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MAGLEV'S MECHANICAL SUBSYSTEM'S IN SPACE OF IT'S STATES MOTION HIERARCHICAL CONSTRUCTION ALGORITHMIC MODEL

АЛГОРИТМІЧНА МОДЕЛЬ ІЄРАРХІЧНОГО ПОБУДУВАННЯ РУХУ МЕХАНІЧНОЇ ПІДСИСТЕМИ МАГНІТОЛЕВІТУЮЧОГО ПОЇЗДА У ПРОСТОРІ ЇЇ СТАНІВ

The key criterion for an a maglev train's evaluating consumer properties is the quality of transportation. Therefore, the construction of the necessary quality of the movements of its trains should be chosen as the ultimate goal of the study of the mentioned system.

Usually, the mechanical system, which can be accepted as an adequate calculation scheme of the mechanical subsystem of the train, is large, significantly non-linear and complex. In addition, with rare exceptions, such a system is multi-connected, and its movement occurs in an unpredictable external and internal environment. The use of single-level regulators for the construction of movements of the described type of systems usually leads to unsatisfactory quality of movements. The resulting collision can be eliminated during their hierarchical construction, which significantly increases the efficiency of the associated processing and use of large arrays of information, and therefore the resulting quality of the controlled movement.

Factors affecting the quality of movement of the train's mechanical subsystem are: properties of this subsystem; the current internal and external situation in which it is implemented; features of the subsystem regulator. Based on the above, the three-level structure of the aforementioned regulator is sufficient: at its grassroots level — the introcontroller, which implements the necessary set of movement patterns of the train's mechanical subsystem, as well as their sustainable synergies; at the intermediate level — an adapter that adapts the movement to the situation; at the top level - a coordinator, which comprehensively solves, in synthetic interaction with blocks of previous levels, the motor task of the mechanical subsystem. So, the resulting movement of the mechanical subsystem of the train is built in the process of synthetic interaction of the three described levels of the regulator.

The main advantage of the proposed algorithmic model for the hierarchical construction of the motion of the mechanical subsystem of the magneto-levitating train in its state space is the possibility of accurate, adequate and heuristic decomposition of the global task of such construction into a number of simpler sub-tasks, many of which, to a large extent, can be solved in advance. Thanks to this, there is a real possibility of a more accurate solution to the mentioned sub-tasks, which, in turn, allows you to significantly increase the quality of the designed movement without using complex control algorithms.

Keywords*: maglev train; mechanical subsystem; motion's quality; hierarchical construction of motion; state space.*

Споживча цінність транспортної системи з магнітолевітуючими поїздами однозначно визначається якістю механічного руху цих поїздів. Тому, як кінцева мета вивчення згаданої системи, повинна бути обрана побудова необхідної якості рухів її поїздів.

Для надання рухам необхідних властивостей, моделюючі рівняння повинні бути сумісними з цільовими співвідношеннями, які описують ці властивості. Якщо згадана сумісність *досягається, то рух підсистеми гарантовано має бажані властивості. Процес переходу від природного до керованого руху називається його побудовою.*

Зазвичай, механічна система, яка може бути прийнята як адекватна розрахункова схема механічної підсистеми поїзда, є великою, істотно нелінійною і складною. Крім того, за рідкісним винятком, така система є багатозв'язковою, а її рух відбувається в непередбачуваній зовнішній та внутрішній обстановці. Використання однорівневих регуляторів для побудови рухів описаного типу систем зазвичай веде до незадовільної якості рухів. Виникаюча колізія може бути усунена при їхній ієрархічній побудові, що значно підвищує ефективність пов'язаної з нею переробки та використання великих масивів інформації, а тому — і результуючу якість керованого руху.

Факторами, які впливають на якість руху механічної підсистеми поїзда, є: властивості цієї підсистеми; поточна внутрішня та зовнішня обстановка, в якій він реалізується; особливості регулятора підсистеми. Виходячи з зазначеного, достатньою є трирівнева структура згаданого регулятора: на його низовому рівні — інтроконтролер, який реалізує необхідний набір патерн рухів механічної підсистеми поїзда, а також їх стійких синергій; на проміжному рівні — адаптер, що пристосовує рух до обстановки; на верхньому рівні — координатор, який вичерпно вирішує, у синтетичній взаємодії з блоками попередніх рівнів, рухову задачу механічної підсистеми. Отже, результуючий рух механічної підсистеми поїзда будується у процесі синтетичної взаємодії трьох описаних рівнів регулятора.

Основна перевага пропонованої алгоритмічної моделі ієрархічної побудови руху механічної підсистеми магнітолевітуючого поїзда в просторі її станів полягають у можливості точної, адекватної та евристичної декомпозиції глобальної задачі такої побудови на низку більш простих підзадач, багато з яких, у значній частині, можуть бути вирішені заздалегідь. Завдяки цьому виникає реальна можливість більш точного вирішення згаданих підзадач, що, у свою чергу, дозволяє істотно підвищувати якість конструйованого руху без використання складних алгоритмів керування ним.

***Ключові слова**: магнітолевітуючий поїзд; механічна підсистема; якість рухів; ієрархічна побудова рухів; простір станів.*

Formulation of the problem

Transport system with magnetically levitating trains is designed to move passengers and cargo. This movement is the main function of this system. Being a complex artifact, it includes various subsystems. Their functioning is based on various physical, chemical, and other natural principles and effects. However, based on the main function of this system, the quality of the mechanical movement of its trains, as a result, unambiguously determines the consumer value of the system as a whole.

Modern stage of development of society is characterized by an exponential increase in the intensity of this development. This has a direct bearing, in particular, on the transport systems that serve it. In this regard, the purely analytical level of research on their functioning is insufficient. Therefore, the paradigm of such research will inevitably have to be shifted in order to achieve its maximum creativity. As for transport systems with magnetically levitated trains, this means, in particular, the need to build, as the ultimate goal of studying such systems, the required quality of their train movements

Analysis of recent research and publications

Until now, researches on the problem of controlled dynamics of the mechanical subsystem of a magnetic levitating train have not been comprehensive. As a rule, either the purely mechanical aspects of this problem were considered separately [1, 2] or its cybernetic issues [3, 4]. This problem was not considered comprehensively. In addition, research on such dynamics has not been performed using subsystem state space methods. This inevitably had a negative impact on the objectivity, and therefore on the resulting value of the results of such research.

Formulation of the research purpose

Natural (i.e., those that occur under the influence of only uncontrollable — natural disturbances) movements of the train's mechanical subsystem can be described by the model [5]

$$a_{\lambda\mu}\cdot\eta^{\mu}=E_{\lambda};\quad a_{\lambda\mu}=c_{\lambda\mu}\cdot p^{(2)}+(\mathrm{C}_{\lambda,\mu\nu}\cdot\eta^{\nu}+\beta_{\lambda\mu})\cdot p+l_{\lambda\mu};\quad p=\frac{d}{dt}\forall\lambda,\mu,\nu\in[\overline{1,L}], \qquad (1)$$

where $\eta^{\mu}\ \forall\mu\in[\overline{1,L}]$, L — generalized coordinates of the design scheme of the mechanical subsystem of the train, as well as the number of such coordinates; $c_{\lambda\mu},C_{\lambda,\mu\nu}\ \forall\lambda,\mu,\nu\in[\overline{1,L}]$ — covariant metric tensor of the mentioned aggregate, as well as its three-index Christoffel symbol of the 1st kind; $\beta_{\lambda\mu},l_{\lambda\mu}\forall\lambda,\mu\in[\overline{1,\mathrm{L}}]$ — dissipative and quasi-elastic coefficients of the above model; $E_{\lambda}\forall\lambda\in[\overline{1,L}]$ — external disturbances of the subsystem.

Natural motions usually do not have the required properties. To give the motions such properties, the modeling equations must be modified so that they become compatible with the target relations that describe these properties and link the components of the subsystem state [6]. For example, control influences can be applied to it $\Pi_{\lambda}\forall\lambda\in[\overline{1,L}]$. If the above compatibility is achieved, the surface described by the target relations becomes an attractor of the subsystem's depicting state point, and its motion is guaranteed to have the desired properties. The process of transition from natural to controlled motion is called its construction [6].

Typically, a mechanical system that can be accepted as an adequate design scheme for a train's mechanical subsystem is large, significantly nonlinear, and complex [7]. In addition, with rare exceptions, such a system is multi-connected, and its movement occurs in an unpredictable external and internal environment. In such cases, as is known [8], the main difficulties that complicate the construction of movements of real technical systems are: a large number of their degrees of freedom to be controlled, the finite rigidity of the links of kinematic chains, as well as the requirement (in the vast majority of cases) of a merged, continuous, interconnected implementation of the phases of such movements in the form of their expedient synergies.

Using single-level controllers to build movements of the described type of systems usually leads to unsatisfactory quality of movements [9]. The arising conflict can be eliminated by their hierarchical construction, which significantly increases the efficiency of the associated processing and use of large amounts of information [10], and therefore the resulting quality of the controlled motion. This is achieved, among other things, through systematization, structuring, level gradation, detailing and specification, and therefore the completeness of coverage and use of the above information about the system state at different levels of its control. Each of these levels is characterized by structural and functional information selectivity and differentiation, and therefore by the ability to implement the range of functions selected for it with high quality. The emergence of such a system is manifested by the hierarchical synthesis of the functioning of the levels of movement construction in its resulting quality.

Presentation of the main material

Results of the analysis of the problem of constructing the movement of the mechanical subsystem of a magnetically levitating train indicate that the main factors affecting the quality of this movement are: the properties of the subsystem that determine its sufficiency (kinematic and dynamic) to perform such movement; the current internal and external environment in which it is implemented; features of the subsystem regulator, first of all, its functioning algorithm.

Based on the above, a three-level structure of the above regulator is sufficient: at its lower level — an introcontroller that implements the required set of movements of the train's mechanical subsystem, as well as their stable synergies; at the intermediate level — an adapter that adapts the movement to the situation; at the upper level - a coordinator that exhaustively solves, in synthetic interaction with the blocks of the previous levels, the motor task of the mechanical subsystem. The functional globosity of these blocks increases in the inverse order: the coordinator is the leading synthesizing level of the controller; the adapter is the intermediate, matching level; the introcontroller is the background, provider level.

If the programmatic relations of the attractor of the depicting point of the subsystem state are complete, then a law can be explicitly obtained from them, which is a constructive representation of the movement that has the desired properties:

$$\eta^{\lambda} = \eta^{\lambda}(t) \ \forall \lambda \in [\overline{1,L}], \tag{2}$$

where t — current time.

For realization of such motion, as mentioned, control influences can be applied to the mechanical subsystem, in particular, to control the motion. Since, in this case, we are talking about the "intra-system" control of the subsystem motion synthesized at the lower level of the controller hierarchy, then (for this case) in equations (1), we should accept $E_{\lambda} \equiv 0 \forall \lambda \in [\overline{1,L}]$ and, in addition, supplement their right-hand sides with the terms $\Pi_{l\lambda} \ \forall \lambda \in [\overline{1,L}]$, which are the basic components of the values $\Pi_{\lambda} \ \forall \lambda \in [\overline{1,L}]$, that are realized in a "pure" form only for the synthesis of the original movement patterns. After that, from the model (1) transformed in the above way, the laws according to which the control of this lower level should change can be found:

$$\Pi_{l\lambda}(t) = c_{\lambda\mu}(t) \cdot \ddot{\eta}^{\mu}(t) + [C_{\lambda,\mu\nu}(t) \cdot \dot{\eta}^{\nu}(t) + \beta_{\lambda\mu}(t)] \cdot \dot{\eta}^{\mu}(t) + l_{\lambda\mu}(t) \cdot \eta^{\mu}(t) \quad \forall \lambda, \mu, \nu \in [\overline{1,L}], \tag{3}$$

that the " inner-system" (i.e., externally undisturbed) motion is described by the necessary equations (2).

Therefore, the considered lower level of motion construction (introcontroller) to best meet its purpose (in addition to wide, accurate and prompt access to the information constituting the first macro group of information support of the regulator) should have the most complete set of laws of type (2) and (3), as well as, of course, a developed search module that allows efficient display of the following types:

$$R : H \to P_l;\ H = \{\eta^{\lambda}(\bullet) \ \forall \lambda \in [\overline{1,L}]\};\ P_l = \{\Pi_{l\lambda}(\bullet) \ \forall \lambda \in [\overline{1,L}]\}, \tag{4}$$

where H, P_l — sets of laws of the desired, externally undisturbed movements of the subsystem, as well as lower-level controls that are necessary for the realization of these movements; R — is a display operator that operates with H in P_l.

Hereinafter, any function with a point in place of an argument implies a set of values of this function for all valid values of such an argument.

One of the expedient forms of organizing this mapping may be to place in the memory of the described controller level the "motion-control" dictionary, the allocation of which as a separate block will simplify the logical structure of the controller algorithm, as well as quite simply change and increase the rules of its response in the process of processing current information flows.

Synthesized movement of a subsystem occurs in a changing environment that is generally unpredictable. However, this movement must remain purposeful. One of the most effective ways to overcome this difficulty is to correct and coordinate the components of the said movement (implemented by the intro controller), which requires, in turn, prompt monitoring of the internal and external environment of the movement. Therefore, the main functional purpose of the intermediate level of construction of such a movement should be to give it the property of adaptability to the environment, which is possible based on the results of processing the second information macro group and requires, first of all, the classification of this environment. For motor adaptation, it is obviously sufficient to classify the environment according to the principle of dichotomy — in the form of successive levels of classes, which should be followed by its parameterization. The latter means that each distinguished class of environment should be unambiguously matched with a set of parameters that are essential for movement, available for observation, and uniquely identify such a class of environment. When solving different motor tasks, the classification (and, as a result, parameterization) of the same environment can differ significantly.

When the external and/or internal environment of the movement changes from class to class, a decision must be made on the strategy for adapting this movement, that is, how to form controlling influences on it $\Pi_{m\lambda}(t) \ \forall \lambda \in [\overline{1,L}]$ from the adaptation level of the regulator (adapter) in the new conditions. Like the situation, solutions must be parameterized. After that, the following dependencies should be established:

$$\alpha_d = \alpha_d(\nu_c, t), \tag{5}$$

where ν_c, α_d — environment and solution parameters.

In other terms, solutions should track the situation. Then the current structure of interaction of the functional modules of the considered level of the controller in the process of building the movement can be determined by the block of classification of the situation depending on the class that has been implemented, and, in each specific situation, be a reflection (generally speaking, ambiguous) of the structure of the situation, for example, according to the ratio

$$\aleph : \Gamma \to S\,, \tag{6}$$

where Γ and S — sets of environment classes and adapter structures; $\aleph$ — is a (ambiguous) mapping operator that operates from Γ in S.

Traffic conditions, as noted, can change unpredictably. Therefore, sufficiently adequate algorithms for synthesizing the necessary laws of the $\Pi_{m\lambda}(t)\ \forall \lambda \in [\overline{1, L}]$ can be constructed only using differential game methods [11], which conceptually guarantee the quality of adaptation, which is assessed by the value of the integrative (multi-criteria characterizing the mentioned quality of adaptation) functional . Then these laws can be determined from expressions such as:

$$I = \inf_{P_m} \sup_{W} \Lambda \,\langle \Pi_{m\lambda}(t), E_\lambda(t) : P_m = \{\Pi_{m\lambda}(\bullet)\}, W = \{E_\lambda(\bullet)\} \quad \forall \lambda \in [\overline{1, L}], t \in [t_s, \tau] \rangle, \tag{7}$$

where P_m, W — sets of controls of the adaptive level of motion construction, as well as its perturbations; Λ — functionality used to assess the quality of motion adaptation; $[t_s, \tau]$ — interval for building the movement of the mechanical subsystem of the train.

Adaptation level of the controller may include a “situation — control” dictionary. To do this, in addition to the situation classification (recognition) unit, which has a rich set of parameterized expected traffic conditions, this level of its construction should include a search module that effectively implements the display of the following:

$$N : \Gamma \to P_m, \tag{8}$$

where N – display operator that operates from Γ in P_m.

The result of the subsystem movement implementation should be an exhaustive solution to the tasks it faces. However, the described levels of construction of this movement (neither individually nor in combination) are not able to provide such a solution. This is purpose of the top level regulator (coordinator). Processing the information of the third macrogroup, and, therefore, based on the global goals of the constructed movement, this level of its construction should, first of all, determine the algorithm for achieving such goals, i.e., display the following:

$$Q : A \to \Xi, \tag{9}$$

where A, Ξ — sets of objectives arising from the motor tasks to be solved, as well as algorithms for solving them; Q — mapping operator (in the general case, ambiguous), which operates from A to Ξ.

Similarly to the mappings (4) and (8), the relation (9) can be reasonably realized by the corresponding search module after placing the coordination level of the “task-algorithm” dictionary controller in the memory.

Movement tasks to be solved (with their detailing to the goals pursued) should be set before the subsystem from the outside (for example, by means of a tasking module) and adjusted to the current situation (which is assessed by the adapter). Therefore, specification as an element of a set A, and the type of operator Q in each case should be carried out taking into account both the goals and the traffic situation. Algorithms that are elements of the set Ξ, in the vast majority of cases, may have a chain structure in the sense that each of them may involve the sequential implementation of a number of more or less diverse groups of movement patterns interconnected by the meaning of the motor task, such that, as a result of this implementation, naturally lead to its exhaustive solution. Therefore, after identifying a general algorithm for such a solution, the motor composition of the task (i.e., the minimum sufficient set of the mentioned movement patterns) should be determined, requests for their implementation should be initiated (under the direct control of the introcontroller in interaction with the adapter), and careful monitoring and adjustment (for example, using the arcane algorithm [6]) of this implementation should be carried out. The result of this block of operations is the synthesized control $\Pi_{u\lambda}(t)\ \forall \lambda \in [\overline{1, L}]$. Thus, at any given moment, both the information flows of the coordinator (between it, on the one hand, and the tasker, adapter, and introcontroller, on the other) and the background patterns of movements that serve its functioning must be relevant to the task they solve (in aggregate). At the same time, the functional organization of such a solution should always precede its motor organization.

Thus, the resulting movement of the train's mechanical subsystem is built in the process of synthetic interaction of the three levels of the controller described above. The leading role in such a construction always belongs to its upper "level - coordinator", which, with the help of the synthesized controls $\Pi_{u\lambda}(t)\ \forall\lambda\in[\overline{1,L}]$, coordinates the work of the two lower levels so that the resulting movement always remains focused, i.e., exhaustively solves the tasks it faces. These tasks, with details of the goals pursued, are set externally, for example, using a tasking module. The basis of the construction is motion patterns, as well as their stable synergies, constructed by the lower level of the controller - the intro controller (taking into account all the "internal" features of the control system) under the influence of the following controls $\Pi_{l\lambda}(t)\forall\lambda\in[\overline{1,L}]$. Finally, motion adaptation to the environment is carried out under the influence of controls $\Pi_{m\lambda}(t)\forall\lambda\in[\overline{1,L}]$, synthesized by an intermediate level of the regulator — an adapter that also adjusts the motor tasks to be solved based on the results of the situation assessment.

Conclusions

Thus, as a result of this work, an algorithmic model of the hierarchical construction of the movement of the mechanical subsystem of a magnetic levitating train in the space of its states has been developed. The main advantage of this model is the possibility of an accurate, adequate and heuristic decomposition of the global problem of such construction into a number of simpler subproblems, many of which can be solved in advance, under stationary conditions at the design stage of the subsystem regulator. Due to this, there is a real possibility of a more accurate solution of these subtasks, which, in turn, allows to significantly improve the quality of the designed motion without the use of complex control algorithms.

References

[1] Liu, Y.; Deng, W. & Gong, P. (2015) Dynamics of the Bogie of Maglev Train with Distributed Magnetic Force. Shock and Vibration. 2015, 1–12. DOI: 10.1155/2015/896410.

[2] Dai, J.; Lim, J. G. & Ang, K. K. (2023). Dynamic Response Analysis of High-Speed Maglev-Guideway System. Journal of Vibration Engineering & Technologies. 11, 2647–2659. DOI: 10.1007/s42417-023-00995-5.

[3] Li, F.; Sun, Y.; Xu, J.; He, Z. & Guobin, Lin G. (2023). Control Methods for Levitation System of EMS-Type Maglev Vehicles: An Overview. Energies. 16(7), 2995. DOI: https://doi.org/10.3390/en16072995.

[4] Jibril, M.; Tadese, M. & Tadese, E. A. (2020). Design and Control of EMS Magnetic Levitation Train using Fuzzy MRAS and PID Controllers. IJARIIE. 6(2), 1023-1031. DOI: 10.48175/568.

[5] Polyakov, V. A. & Hachapuridze, N. M. (2016) *Modelirovanie protsessa realizatsii tyagovoy silyi dvigatelem magnitolevitiruyuschego poezda* [The traction force process implementing by a magnetically levitated train's motor modeling]. *Nauka ta prohres transportu.* 4(64), 55–62. Retrieved from: https://stp.ust.edu.ua/article/view/77909/75717.

[6] Mishchenko, I. V. (2023) *Teoretychna mekhanika: konspekt lektsii*. [Theoretical mechanics: lecture notes]. Kharkiv: KhNADU. Retrieved from: https://dspace.khadi.kharkov.ua/items/236411b3-ee91-4a61-bded-f8fe3d9ecfaf/full.

[7] Dzenzerskiy, V. A.; Radchenko, N. A. & Malyiy, V. V. (2015) *Dinamika magnitolevitiruyuschih ekipazhey. Dinamika ekipazhey netraditsionnyih konstruktsiy na sverhprovodyaschih magnitah.* [Magnetic levitating vehicles's dynamics. Vehicles's of non-traditional designs on superconducting magnets dynamics]. Palmarium academic publishing. 256 p. Retrieved from: https://www.old.nas.gov.ua/UA/Book/Pages/default.aspx?BookID=0000009533.

[8] Úednícek, Z. & Maloch, J. (2020) Active damping of multidimensional mechanic systems. MATEC Web of Conferences. Retrieved from: https://www.matec-conferences.org/articles/matecconf/pdf/2017/39/matecconf_cscc2017_02020.pdfhttps://www.matec-conferences.org/articles/matecconf/pdf/2017/39/matecconf_cscc2017_02020.pdf// DOI: 10.1051/02020 (2017) 71250 1 MATEC Web of Conferences 25 matecconf/201 CSCC 2017 2020.

[9] Roszkowska, E.; Makowski-Czerski, P. & Janie, L. (2023) Multi-level control for multiple mobile robot systems. Discrete Event Systems. 33, 425–453. DOI: 10.1007/s10626-023-00383-x.

[10] Ud Din, W.; Zeb, K.; Ishfaq, M.; Islam, S.; Khan, I. & Kim, H.J. (2019) Control of Internal Dynamics of Grid-Connected Modular Multilevel Converter Using an Integral Backstepping Controller. Electronics. *8*, 456. DOI: 10.3390/electronics8040456.

[11] Gammoudi, N. & Zidani, H. A (2022) Differential game control problem with state constraints. Mathematical Control and Related Fields. 10, 1–28. DOI: 10.1016/j.camwa.2022.01.016.

Список використаної літератури

1. Liu Y., Deng W., Gong P. Dynamics of the Bogie of Maglev Train with Distributed Magnetic Force. *Shock and Vibration.* 2015. Vol. 2015, P. 1–12. DOI: 10.1155/2015/896410.
2. Dai J., Lim J. G., Ang K. K. Dynamic Response Analysis of High-Speed Maglev-Guideway System. *Journal of Vibration Engineering & Technologies.* 2023. Vol. 11. P. 2647–2659. DOI: 10.1007/s42417-023-00995-5.
3. Li F., Sun Y., Xu J., He Z., Guobin Lin G. Control Methods for Levitation System of EMS-Type Maglev Vehicles: An Overview. *Energies* 2023, No. 16(7), 2995. DOI: https://doi.org/10.3390/en16072995
4. Jibril M., Tadese M., Tadese E. A. Design and Control of EMS Magnetic Levitation Train using Fuzzy MRAS and PID Controllers. *IJARIIE.* 2020. Vol. 6 Issue 2. P. 1023–1031. DOI: 10.48175/568.
5. Поляков В. А., Хачапуридзе Н. М. Моделирование процесса реализации тяговой силы двигателем магнитолевитирующего поезда. *Наука та прогрес транспорту.* 2016, No. 4 (64) С. 55–62. DOI: 10.15802/stp2016/77909
6. Міщенко, І. В. Теоретична механіка: конспект лекцій. Харків: ХНАДУ, 2023. 207 с. URL: https://dspace.khadi.kharkov.ua/items/236411b3-ee91-4a61-bded-f8fe3d9ecfaf/full.
7. Дзензерский В.А., Радченко Н.А., Малый В.В. Динамика магнитолевитирующих экипажей. Динамика экипажей нетрадиционных конструкций на сверхпроводящих магнитах. Palmarium academic publishing. 2015. 256 с. URL: https://nvd-nanu.org.ua/f107e611-d98f-c0d1-eb6a-9756e31c593b/.
8. Úednícek Z., Maloch J. Active damping of multidimensional mechanic systems. *MATEC Web of Conferences*. DOI: 10.1051/02020 (2017) 71250 1 MATEC Web of Conferences 25 matecconf/201 CSCC 2017 2020
9. Roszkowska E., Makowski-Czerski P., Janiec L. Multi-level control for multiple mobile robot systems. *Discrete Event Systems*. 2023. Vol. 33. P. 425–453. DOI: 10.1007/s10626-023-00383-x.
10. Ud Din W., Zeb K., Ishfaq M.; Islam S., Khan I., Kim H.J. Control of Internal Dynamics of Grid-Connected Modular Multilevel Converter Using an Integral Backstepping Controller. *Electronics*. 2019. No. *8*, 456. DOI: 10.3390/electronics8040456.
11. Gammoudi N., Zidani H. A Differential game control problem with state constraints. *Mathematical Control and Related Fields.* 2022. No. 10. P. 1–28. DOI: 10.1016/j.camwa.2022.01.016.

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