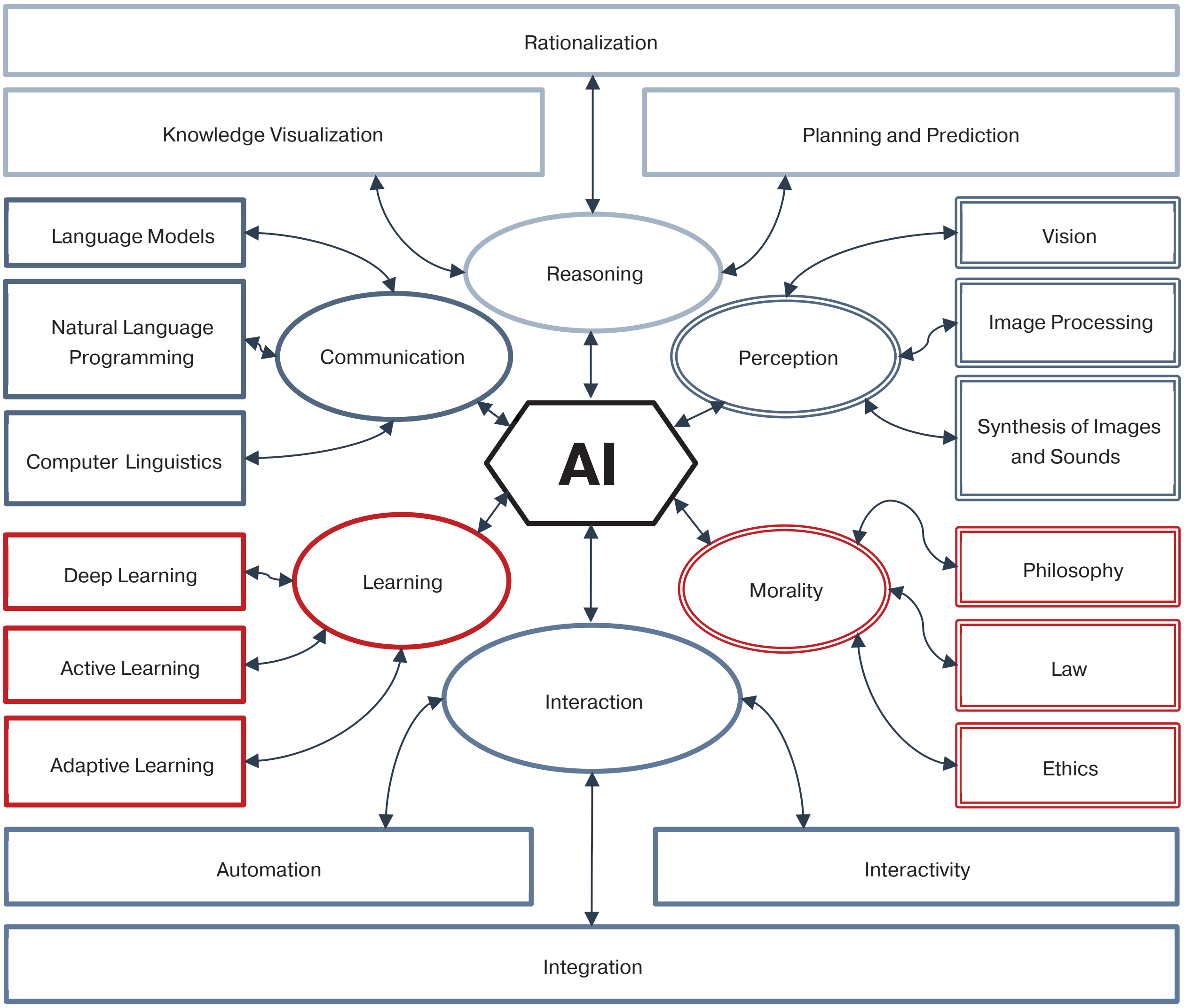

Fig. 2. AI in the space of the meta-technological connections

Table 2. Taxonomy of key structural elements of the AI meta-technology package

Functional element	Act of impact/interaction with a person	Key areas of the TP technological content
Reasoning	Knowledge visualization, automated reasoning, common sense reasoning	Case-based reasoning, inductive programming, causal inference, information theory, causal models, knowledge and reasoning representation
Planning	Planning optimization, search query processing	Bayesian optimization, hierarchical problem network, constraint satisfaction problems, metaheuristic optimization
Learning	Machine learning	Active learning, adaptive learning, generative adversarial network, generative models, deep learning
Communication	Interaction/programming in natural languages	Chatbots, natural language generation, computational linguistics, machine translation, conversational models
Perception	Computer vision	Action recognition, object recognition, face recognition
	Audio signals processing	Sound synthesis, speech recognition, sound source separation, speech synthesis
Integration and interaction	Multi-agent intelligent systems	Agent-based modeling, network intelligence, game theory, swarm intelligence, intelligent agents
	Automation and robotics	Cognitive systems, robotic systems, human-machine interaction
	Automated and automatic vehicles	Autonomous driving, unmanned systems, autonomous systems
Morality and ethics	AI ethics	Accountability, reliability, explainability
	AI philosophy	Philosophy of "weak (narrow) AI", philosophy of "strong (general) AI"

The taxonomy of the meta-technology package is designed to enable the transfer of creative functions, which have traditionally been performed by humans, to intelligent systems that operate on AI technological principles. Of course, at the current stage of systems development, it is not possible to delegate all the creative functions of a human being, whether as an individual or as a collective subject, to AI. The design of the meta-technology package deals with the fundamental functions that support the human creative process and creative communication. These functions include rationalization/planning, learning, communicative interaction, perception, activity interaction, and perception. Each of these functions can be easily associated with technological systems and AI components (Table 2).

The taxonomy of key structural elements of the AI meta-technology package incorporates:

- functional elements fully or partially associated with human creative functions: reasoning, planning, learning, communication, perception, integration and interaction, morality, and ethics;
- acts of influence/interaction of functional elements with humans: information and knowledge display, automated reasoning/rationalization, planning optimization, machine learning, natural language programming, computer vision, robotics and automation, integrated AI services, AI ethics;
- technological content allows for the performance of acts of influence or interaction between functional elements and a human being.

CONCLUSIONS

This study shows the need for AI to be moved beyond the narrow paradigm of its perception as a set of loosely coupled technological tools isolated from the multidimensional social context in which they can be applied. On the contrary, due to its ability for self-learning and its demonstration of limited tendencies towards self-development, AI should be viewed as an evolving complex technosocial phenomenon, as a technological package that includes technology, social relations, infrastructural elements, institutional support, among other factors.

This paper presents such a structured representation of AI for the first time in Russian and international practice.

At the same time, considering the intricate nature of AI as a set of technological solutions that mimic human cognitive functions and achieve comparable results to human intellectual activity in specific tasks, this study introduces and provides theoretical support for the concept of AI meta-technology.

It is deemed to be a technology which transforms under the influence of the environment and acquires a qualitatively new state, namely, the state of AI commensurate with a human being, included in the maximum number of types of human thought. The significance of this new concept is emphasized by the specificity of AI as a rapidly evolving phenomenon. At present, there is no finalized theoretical and methodological framework capable of encompassing all the features of AI.

Within the framework of the TP concept, AI inevitably acquires economic, social, legal, and cultural significance, becoming a truly cross-cutting technology that permeates practically all spheres of human life. This fact highlights the need for new requirements in the strategies, methodological documents, and state programs that govern the development of AI systems at both the state and industry levels. In the technosocial dimension, the AI development strategy should encompass all areas where it can be implemented, using a comprehensive multifactor model to assess the potential opportunities, risks, and threats associated with the introduction of this transformative technology.

The perception of AI as a package of technologies contributes to the holistic semantic representation of this technology in the methodological and regulatory legal environment. This will facilitate harmonized AI implementation at the state and sectoral levels. It will reduce technological tension in society and, consequently, alleviate certain social contradictions caused by the implementation of new technologies.

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RESEARCH ARTICLE

Architecture of distributed geoinformation technology for snow cover monitoring in circumstances of limited telecommunications accessibility

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Abstract

Objectives. Snow cover has a complex multifactorial impact on the environment as a link between global climatic processes and the system of the Earth's surface. Snow cover monitoring is one of the key tasks of hydrometeorology which also requires the systematic regular collection of its indicators. This work aims to develop an architecture of geoinformation technology for snow cover monitoring with the purpose of addressing the problem of automating the collection of snow cover indicators and their further maintenance. This architecture can also be used for other hydrometeorological monitoring tasks.

Methods. This paper analyzes the existing fundamental basis of snow cover data collection and uses the method of systems approach to describe the architecture of distributed geoinformation technology.

Results. The paper presents an architecture of distributed geoinformation technology focused on snow cover monitoring from measurements, data aggregation, and validation to their transfer to a centralized processing system. A prototype of portable user terminal modules for testing this technology is developed.

Conclusions. The proposed architecture is capable of functioning in circumstances of limited telecommunication availability, while ensuring data integrity control and personalization of responsibility by introducing an electronic signature of each measurement session. This architecture can be expanded by developing and implementing modules for other types of measurements.

Keywords: snow measuring route, snow measuring survey, data collection, geoinformation system, monitoring, geoinformation system architecture

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НАУЧНАЯ СТАТЬЯ

Об архитектуре распределенной геоинформационной технологии мониторинга снежного покрова, функционирующей в обстоятельствах ограниченной телекоммуникационной доступности

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Резюме
Цель. Снежный покров оказывает комплексное многофакторное влияние на окружающую среду, являясь связующим звеном между глобальными климатическими процессами и системой земной поверхности. Мониторинг снежного покрова является одной из ключевых задач гидрометеорологии, в рамках которого проводится систематический регулярный сбор его показателей. Целью работы является разработка архитектуры геоинформационной технологии мониторинга снежного покрова, комплексно решающей проблему автоматизации сбора показателей снежного покрова и их дальнейшего сопровождения, а также расширяемой для других задач гидрометеорологического мониторинга.
Методы. Используется метод анализа существующей фундаментальной базы в области сбора данных снежного покрова, а также метод системного подхода при описании архитектуры распределенной геоинформационной технологии.
Результаты. Разработана архитектура распределенной геоинформационной технологии, ориентированная на мониторинг снежного покрова, от выполнения измерений, агрегации данных и их валидации до их передачи в централизованную систему обработки. Разработан прототип модулей носимого пользовательского терминала, позволяющий провести апробацию данной технологии.
Выводы. Предложенная архитектура способна функционировать в обстоятельствах ограниченной телекоммуникационной доступности, а также обеспечивать контроль целостности данных и персонализацию ответственности за их получение путем введения электронной подписи каждого сеанса измерений. Данная архитектура может быть расширена путем разработки и внедрения модулей для других типов измерений.

Ключевые слова: снегомерный маршрут, снегомерная съемка, сбор данных, геоинформационная система, мониторинг, архитектура геоинформационной системы

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INTRODUCTION

Snow cover has a complex multifactorial impact on the environment. It is a link between global climatic processes and the Earth's surface system. It determines the following factors: magnitude of annual runoff; the level of spring flooding; the ice regime of rivers; the intensity of ice and avalanche processes; and the annual balance of glaciers [1]. The combined radiative, reflective and insulating properties of snow cover significantly reduce the arrival of shortwave radiation to the earth's surface. This impacts the climatic component and leads to air cooling and the formation of surface radiation temperature inversions [2, 3]. At the same time, by reducing heat losses to the atmosphere, it reduces soil freezing and the amplitude of temperature fluctuations, preventing the freezing of agricultural crops [4].

Snow cover is an indicator of atmospheric air pollution and subsequent pollution of soil, surface and groundwater [5]. This allows us to estimate the total pollution parameters in winter [6, 7]. In addition, snow cover provides water resources for a significant part of the Earth's population [8].

Therefore, snow cover monitoring is one of the key tasks of hydrometeorology, involving systematic regular collection of snow cover indicators such as:

- total snow cover height;
- distribution of snow cover density by its thickness;
- presence and concentration of admixtures: suspended solids, carbon oxide, nitrogen dioxide, hydrogen sulfide, phenol, toluene, xylene, benzene, formaldehyde, and benz(a)pyrene.

These in turn make it possible to assess the key indicators for business activity:

- water stock (water equivalent) in the snow cover;
- annual river flow volume;
- spring high water level;
- river ice conditions;
- intensity of ice and avalanche processes;
- annual glacier balance;
- duration of snow cover accumulation;
- timing of snow cover breakdown (in order to determine the duration of the vegetation season).

At present, there are many approaches to measuring snow cover indicators based on methods of remote sensing of the Earth by means of space [9, 10, 11] and in-atmosphere vehicles[1] [12] including modern unmanned aerial vehicles [13, 14]. Other methods involve the direct presence on the ground of automated measuring stations[2] which collect, inter alia, visual (photo-video) materials [15, 16], or meteorologists [17] who use both destructive and non-destructive techniques, for example, based on laser[3] or radio emission [18]. The use of mobile devices, e.g., for pressure measurements, allows us to ensure unprecedented coverage density and spatial coverage [19]. Furthermore, their use for precipitation data collection allows us to compile complementary forecast maps [20].

Unfortunately, the current level of technology development does not enable us to collect all the necessary indicators without the use of field methods, most importantly, without the regular presence of a qualified specialist-hydrometeorologist "in the field." Moreover, in domestic practice there is no systematic approach to the problem of automation of field work of meteorologists. Much of the work is done manually, using analog instruments and paper logs for the measurement results. This requires their subsequent digitization, and consequently can be a potential source of errors and vulnerability of the system to the human factor.

According to [21][4] there have been changes to the working plan of the meteorological network, in particular the reduction of snow measurements, due to the lack of instruments and insufficient qualification of personnel.

The purpose of the work is to develop the architecture of geoinformation technology for snow cover monitoring, in order to comprehensively resolve the problem of automating the collection of snow cover indicators and their further maintenance. A further aim is to make them expandable to other tasks of hydrometeorological monitoring.

RESEARCHING THE REQUIREMENTS FOR THE GEOGRAPHIC INFORMATION SYSTEM

For the purposes of this objective, a functionally scalable and integratable system needs to be created which will allow us to interact with a multitude of potential data consumers. These include already extant information and geoinformation systems, as well as automated measuring complexes, individual primary (measuring) converters, receivers of satellite navigation systems (GPS, GLONASS, etc.), photo-video

[1] Koch F., Appel F. et al. *GPS-based measurements of snow cover properties for snow-hydrological, risk and snow quality applications.* Conference: EGU General Assembly At: Vienna; 2019.

[2] State registration certificate. *Automated meteorological stations "Snow"*. State registration number: 52771-13 (in Russ.).

[3] Roy A., Langlois A., Montpetit B., Royer A., Champolion N., Ghislain R., Domine F., Fily M. *Field measurements of snow grain specific surface area using near-infrared photography and laser reflectometry in Northern Canadian tundra*. AGU Fall Meeting Abstracts. 2010.

[4] *Review of the State of the Hydrological Observing System, Data Processing and Preparation of Information Products in 2020*: Reference Edition. St. Petersburg: RIAL; 2021. 56 p. (in Russ.).

fixation means and specialized measuring equipment, without excluding the following.

Due to the potentially high importance of the information collected, all primary and intermediate data, as well as related information, need to be collected and stored in such a way that both the fact of measurement and the correctness of the measurement procedure can be confirmed later, and that all the required calculations can be reproduced. It is also necessary to ensure that each series of measurements can be certified by an electronic signature associated with a specific person performing the measurements or with a separate measuring instrument or system.

Monitoring the vast and heterogeneous territory characteristic of the Russian Federation requires that the geographical distribution of observation points be taken into account. This includes hard-to-reach areas and the level of their technological equipment.

The main requirement for the technological equipment of the potential system is that it takes into account the limited availability of telecommunications: absence or irregularity of access to public telecommunication networks for portable user terminals and the local network of the observation point; poor communication between the user terminal and the local network of the observation point; slow and unstable communication channels, including asymmetric ones. In some cases, direct telecommunication accessibility may not be possible, and data transmission may be possible only by means of removable data carriers.

A significant part of the computer equipment at the individual observation sites, mainly portable user terminals, can operate under extreme conditions. This implies a high probability of the failure of individual devices. In order to create a functional system, this must be compensated for by redundant storage of the most valuable data.

Consumer mobile devices based on the Android platform, such as smartphones and tablets, may be used as portable user terminals. Other system components can be based on personal computers, general-purpose servers, and specialized devices with limited computing resources.

GEOINFORMATION SYSTEM ARCHITECTURE

The key solution of the proposed architecture is a peer-to-peer communication model. This implies the formation of the system as a set of homogeneous nodes which exchange unchangeable data packets. This model is conceptually similar to distributed data storage networks, for example, interplanetary file system (IPFS)[5]. It can be considered as a simplified version of another development by the authors [22], which differs only in data collection, but without providing them (or services based on them) to consumers.

The unit of data storage and transmission between network nodes is a *packet*. Each packet in the system is uniquely identified by the following set of metadata:

- date and time of creation according to Coordinated Universal Time (UTC);
- the identifier of the node which created the packet (universally unique identifier (UUID));
- UUID may be repeated for several packets in case they belong to the same series of measurements;
- packet priority;
- packet type code;
- content hash sum.

A packet can be unambiguously represented as a file, enabling the user to apply any method available to them for transmission.

For operational convenience, the system core can directly support multiple file exchange protocols. Any file-oriented protocol can be used, if there is direct telecommunication availability, even intermittent. Modern cryptographically secure protocols are represented by SFTP (secure file transfer protocol)[6] and UFTP (UDP-based file transfer protocol, UDP—user datagram protocol)[7]. An important advantage of UFTP for the purposes of this system is the possibility of its application in communication channels with high bandwidth, but high latency. This is typical, for example, of satellite communications used in hard-to-reach areas. In the absence of direct telecommunication availability, data transmission based on removable media can be used. This is also referred to as SneakerNet [23]. A software package which can be used to achieve the necessary functionality is NNCP (node to node copy)[8].

Packet prioritization enabled the data most valuable for operational processing to be transmitted first.

Assumed packet types and priorities are summarized in Table 1.

The diagram of the network node is shown in Fig. 1.

In addition to the basic modules common to all nodes, there are separate types of nodes oriented to different tasks in the network:

[5] Benet J. *Content Addressed*, Versioned, P2P File System. IPFS. 2014.

[6] Ylonen T., Lehtinen S. *SSH File Transfer Protocol draft-ietf-secsh-filexfer-02.txt.* SSH Communications Security Corp. October, 2001. URL: https://datatracker.ietf.org/doc/html/draft-ietf-secsh-filexfer-02. Accessed November 01, 2023.

[7] UFTP—Encrypted UDP based FTP with multicast. URL: https://uftp-multicast.sourceforge.net/. Accessed November 01, 2023.

[8] NNCP. URL: http://www.nncpgo.org/. Accessed November 01, 2023.

Table 1. Types and priorities of data packets in a distributed geoinformation system

Priority	Type	Description
1	Manifest	Declares the fact that measurements are present. Contains limiting rectangles that enable the construction of a spatial index of the data without their presence. Must be of minimum size
2	Measurement result	Contains a valuable measurement result for further processing
3	Initial data	For complex measuring instruments, it contains initial data allowing the repeat calculation of the result
4	Associated data	Contains data of no direct value, but enables confirmation of the validity of the results obtained, e.g., photo-video data, satellite navigation system tracks, etc.

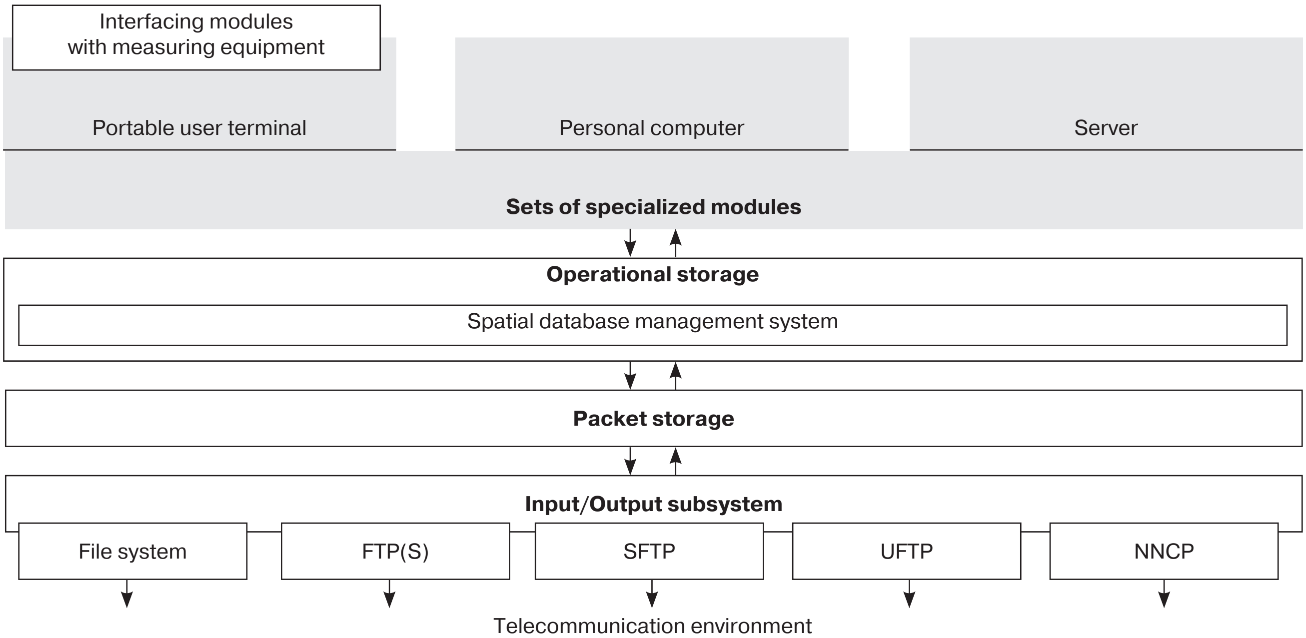


Fig. 1. Principle diagram of the distributed geoinformation system node. DBMS is database management system, FTP(S) stands for file transfer protocol + secure sockets layer

- portable user terminals: data acquisition, manual input, interaction with measuring equipment;
- automated data acquisition units: saving data from measuring equipment;
- observation site personal computers: data aggregation, primary analysis, visualization;
- server: aggregate data from a large number of sources, store large amounts of data, provide a web interface.

Node levels and the following rules are introduced to direct data flows between nodes:

- level 1 is assigned to portable user terminals that directly collect data;
- higher levels are assigned to nodes of local observing sites, and further to regional and federal nodes;
- when nodes of the same layer interact, data is synchronized in both directions, providing backups;
- when nodes of different levels interact, data is transferred from a lower-level node to a higher-level node, providing information aggregation.

AUTOMATION OF THE FIELD MEASUREMENT PROCEDURE

Automation of the field measurement procedure is performed by software modules designed to be placed on a portable user terminal. They provide for the possibility of primary input and the correction of measured values, performing calculations, as well as visualization of data in tabular and graphical formats.

The measurement results are entered into the appendix directly during measurements on the route. The calculation of average parameters and water reserve is done automatically.

In order to perform a snow survey, a gauge rod and a weight snow gauge are required. The snow survey process involves collecting data for the following measurements:

- snow cover height (counting on the scale of a gauge rod);
- reading from the scale of the cylinder on the weighing snow gauge;

- reading from the scale bar of the weighing snow gauge;
- ice crust thickness (measured on the scale of a gauge rod);
- thickness of the snow layer saturated with water (counted on the scale of a gauge rod);
- snow cover structure;
- snow coverage degree;
- ice crusting degree;
- condition of the soil surface under snow (melted, frozen).

Observations of snow cover on snow gauge trails begin when there are 6 points or more of snow coverage of the visible neighborhood. They end when stable snow cover has been destroyed (less than 5 points of coverage).

The procedure for making observations using the developed program modules is as follows:

1. Identification and authentication by a specialist meteorologist.
2. Enabling geopositioning at the first snow cover height measurement point.
3. The snow cover height is measured every twenty meters, and the measurements are recorded in the corresponding cells. The MEASURE #_ cell indicates how many measurements were taken.
4. The first point for measuring the mass of snow cover is chosen at a distance of 50–100 m from the beginning of the route. Further measurements are made every 200 m. The total number of snow cover density measurements is 10. Measurements of the snow cover height on the cylinder are taken, in order to calculate the snow cover density. Data regarding the snow cover height from the cylinder of the weighing snow gauge is entered in the corresponding cell. The CYLINDER SCALE REPORT #_ cell indicates how many snow cover height measurements were made with the cylinder.
5. After measuring the snow cover height on the cylinder of the weighing snow gauge, the snow cover is weighed. The weighing data is entered into the appropriate cell. The REPORT #_ BY WEIGHTS cell indicates how many measurements are required to determine the mass of the snow cover. The density is calculated automatically. Density calculation can be viewed by clicking on the DENSITY tab. The numbering of DENSITY #_ cells shows how many measurements have been made for the purpose if density calculation. In addition to density measurements at selected points, the thickness of the meltwater layer, the water saturated snow layer, the thickness of the ice crust, and the condition of the soil under the snow cover (frozen or melted) are measured. The data entry boxes are opened one by one after the measurement results for each point have been entered. If no measurements were made due to missing data, a dash is entered. The soil surface condition is selected from the list: thawed, or frozen. The presence of snow crust inside the snow cover and on the surface of the snow cover is noted: yes, no.
6. After passing the route, the meteorologist takes a snapshot of the field and uploads it to the app, in order to characterize the entire snow measuring route. The image is automatically saved.

AUTOMATION OF THE FIELD MEASUREMENT VALIDATION PROCEDURE

Automation of the field measurement validation procedure is performed by modules designed to be placed on the portable user terminal, as well as on the nodes where additional quality control of measurements is performed.

At the present time, checks which may result in a warning being issued to a user are based on the following developed algorithm:

- the number of measurements on the snow measurement route must be within the permissible range;
- the average snow cover height on the route line shall be greater than or equal to the minimum snow cover height or less than or equal to the maximum snow cover height on the rod;
- the average snow density calculated from the snow route measurements shall be greater than or equal to the minimum snow density, and less than or equal to the maximum snow density calculated from snow measurement route data;
- the average water content in the snow cover calculated from the snow route measurements shall be greater than or equal to the minimum value of the snow route, and less than or equal to the maximum water content of the snow measurement route.

Using the graph displayed in the appendix, questionable (potentially poor-quality) measurements can be identified directly on the route and re-measured. Poor measurements can occur due to human error. In some cases, the meteorologist may make a mistake when entering measurements. The route line on the chart is formed on the basis of measurements made directly on the snow survey route.

PROTOTYPE OF THE GEOINFORMATION TECHNOLOGY

The authors have designed a prototype of modules for a wearable user terminal (Android operating system version 10 or higher). Special attention is paid to those elements which enable the data quality to be enhanced by promptly detecting questionable measurements directly in the process of snow surveying. Thus, the snow measurement route graph (Fig. 2) reflects the number of the snow survey, the number of meteorological station, the length of the route traveled, the length of the remaining route, as well as the minimum and maximum measurement altitudes. Given that the meteorologist surveys the snow survey route well in advance of the snow cover, they have a schematic plan of the route line with indication of gradients and elevations, as well as markings of the location of objects (road, trees, bushes, etc.) located on the route line and in the area surrounding the perimeter of the route line. The sub-map data allows questionable measurements to be identified from the snow survey data. Points on the line highlighted in a distinctive color indicate elevation differences in the snow gauged route. The table of average parameter calculations helps dubious measurements to be identified immediately on the snow measurement route. Such dubious values are highlighted in a separate font, indicating possible measurement error (Fig. 3).

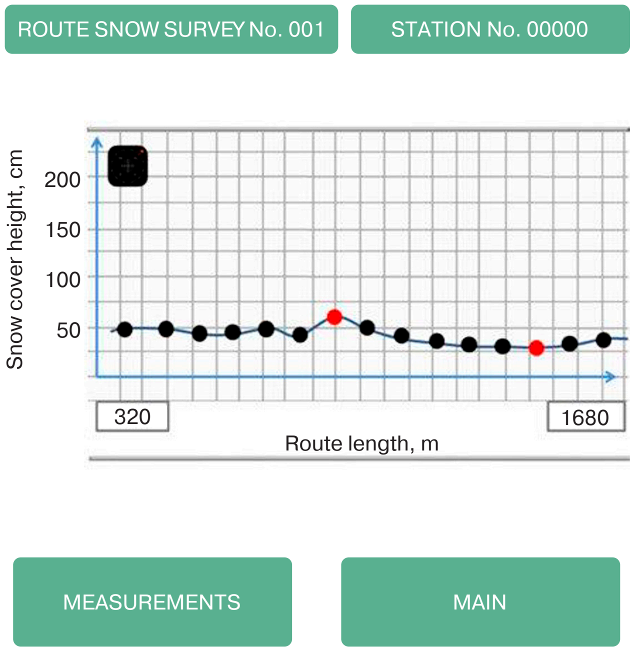
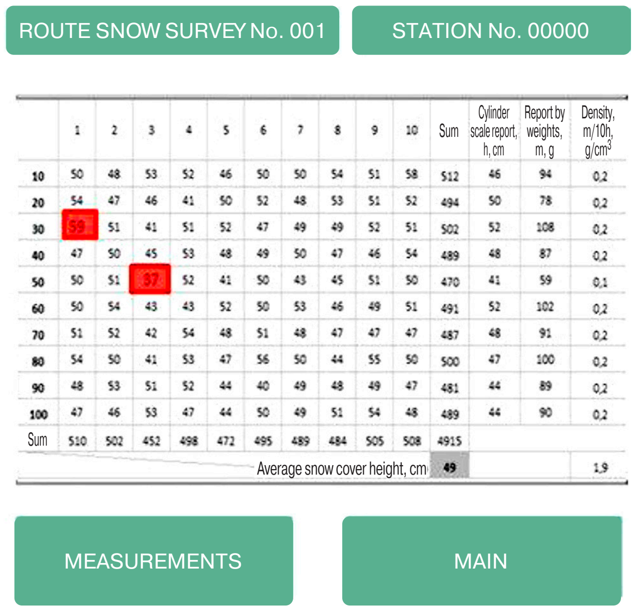


Fig. 2. Diagram of snow survey route with marking of measurement points



	1	2	3	4	5	6	7	8	9	10	Sum	Cylinder scale report, h, cm	Report by weights, m, g	Density, m/10h, g/cm^3
10	50	48	53	52	46	50	50	54	51	58	512	46	94	0,2
20	54	47	46	41	50	52	48	53	51	52	494	50	78	0,2
30	59	51	41	51	52	47	49	49	52	51	502	52	108	0,2
40	47	50	45	53	48	49	50	47	46	54	489	48	87	0,2
50	50	51	37	52	41	50	43	45	51	50	470	41	59	0,1
60	50	54	43	43	52	50	53	46	49	51	491	52	102	0,2
70	51	52	42	54	48	51	48	47	47	47	487	48	91	0,2
80	54	50	41	53	47	56	50	44	55	50	500	47	100	0,2
90	48	53	51	52	44	40	49	48	49	47	481	44	89	0,2
100	47	46	53	47	44	50	49	51	54	48	489	44	90	0,2
Sum	510	502	452	498	472	495	489	484	505	508	4915			
Average snow cover height, cm											49			1,9

Fig. 3. Table of general measurements with the calculation of the average parameters of the snow cover on the route snow survey

CONCLUSIONS

The architecture of the distributed geoinformation technology proposed by the authors is designed to support snow cover monitoring procedures based on measurements, data aggregation and validation to their transfer to a centralized processing system. It is capable of functioning in circumstances of limited telecommunication availability, as well as ensuring data integrity control and personalization of responsibility for their receipt by introducing an electronic signature of each measurement session. This architecture can be extended by developing and implementing modules for other types of measurements.

A prototype of the wearable user terminal modules has now been developed, in order to enable their validation.

Further research by the authors will focus on snow gauge route data collection using species information.

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