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PARALLEL DATA PROCESSING IN AUTOMATED RAILWAY TRANSPORT DISPATCHING SYSTEM

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Abstract. In modern railway transport, ensuring the quality, reliability, and durability of rolling stock (RS) and track machines (TM) is a key factor for operational efficiency. The research topic is justified by the challenge of integrating traditional, additive, and nanotechnologies into manufacturing processes aimed at improving the performance of railway components. Research aim: to analyze and optimize engineering processes in railway transport using traditional, additive, and nanotechnologies to enhance the quality and reliability of parts. Research objectives: to investigate the potential of additive technologies (3D printing) for producing complex components; to evaluate the effectiveness of nanotechnologies in improving strength, wear resistance, and corrosion resistance of parts and assemblies; to develop and optimize quality control methods using modern sensors and devices, including industrial computed tomography; to assess the economic impact of implementing nanostructured coatings and advanced production processes. Results: additive technologies allow the production of complex parts, reduce component weight, and eliminate material waste. Nanotechnologies enable the creation of defect-free materials and nanoscale structures, increasing durability and service life by 2–5 times. Quality control is performed through surface diagnostics, incoming material inspection, and monitoring of technological parameters. Nanostructured coatings on cutting tools, springs, and RS/TM components improve wear resistance, strength, and reliability. The integration of traditional, additive, and nanotechnologies with flexible manufacturing systems and advanced control tools significantly improves the quality, reliability, and economic efficiency of railway component production. The results provide opportunities for broader applications in other engineering sectors and lay the foundation for further scientific research.

Keywords: nanotechnology, additive technologies, railway engineering, flexible manufacturing systems, nanocoatings, quality control, 3D printing

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ТЕМІРЖОЛ КӨЛІГІ ДИСПЕТЧЕРІНІҢ АВТОМАТТАНДЫРЫЛҒАН ЖҮЙЕСІНДЕ ДЕРЕКТЕРДІ ҚАТАР ӨҢДЕУ

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Аннотация. Қазіргі теміржол тасымалында подвижной құраманың (ПС) және жол машиналарының (ПМ) сапасы, сенімділігі және ұзақ қызмет мерзімі маңызды фактор болып табылады. Зерттеу тақырыбы дәстүрлі, аддитивті және нанотехнологияларды өндіріс процестеріне интеграциялау мәселесін шешу қажеттілігінен туындады, бұл теміржол құрамаларының бөлшектері мен агрегаттарының эксплуатациялық сипаттамаларын жақсартуға бағытталған.Зерттеудің мақсаты: дәстүрлі, аддитивті және нанотехнологияларды пайдалана отырып, теміржол машиностроениясы өндіріс процестерін талдау және оңтайландыру арқылы бөлшектердің сапасы мен сенімділігін арттыру. Зерттеу міндеттері: күрделі бөлшектерді шығару үшін аддитивті технологиялардың (3D-басып шығару) әлеуетін зерттеу; бөлшектер мен агрегаттардың беріктігін, тозуға және коррозияға төзімділігін арттыруда нанотехнологиялардың тиімділігін бағалау; қазіргі сенсорлар мен құрылғыларды, соның ішінде өндірістік компьютерлік томографияны қолдану арқылы сапаны бақылау әдістерін әзірлеу және оңтайландыру; нанақабаттарды және заманауи өндіріс технологияларын енгізудің экономикалық әсерін бағалау. Нәтижелер: аддитивті технологиялар күрделі бөлшектерді шығаруға, компоненттердің салмағын азайтуға және материалдық қалдықтарды жоюға мүмкіндік береді. Нанотехнологиялар ақаусыз материалдар мен наномасштабты құрылымдар жасауды қамтамасыз етеді, бұл бөлшектердің беріктігін және қызмет мерзімін 2–5 есе арттырады. Сапаны бақылау беткі диагностика, кіріс материалдарды тексеру және технологиялық параметрлерді мониторинг арқылы жүзеге асырылады. Нанақабаттар кескіш құралдарда, серіппелерде және ПС/ПМ бөлшектерінде тозуға төзімділікті, беріктікті және сенімділікті арттырады. Дәстүрлі, аддитивті және нанотехнологияларды икемді өндірістік жүйелер мен заманауи бақылау құралдарымен интеграциялау теміржол бөлшектерінің өндірісінде сапаны, сенімділікті және экономикалық тиімділікті елеулі жақсартады. Бұл нәтижелер басқа машиналық инженерлік салаларда да қолдануға мүмкіндік береді және одан әрі ғылыми зерттеулердің негізін қалайды.

Түйін сөздер: нанотехнология, аддитивті технологиялар, теміржол машиностроениясы, икемді өндірістік жүйелер, нанақабаттар, сапаны бақылау, 3D-басып шығару

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ПАРАЛЛЕЛЬНАЯ ОБРАБОТКА ДАННЫХ В АВТОМАТИЗИРОВАННОЙ СИСТЕМЕ ДИСПЕТЧЕРА ЖЕЛЕЗНОДОРОЖНОГО ТРАНСПОРТНОГО СРЕДСТВА

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Аннотация. В современном железнодорожном транспорте обеспечение качества, надежности и долговечности подвижного состава (ПС) и путевых машин (ПМ) является ключевым фактором эффективности эксплуатации. Выбор темы исследования обусловлен проблемой интеграции традиционных, аддитивных и нанотехнологий в производственные процессы, направленные на улучшение эксплуатационных характеристик деталей, узлов и агрегатов железнодорожного транспорта. Цель исследования – анализ и оптимизация технологических процессов машиностроения железнодорожного транспорта с использованием традиционных, аддитивных и нанотехнологий для повышения качества и надежности деталей. Задачи исследования: изучение потенциала аддитивных технологий (3D-печать) для производства сложных деталей; оценка эффективности нанотехнологий для улучшения прочности, износостойкости и коррозионной стойкости деталей и узлов; разработка и оптимизация методов контроля качества с применением современных датчиков и устройств, включая промышленную компьютерную томографию; оценка экономического эффекта внедрения наноструктурированных покрытий и современных производственных технологий. Результаты: аддитивные технологии позволяют изготавливать детали любой сложности, снижать массу компонентов и исключать производственные отходы. Нанотехнологии обеспечивают формирование бездефектных материалов и наноразмерных структур, увеличивая долговечность и ресурс деталей в 2–5 раз. Контроль качества осуществляется через диагностику поверхности, входной контроль материалов и мониторинг технологических параметров. Наноструктурированные покрытия на режущем инструменте, пружинах и элементах ПС/ПМ повышают износостойкость, прочность и надежность. Интеграция традиционных, аддитивных и нанотехнологий с гибкими производственными системами и современными средствами контроля существенно улучшает качество, надежность и экономическую эффективность производства деталей железнодорожного транспорта. Полученные результаты открывают перспективы применения этих технологий в других отраслях машиностроения и обеспечивают основу для дальнейших научных исследований.

Ключевые слова: нанотехнологии, аддитивные технологии, железнодорожное машиностроение, гибкие производственные системы, нанопокрытия, контроль качества, 3D-печать

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Introduction

In modern railway transport, ensuring the quality, reliability, and durability of rolling stock (RS) and track machines (TM) is a critical factor for operational efficiency and safety. The choice of this research topic is justified by the observed problematic situation: despite significant achievements in traditional mechanical engineering, there is an urgent need for new technologies and materials that can substantially improve the operational performance of railway components. Analysis of previous studies (Pervertov et al.) shows that although flexible manufacturing systems and additive technologies have been actively implemented, unresolved issues remain regarding the comprehensive integration of traditional, additive, and nanotechnologies for optimizing production processes and quality control.

The relevance of the study is determined by increasing demands for reliability and durability of railway equipment, the need to reduce production costs, minimize material waste, and enhance the economic efficiency of railway engineering. At the same time, modern control and diagnostic methods, such as industrial computed tomography, high-precision sensors, and photonic fiber-optic devices, allow for significantly improved accuracy and reliability of manufacturing processes, but their application requires systematic analysis and optimization.

Research object: technological processes for manufacturing railway transport parts, components, and assemblies.

Research subject: the use of traditional, additive, and nanotechnologies in engineering to improve the quality, reliability, and economic efficiency of railway transport components.

Research aim: to analyze and optimize engineering processes in railway mechanical engineering by integrating traditional, additive, and nanotechnologies, and developing quality control methods to enhance durability and reliability of parts.

Research objectives:

- To investigate the potential of additive technologies (3D printing) for producing complex parts and reducing component weight without compromising strength.
- To evaluate the effectiveness of nanotechnologies in improving strength, wear resistance, and corrosion resistance of parts and assemblies.
- To develop and optimize quality control methods using modern sensors and devices, including industrial computed tomography.
- To assess the economic impact of implementing nanostructured coatings and advanced production processes.

Methods and approaches: combined literature analysis, modeling of technological processes, experimental quality control of parts, and assessment of economic efficiency of technology implementation.

Research hypothesis: integration of traditional, additive, and nanotechnologies with modern control systems will improve the quality, reliability, and economic efficiency of railway component production, creating conditions for their wide industrial application.

Materials and мethods.

The idea of using parallel computations in dispatching RS movement tasks were previously considered by various experts (Gapanovich et al. 2011: 5–11). At the same time, in a number of papers, for example, in (Mozharova, 2011: 216–217; Arkatov, 2012: 22–28), it was noted that an important direction for modernization of the existing and design of new ADCS, primarily for HSRT, are the tasks related to RS HSRT movement coordination in conditions imposed on solving time constraints. We should note that many of the proposed models (Arkatov, 2012: 22–28; Smagulova et al., 2016: 247–256.) due to the complexity of the algorithms were not implemented.

In works (Smagulova et al., 2016: 247–256; Agafonov, 2017: 9) there were analyzed circumstances that contribute to the imposition of restrictions on the time for solving tasks of RS movement coordination (including HSRT). They include:

design, technological and algorithmic constraints imposed on the parameters of the maximum speed of computers that use sequential algorithms in the calculations;

the need to make decisions in ADCS during small time periods, taking into account the speed of the modern railway transport, especially HSRT.

In works (Borushko, 2007: 33–37; Levin, 2016: 38–41) the authors carried out a detailed review and analysis of various information systems, which allow to automate the dispatching processes of the railway transport, including HSRT. An analysis of these and other publications (Davidsson et al., 2005: 255–271; Fay, 2000: 719–729) on the subject of our research showed that the task of dispatching control and movement coordination in the existing automated systems on the railway transport requires further generalization. This is evidenced by the performance of the timetable correction mainly by dispatchers. Also, there are no systems and software products that automate this process in real-time, for example, for HSRT.

According to the analysis of a number of publications (Agafonov, 2017: 9) it was revealed that a promising direction of the research in this subject area is the organization of decision-making assistance by the driver and data relevance control which is transmitted to the mobile means of HSRT. Therefore, it is proposed to supplement the existing automated system of railway transport, including HSRT, through the implementation of an automated movement dispatching information system.

The organization of parallel calculations in the process of solving dispatching tasks and RS movement coordination, including HSRT, is implemented mainly through the introduction of the multiprocessor systems (Arkatov, 2012: 22–28; Borushko, 2007: 33–37; Ning et al., 2006: 80–83; Ning et al., 2011: 473–1483). As shown on (Levin, 2016: 38–41) this approach allows one-time execution of several operations during data processing. At the same time, the processes of performing computational tasks are significantly accelerated, for example, in a situation when the algorithm can be broken down into information independent components. At the same time, the implementation organization of each of the parts of calculations is implemented on different servers of automated railway systems. As the researches have shown (Davidsson et al., 2005: 255–271; Fay, 2000: 719–729) this approach has significantly reduced time costs in comparison with the classical approach, when each task is assigned only by existing server (Davidsson et al., 2005: 255–271; Fay, 2000: 719–729; Coll et al., 1990: 244–255). However, as the authors note themselves, this approach to the parallelism in the implementation of computational tasks of dispatching and RS movement coordination on the railway transport has not been implemented.

Also, as the analysis of the researches showed (Arkatov, 2012: 22–28; Agafonov, 2017: 9; Ning et al., 2011: 1473–1483; Fay, 2000: 719–729; Coll et al., 1990: 244–255), the problem of parallelization was not solved from the point of view of increasing the efficiency of existing algorithms. In addition, in these papers, there is no mention about an important aspect of algorithm computational capability optimization, for example, if necessary, in order to obtain the results of calculations for a limited time.

All the above conditioned makes the theme of our research relevant.

Development of algorithm models used in dispatching tasks by the movement of rolling stock of the railways of the Republic of Kazakhstan, including high-speed transport, and its coordination on the basis of parallel calculations.

In order to improve the efficiency and safety of railway transport, as well as the account of time constraints in the ADCS, imposed on the calculations, it seems necessary to divide the RS into separate groups. At the same time, by introducing parallel processing modes, it is possible to achieve the execution of algorithms in solving problems of dispatching and coordination of RS, including HSRT.

We believe that the railway network of Kazakhstan is divided into separate dispatcher responsibility areas (DRA). Inside the DRA there is a dispatching of RS moving exclusively in DRA. If RS move between the areas, the dispatcher coordinates the movement in the central railway transport control room of Kazakhstan.

The basis of the developed system is a communication standard that satisfies the necessary requirements for the functioning of the system as a whole. For example, the GSM standard can be used as a mobile communication standard, see fig. 1. The application server is connected with the automated workplaces of DRA dispatchers, as well as with the database server and the RS onboard computers.

Let introduce the definitions. The reference point (RP) - a point on the navigation map, in which for the analyzed RS there is performed a check for the presence/absence of conflicts in the movement schedule. We believe that if such a conflict is detected, then a control action is generated by the ADCS. We put the RP in such a way in order to provide time for decision-making.

It has been revealed that a promising approach is the organization of decision support systems by the driver and control of the data relevance that is transmitted to the locomotives (diesel locomotives and electric locomotives, including HSRT). Therefore, it is proposed to supplement the existing automated railway transport system by implementing the traffic dispatch information system Fig. 1.

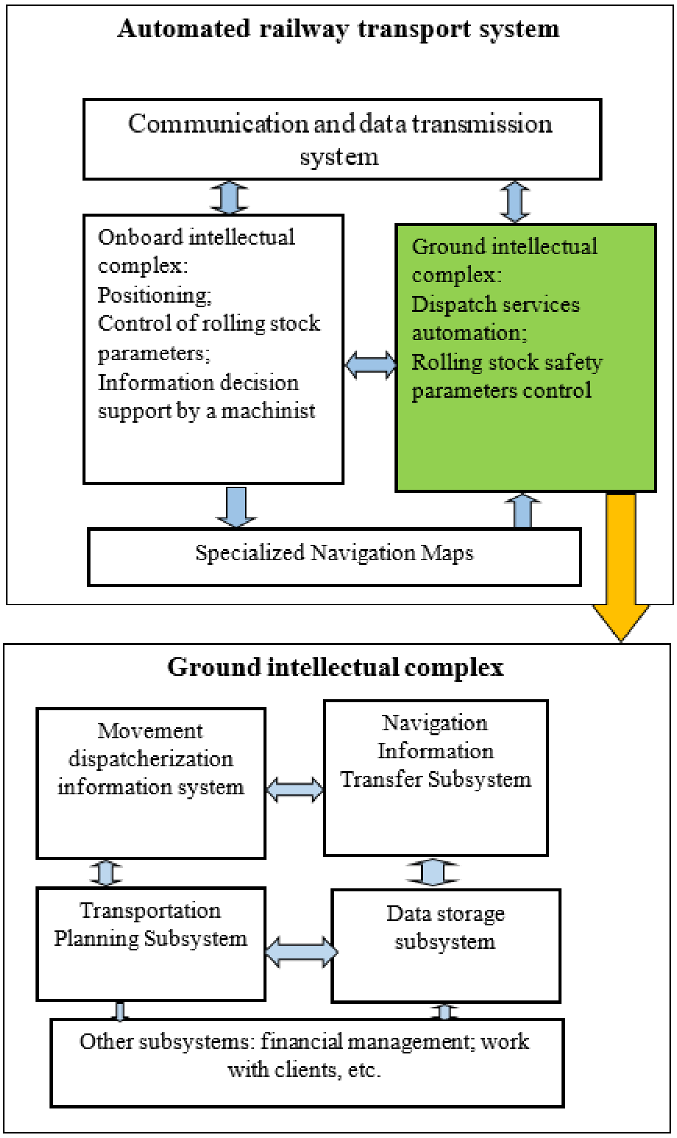

Fig. 1. Movement dispatcherization information system as part of a ground intellectual complex

Results and discussion.

For the full functioning of the automated dispatching control system (ADCS), it is necessary to use navigation equipment and on-board intellectual systems (Skalozub et al., 2013; Gapanovich et al., 2011: 5–11), which are installed on the HSRT rolling stock. They provide information transmission about the HSRT location as well as management decision-making. In this case, the following dilemma arises - an increase of the HSRT amount will increase the network load in the communication channels. This, in turn, will require the use of wider frequency channels in comparison with the usual ones for mobile communication systems. With the development of HSRT in the Republic of Kazakhstan, it will be necessary to use highly effective approaches for channel resource control. Then it is necessary to solve the problem of estimating the existing GPRS systems that provide communication and transmission of HSRT data.

Information exchange technology of the movement coordination system. In general, the information exchange of the movement coordination system of the rolling stock can be presented by the scheme shown in Fig. 2

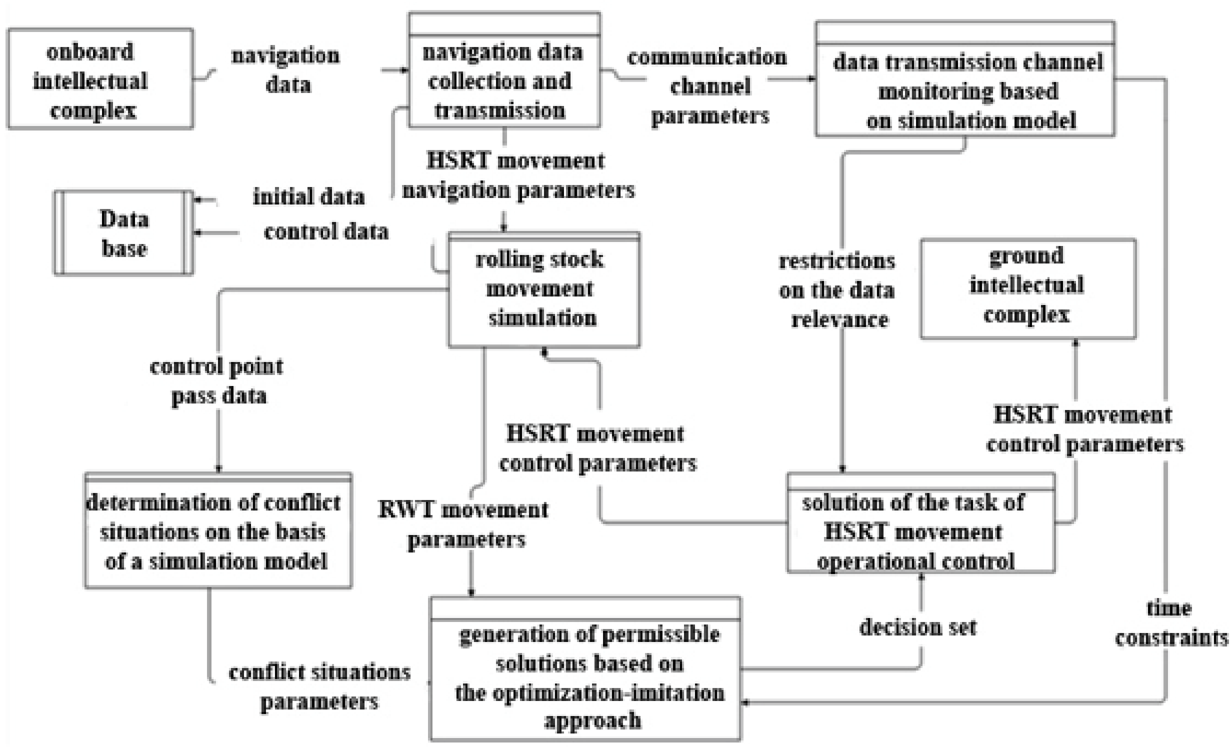

Fig. 2. The modernized information system for the movement dispatching automation as part of the ground intellectual complex for the HSRT control of the Republic of Kazakhstan

Navigation signals of GNSS satellites are received using special GPS/GSM receivers that process them and receive navigation data in the WGS-84 coordinate system (latitude, longitude, time, etc.). This system uses receivers with a frequency of information updating at least 5 times per second (5 Hz), since they provide the necessary accuracy in calculating the location of an object on the map.

Navigation signals are received at a frequency of 1227.6 MHz using GNSS Navstar/GPS and 1200 MHz using GLONASS. In order to obtain data on the location of a train, the receiver must “see” at least 4 satellites (otherwise the error may be significant).

The use of GPRS technology on therailway transport led to a significant increase in the capacity of data transmission channels. For example, the maximum transmission rate, in the condition of 8 timeslot use, can be approximately 172 kbps. The packet switching application is also possible. This approach distinguishes from circuit switching in CSD/HSCSD (Smagulova et al., 2016: 247–256; Davidsson et al., 2005: 55–271).

This approach ultimately allows to maximize the efficiency of base stations resource use. But at the same time, in order to implement this technology, it is necessary to supplement the network structure with new components, for example, such as SGSN, GGSN (Mozharova, 2011: 216–217).

In the case of the possibility of EDGE (Mozharova, 2011: 216–217; Agafonov, 2017: 9) technology use, which is a little different from GPRS, it can also be implemented on the existing networks. Modernization of the dispatching system during the EDGE implementation will entail the need to solve other problems. This, in particular, relates to issues that relate to changes in coding schemes, as well as modernization in software on network components. We should that the maximum speed that EDGE can provide is about 474 kbps (8 timeslots of approximately 60 kbps) (Agafonov, 2017: 9; Davidsson et al., 2005: 255–271).

With the help of a special matrix the obtained coordinates are recalculated into the coordinate system of navigation maps created to work with a system for movement coordination the of the rolling stock and HSRT.

Output coordinates are transmitted to the server of the mobile operator using CSD/GPRS technology. Note that the coordinates, which were calculated, are used to display the location of the rolling stock on the onboard computers of the HSRT. The mobile operator must provide the speed of information transmission using a GPRS channel of at least 50 kbit/s and APN free from the total traffic (Mozharova, 2011: 216–217).

The server part of the software is located on a computer with a permanent connection to the Internet and an to the IP address. The tasks of the server part can be formulated as follows:

- to receive data from mobile devices on the location (current coordinates) of HSRT (or conventional railway transport);
- to ensure the security of the connection, encoding and data decoding;
- to store the received data.

This ensures the reliability of the transmission and storage of route data and the dispatcherization parameters of the HSRT. And it is also necessary in the tasks of movement coordination of the rolling stock.

Considering the possibility of communication loss between the mobile equipment and the server, it is necessary to provide special functions that allow to transfer to the server all the data that was accumulated during the period when the object was not in the GSM coverage area.

The client part (dispatcher workplace) is a software product. This software product is able to work on ordinary computers that have access to the Internet, and also receive data both in real time and can accumulate the history of data received from the database server (DB).

The database server also stores GPS control data of the HSRT.

Data from the database can be visualized on electronic maps, with the reference to the current location of the HSRT object.

Such a construction of the dispatching and HSRT movement coordination system based on GPS navigation allows the dispatcher to make prompt decisions necessary for elimination the conflict situations on the road.

A special place among the information geographically distributed systems occupy data transmission systems for hard-to-reach objects - for example, the system for HSRT movement coordination. A feature of such data transmission systems is, above all, the use of wireless communication channels – radio, satellite, and mobile communication channels. In this connection, the task of optimizing a communication system with such parameters as time, cost and reliability of message delivery has a particular importance.

It should be noted that in the developed system it is necessary to provide an equal access mode of HSRT rolling stock to the provided communication channels. Users should have a technologically equal opportunity to transfer data packets related to the HSRT state or voice calls. There is considered the possibility of implementing a scenario in which voice traffic detection between the dispatcher and the HSRT driver should have a higher priority than the service of

GPRS packets. This can be adjusted by prioritizing the call or data transmission. In the designed automation dispatch control system, we should also provide a storage drive for servicing only GPRS packages.

In regard of the review, it is proposed to supplement the existing automated railway transport system (including HSRT) through the implementation of the movement dispatchirization information system, which is shown on Fig. 2

The proposed system (Fig. 2) has a hierarchical structure, the components of which are the automated workplaces (AWPs) of the railway dispatchers, the AWS of the RWCh dispatcher, message switching centers (SSGN) and communication channels. At the upper level of the hierarchy there is the dispatcher AWP of the corresponding dispatcher area (DA), and the lower level of the hierarchy is represented by rolling stock of railways, in particular, the HSRT.

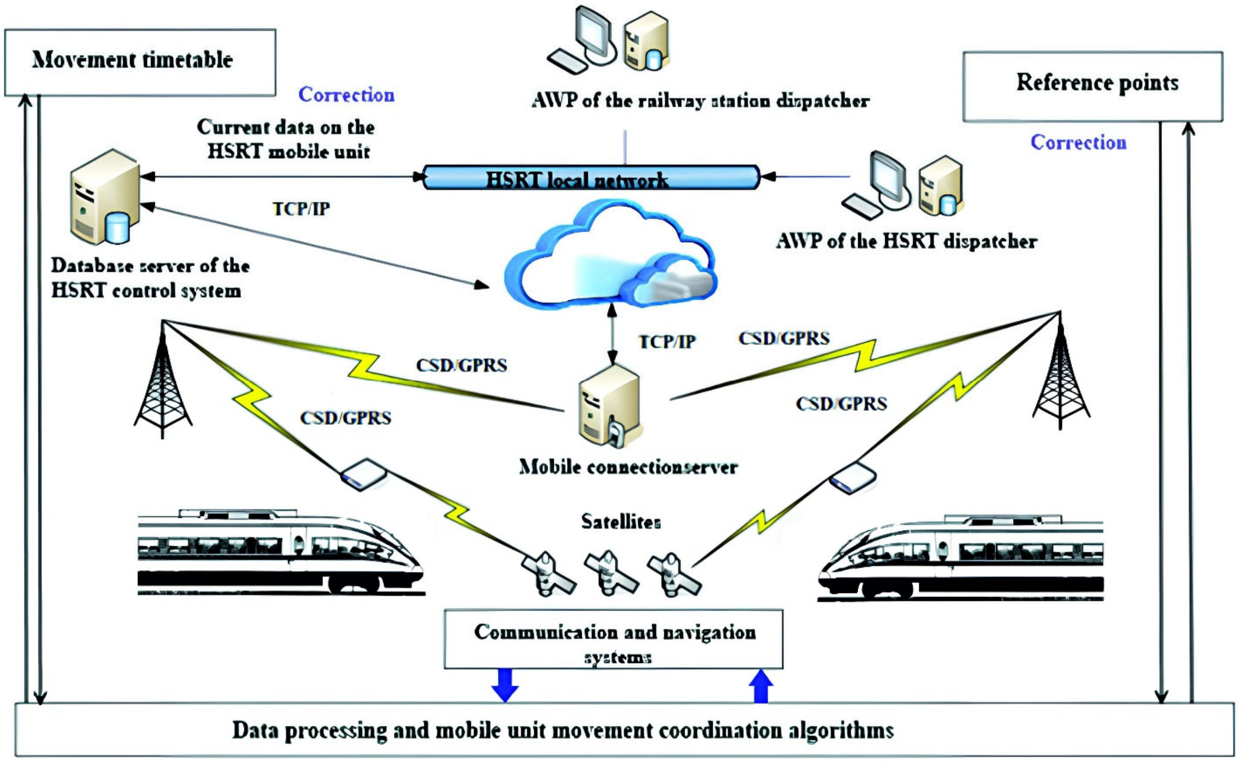

Fig. 3. Scheme of the information exchange of the railway transport movement coordination and dispatching system of the Republic of Kazakhstan

Navigation information for ADCS is a set of coordinates and speed of RS movement. This information comes from the GPS/GPRS-modems installed, for example, on the RS. This allows to position clearly the RS units on the navigation maps. At the same time, the current speed of the RS movement allows to estimate time intervals until reaching the RP.

Developing a parallel algorithm, we must first of all evaluate the effectiveness of its application in comparison with the sequential problem solution. We believe that the developed algorithm should solve the problem of RS movement coordination. Let introduce the sequence of the indicated problem solution in the form of a directed graph, see fig. 2. The presented graph allows to create an algorithm for parallel calculations for the tasks of making corrections to the RS schedule. In this case, the initial data will be information about the RS location and the check for conflict absence in the schedule. In order to obtain the initial data there was involved a subsystem, including navigation equipment installed on the RS. This information is sent to the database server (DB). The server is located in the corresponding DRA or in another point of the railway transport network.

We believe that a more productive approach will be an approach when the organization of the computational process makes it possible to reduce the time intervals for solving the RS coordination problem. In particular, due to the parallel execution of the algorithm for calculating the set of trains moving to the DRA, and their movement coordination.

If along the route the RS movements pass through several DRA, the results of the algorithm work, coordinating RS graphs, are combined. Further correction is performed in the schedule. On the graph (see Fig. 4) the vertices without input arcs are used in order to obtain navigation information. Vertices without output arcs - to make corrections to the RS schedule.

We will assume that there are a number of trains in DRA – $MTR_i = \{1,2,...,j,...,N-1\}$, where $i-$ index of the analyzed DRA in ADCS. On the navigation maps used by the dispatcher or the ADCS, there are indicated RP - $MCP_i = (1,...M_i)$. With the help of ADCS, it is necessary to determine time intervals or a specific time of departure/arrival of the mobile unit (hereinafter RS), i.e. to find $t^r(pr = 1,2,...,N-1)$, where $r-$ the sequence of RS occurrence in DRA.

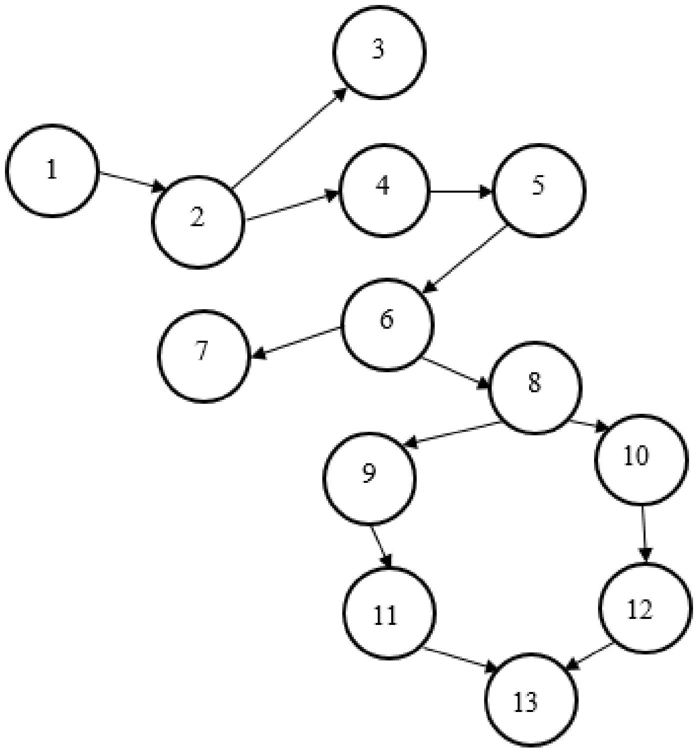

Fig. 4. Graph diagram of the algorithm for the RS schedule correction for the option of tasks parallelization

Positions: 1 – to determine the dispatcher responsibility area (DRA); 2 – to receive information from navigation equipment installed on the RS; 3 – to create a list of RS, which is not checked by the dispatcher; 4 – to determine the RS for verification at reference points (RP); 5 – verification of the RS movement schedule; 6 – check for conflict absence in the schedule; 7 – to form a set of RS which moves without conflicts in the schedule; 8 – to form a set of RS, which have a conflict in the schedule; 9 – to check for the possibility of making corrections to the schedule; 10 – to perform the following test for RP; 11 – development of control action; 12 – new RP; 13 – movement correction for DRA

We believe that for MTR_i using the ADCS, the specific time of RS departure/arrival is calculated, i.e. $t_j^{pr^*}(pr \in MTR)$, $j \in MTR_i^*$, where $MTR_i^* = \{1,2,...,j,...,N-1\}-$ is the ordered set of MTR_i in ascending order t^{pr}. Then t_j^{pr} $-$ the estimated time of RS arrival, and $j-$ the index of the departure/arrival order of the RS.

Let suppose that in a particular DRA there is appeared a RS with a number N and estimated time t_x^N, $x-$ an unknown index that can be found from the inequality:

$$t_{i-1}^{pr_i} < t_x^N < t_i^{MTR_i}. \quad (1)$$

Therefore, if $x = i$, then the index j will increase by 1, starting from t_j^{MTR}.

You can check the condition for conflict absence in the RS departure/arrival schedule:

$$\begin{aligned} & t_i^N - t_{i-1}^{pr^*} \geq \tau_{\min}, \\ & t_{i-1}^{MTR_i^*} - t_i^N, \end{aligned} \quad (2)$$

where $\tau_{\min} -$ safe time interval between RS (in ADCS there is considered the way from which or on which the RS arrives/is sent).

If inequalities (1) and (2) are fulfilled, then we find the real time of RS arrival/departure: $t_i^N = t_i^{N^*}$. If (1) or (2) are not fulfilled, then for RS with a number N there may occur a conflict. All trains (or RS) for which a conflict in the timetable is possible, form a subset $MTR_{1i}^* \notin MTR_i^*$.

We can find the capacity of MTR_{1i}^* by analyzing the implementation of the following inequalities:

$$\begin{aligned} & t_{i-m}^{z^*} - t_{i-m+1}^{pr^*} \leq \lambda \cdot \tau_{\min}, \\ & m = 2, \ldots, i-1, \\ & t_{i+n}^{MTR^*} - t_{i+n-1}^{o^*} \leq \lambda \cdot \tau_{\min}, \\ & n = 2, \ldots, N-i, \\ & (z, o, pr, mtr \in MTR_i), \end{aligned} \quad (3)$$

where $\lambda = 2$, because all RS, except z, have safe time interval in the schedule τ;

$t_{i-m}^{z^*}$ – time of RS arrival/departure with a number different from z by m positions;

$o-$ queue length in case of conflicts in the schedule;

$t_{i+n-1}^{o^*}$ – time for RS movement in the queue with a sequence number different from z by $n-1$ position;

$pr-$ RS arrival/departure in RP.

For example, we need to determine the delay time of the RS, i.e. to find Δt_j^{pr}. Delay time is determined for the subset MTR_1^*, using this dependence for minimization:

$$\begin{aligned} & \min \Theta = \sum_{j=i-m_1+1}^{i+n_1-1} k_j \cdot \left| \Delta t_j^{pr} \right|, \; j \in MTR_1^*, \\ & pr \in MTR_i, \end{aligned} \quad (4)$$

where k_j – RS weight coefficient with a number j.

We should note that at determining the value k_j we take into account the calculated data on the cost per hour of the rolling stock.

Then we will find the safety evaluation for the time intervals of RS arrival/departure in the process of checking the following inequality:

$$t_{j+1}^{pr}-\Delta t_{j+1}^{pr}-t_{j}^{MTR}+\Delta t_{j}^{MTR}\geq$$
$$\geq\tau_{\min},\ j=i-m_1+1,...,i+n_1-1, \qquad (5)$$
$$pr,mtr\in MTR,$$

where $t_j^{mtr^*}$ – real time of RS arrival/departure (mtr), in the conditions of priority, i.e. $j\in MTR_{1i}^{*}$.

We believe that by applying the ADCS and the corresponding control actions, all Δt_j^{pr} can be eliminated.

Therefore, on the basis of dependencies (1) - (5) there was developed an algorithm for parallel calculations of movement coordination and RS dispatching.

This algorithm is only a small part of the software systems included in the software package for the ADCS. The main objective of this research was to test the hypothesis about the desirability of replacing the classical approach with the sequential calculation of the PS coordination parameters, which, in our opinion, is expedient with the computer equipment replacement in the ADCS. The fact of using the advantages of multi-step and parallel programming on modern processors such as i5, i7 was also taken into account.

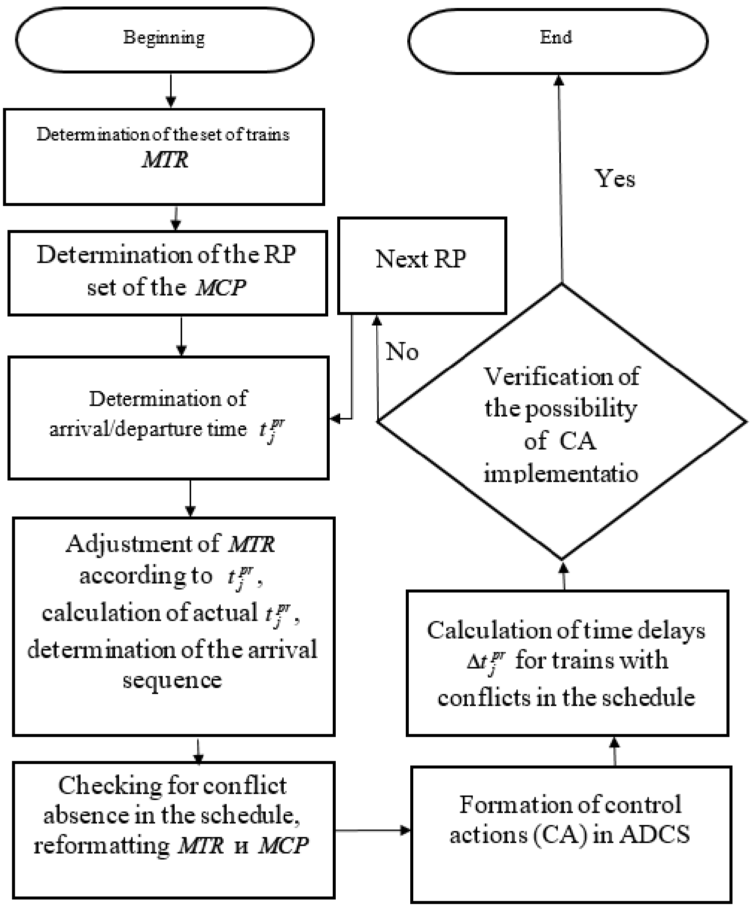

Fig. 5. Algorithm for parallel calculations of the RS movement coordination and dispatching

The Fig. 5 shows an algorithm for parallel calculations of the RS movement coordination and dispatching, obtained on the basis of our model. The algorithm involves the creation of two flows that can be processed in parallel on different cores of multi-core processors. Therefore, there is achieved an increase in the rate of control actions (CA) generation in a situation when there is occurred a large amount of conflict situations with the railway RS arrival/departure, which is primarily important for high-speed railway transport in the Republic of Kazakhstan

In order to test the effectiveness of the algorithm, there was performed an experimental check in comparison with the sequential problem solution.

The Fig. 6 shows the results of testing the parallel data processing algorithm solving problems of the RS movement coordination and dispatching. Simulation experiments were performed on a PC with an i5 processor.

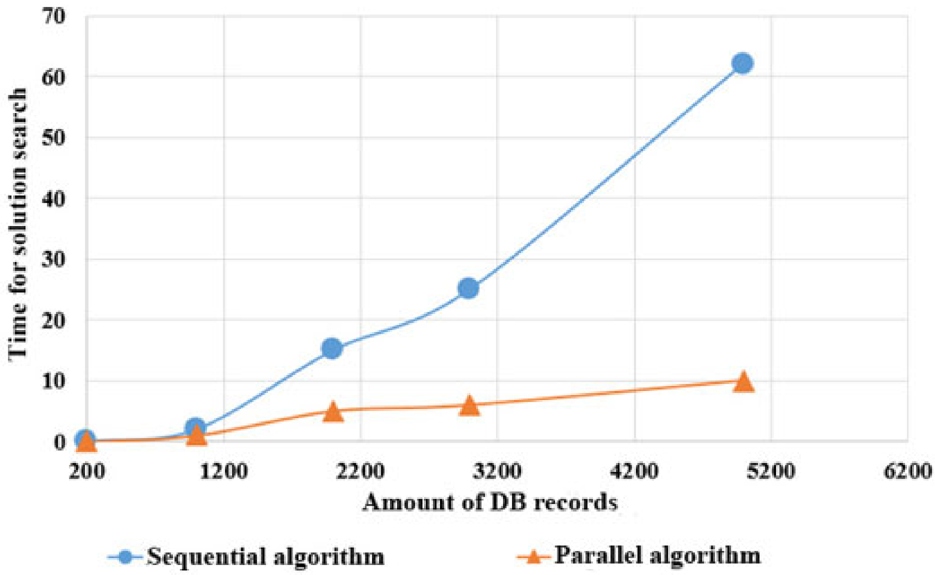

Fig. 6. Algorithm testing results

The results of simulation experiments showed that the effect from the use of parallel calculations (in comparison with the conventional railway sequential algorithm for calculating the movement schedule) is achieved through parallelization by the flow accessing the database. With the increase in the amount of records in the database, the solution time was reduced on average by 2.5–3.5 times.

Therefore, during the simulation there was tested a model and algorithm for parallel data processing. The proposed algorithm for solving the initial dispatching task is divided into separate processes. The execution of processes is carried out in parallel mode. Thus, the computational ability of the algorithm is significantly increased under the conditions of time constraints.

In our opinion, the advantage of the proposed approach is the fact that a new algorithm has been developed for solving the problems of the movement coordination and dispatching of the RS schedule. The algorithm, in comparison with the existing solutions, takes into account the possibility of using parallel computing technologies. Experimental verification of the proposed algorithm showed that the actual processing time of the received data and the generation of control actions for the PS dispatching, compared with the sequential processing of the initial data, decreased by 24–47 %.

Prospects for further research are following: it is necessary to test a model that minimizes the deviations of the time intervals of the PS arrival at the station; to minimize control costs associated with the modernization of the ADCS.

Conclusion

The present study comprehensively analyzed the integration of traditional, additive, and nanotechnologies in railway engineering, focusing on improving the quality, reliability, and durability of rolling stock (RS) and track machines (TM). The research objectives—investigating additive technologies, evaluating nanotechnologies, optimizing quality control methods, and assessing economic impacts—have been successfully realized through a combination of theoretical analysis, experimental investigations, and process modeling.

The findings demonstrate that additive technologies (3D printing) provide unprecedented flexibility in the production of complex components. Unlike conventional manufacturing methods, additive processes allow for layer-by-layer construction of parts directly from digital models, minimizing material waste, reducing production costs, and enabling weight reduction without compromising structural integrity. This contributes not only to improved operational efficiency but also to environmental sustainability by decreasing raw material consumption.

Nanotechnologies were shown to have a transformative impact on component performance. By manipulating materials at the atomic and molecular scale, it is possible to produce defect-free structures with enhanced physical, chemical, and mechanical properties. The application of nanostructured coatings to cutting tools, springs, bearings, and critical RS/TM components significantly increases wear resistance, corrosion resistance, and durability. In particular, ultra-high-strength springs produced with optimized thermal and mechanical processing demonstrated improved fatigue resistance, reliability under low-temperature conditions, and extended operational lifespan. These innovations have the potential to increase component life by 2–5 times, reduce maintenance requirements, and improve overall safety in railway operations.

Quality control methods, including high-precision sensors, fiber-optic photonic devices, and industrial computed tomography (CT), were integrated into production processes to monitor part geometry, material composition, and microstructural integrity. This ensures that any deviations from required specifications are detected early, thereby reducing scrap rates and enhancing the reliability of manufactured components. Such measures also allow for optimization of production parameters before part fabrication, minimizing errors and improving economic efficiency.

The practical significance of this research is substantial. The proposed integration of additive and nanotechnologies, alongside flexible manufacturing systems and advanced diagnostic tools, provides a pathway to modernize railway engineering, reduce production costs, improve energy efficiency, and extend maintenance intervals. The technologies and methods developed in this study can be applied across various sectors of transport engineering, including automotive, aerospace, and high-precision industrial manufacturing. Additionally, these solutions support import substitution strategies by producing high-performance components that match or exceed the quality of foreign analogues.

From a scientific perspective, the study contributes to the advancement of knowledge in manufacturing technologies, materials science, and industrial engineering. It demonstrates the feasibility of synergistically combining traditional, additive, and nanotechnologies within a single production framework, highlighting the benefits of multidisciplinary approaches for complex engineering systems.

Future research directions include:

- Further optimization of additive manufacturing processes using artificial intelligence, machine learning, and digital twin simulations.
- Development of novel nanomaterials with enhanced mechanical, thermal, and tribological properties for railway components.
- Expansion of in-line and non-destructive quality control using industrial CT, advanced sensors, and real-time monitoring systems.
- Comprehensive economic analysis of integrating these advanced technologies at large-scale industrial operations.
- Exploration of additional applications of nanocoatings and additive manufacturing in other transport and industrial sectors, including energy and construction machinery.

In conclusion, this study confirms that the integration of traditional, additive, and nanotechnologies, combined with flexible manufacturing systems and advanced quality control methods, significantly improves the reliability, durability, and economic efficiency of railway components. The findings provide a strong foundation for further technological innovation, ensuring safer, more efficient, and more sustainable railway operations, and represent a meaningful contribution to the scientific and practical development of modern railway engineering.

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