UDC 681.5+ 004.94
DOI https://doi.org/10.32782/2072-2052.2024.4.67.2

AUTOMATED WAREHOUSE LOGISTICS SYSTEMS ENERGY EFFICIENCY IMPROVMENT

Maksym Vzhesnievskyi
PhD student at the third (educational and scientific) level of higher education in the educational at the Department of Computer-Integrated Technologies, Automation and Robotics,
Kharkiv National University of Radio Electronics, 14 Nauky ave., Kharkiv, Ukraine, 61166, maksym.vzhesnievskyi@nure.ua
ORCID: 0000-0002-7585-628X

Olena Chala
Candidate of Technical Sciences, Associate Professor, Associate Professor at the Department of Computer Integrated Technologies, Automation and Robotics,
Kharkiv National University of Radio Electronics, 14 Nauky ave., Kharkiv, Ukraine, 61166, olena.chala@nure.ua
ORCID: 0000-0003-2454-3774

The paper presents ways to increase the energy efficiency of automated warehouse logistics systems by selecting the optimal speeds of an automatic shuttle vehicle. Relevant field tests were carried out, corresponding to different average speeds. The problem of the movement automatic control for a shuttle vehicle in intrawarehouse systems under conditions of uncertainty is investigated, which uses mathematical models when selecting the parameters of the best control solution – to increase the energy efficiency and productivity of technological systems within the INDUSTRY 5.0 concept. The object of the study is the process of automatic control of shuttle vehicles in automated intra-warehouse systems. The subject of the study is a set of mathematical models and methods that describe the process of automatic control of shuttle vehicles. A mathematical model of the controlled technological process of the functioning of a shuttle vehicle in automated intra-warehouse systems was improved, which is based on the use of controllers with intelligent systems, which is based on the justification of the current parameters of production processes using computer-integrated technologies, which made it possible to ensure the saving of electric energy of intelligent shuttle vehicles by optimizing speed. To verify the reliability of the constructed differential equations of the mathematical model of electromechanical processes in the shuttle vehicle, it is proposed to build an experimental setup for studying an electromechanical system equivalent in terms of differential equations in the form of a DC electric motor with a gearbox and a test wheel for modeling viscous resistance. The measurement results obtained during such field tests indicate that electric energy can be saved by selecting optimal speeds in the range of approximately 1.4% to 3.4%, depending on the average speed.

Key words: Automation, Logistics, Energy Efficiency, Mobile Transportation Robot, PID Controller, Speed.

RELEVANCE. Energy efficiency and energy saving are integral components of the energy security of the state, as well as its innovative sustainable development. Against the background of today's events in the global energy arena, they appear more often and once again prove their strategic importance not only for the development and reliable energy supply, but also directly for the sovereignty and independence of the state.

The ways to increase energy efficiency can be different. You can use the path of complete replacement and transition to complex energy-saving production, but this requires quite large financial, time and project investments.

In the opinion of the authors, the path of improving existing systems by developing and modernizing their individual components is more appropriate, which entails lower costs, both financial and time.

The purpose of the work is to improve automation systems in intra-warehouse logistics, taking into account energy efficiency requirements, by developing models and methods for automatic control of shuttle vehicles.

The authors proposed a method based on an improved mathematical model of automatic control of a shuttle vehicle in automated intra-warehouse systems, which is based on the use of PID controllers with elements of intellectualization and substantiation of optimal speed parameters, which made it possible to ensure energy efficiency of intra-warehouse logistics systems.

MATERIALS AND RESEARCH RESULTS. An automatic shuttle vehicle (essentially a mobile transport robot) is a complex electromechanical system, but the mathematical model proposed by the authors [1] in the form of a nonlinear system of differential equations with initial conditions allows us to evaluate the processes in it.

Such a definition involves solving the corresponding nonlinear system of two second-order differential equations with the corresponding initial conditions [2–5], which in fact represents a rather complex mathematical problem, which in the general case can only be solved approximately using computational methods.

Second-order differential equations, due to their compact form, are quite convenient for representing a mathematical model of processes in a shuttle vehicle [7–9].

$$x_1 = q_1,\ x_2 = q_2,\ x_3 = \dot{q}_1,\ x_4 = \dot{q}_2, \tag{1}$$

where x_1, x_2, x_3 and x_4 – new variables, which are the generalized coordinates and velocities of the shuttle vehicle as an electromechanical system.

Let us transform the differential equations to the form:

$$\ddot{q}_1 = \frac{1}{J} M\left(\dot{q}_1, \dot{q}_2\right), \tag{2}$$

$$\ddot{q}_2 = -\frac{B_e}{L_e}\dot{q}_1 - \frac{R_e}{L_e}\dot{q}_2 + \frac{1}{L_e}U_e\left(t\right). \tag{3}$$

Thanks to the introduced new variables (1), the differential equations (2), (3) of the mathematical model of the processes occurring in the shuttle vehicle will be written as a system of four first-order differential equations:

$$\begin{cases} \dot{x}_1 = x_3, \\ \dot{x}_2 = x_4, \\ \dot{x}_3 = \dfrac{1}{J} M\left(x_3, x_4\right), \\ \dot{x}_4 = -\dfrac{B_e}{L_e}x_3 - \dfrac{R_e}{L_e}x_4 + \dfrac{1}{L_e}U_e\left(t\right), \end{cases} \tag{4}$$

$$x_1\left(t_0\right) = \varphi_0,\ x_2\left(t_0\right) = \omega_0,\ x_3\left(t_0\right) = \kappa_0,\ x_4\left(t_0\right) = I_0. \tag{5}$$

The third differential equation uses the generalized force expression, and this expression for the new variables (1) will take the form:

$$M\left(x_3, x_4\right) = \begin{cases} -Bx_3 + 2B_e x_4 - mg\delta \,\mathrm{sign}\left(x_3\right), & x_3 \neq 0, \\ \dfrac{1}{2}\left(\left|2B_e\left|x_4\right| - mg\delta\right| + 2B_e\left|x_4\right| - mg\delta\right)\mathrm{sign}\left(x_4\right), & x_3 = 0. \end{cases} \tag{6}$$

Thus, in the form (4)–(6) we have a mathematical model of the processes occurring in the shuttle vehicle as in an electromechanical system, and this form corresponds to the standard form of recording differential equations, which is assumed in most computational methods.

For computer modeling of the processes occurring in the shuttle vehicle, the free-to-use universal open-source computer system Scilab was used, which was developed specifically for performing scientific and engineering calculations, as well as for modeling processes [10–11].

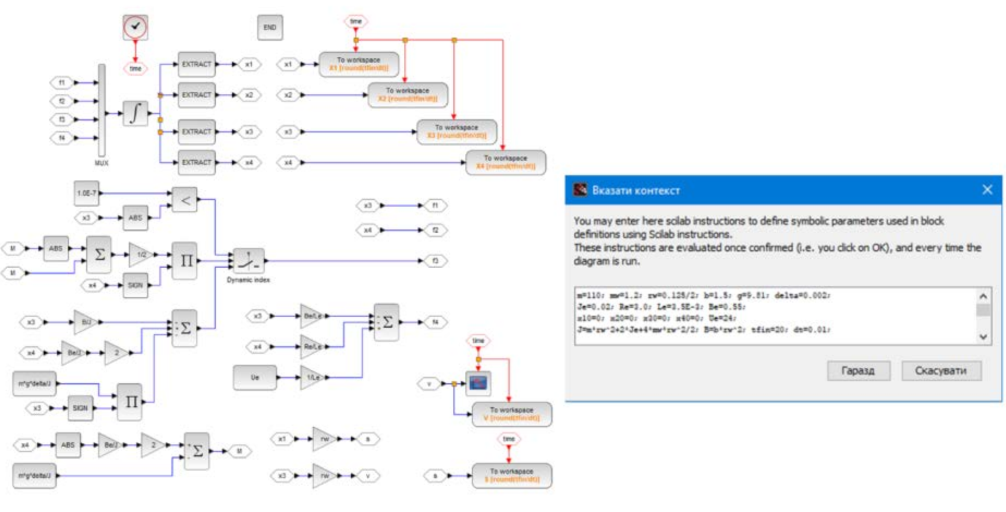
When performing computer modeling, the following initial data were taken:

$$m = 110\ \text{кг},\ b = 1{,}5\,\frac{\text{кг}}{\text{с}},\ m_w = 1{,}2\ \text{кг},\ r_w = 62{,}5\ \text{мм},\ \delta = 2\ \text{мм}, \tag{7}$$

$$J_e = 0{,}02\ \text{кг}\cdot\text{м}^2,\ R_e = 2{,}0\ \text{Ом},\ L_e = 25\ \text{мГн},\ B_e = 0{,}55\,\frac{\text{Н}\cdot\text{м}}{\text{А}} \tag{8}$$

The initial data (2), (9) approximately correspond to the shuttle vehicle, the design of which was developed by the authors in [2] Fig. 1, and take into account the self-weight of the shuttle vehicle and the cargo, and a computer model was developed.

In the developed computer model (Fig. 1), the generalized force of the mechanical part is consid-



(a) (b)

Fig. 1. Computer model (a) and its parameters (b) for studying the processes occurring in the shuttle vehicle

ered in the general nonlinear form (6), but the specifics of performing approximate calculations are taken into account, in which irrational real numbers are represented using a finite number of decimal places, and instead of expression (6), the following is used:

$$M(x_3, x_4) = \begin{cases} -Bx_3 + 2B_e x_4 - mg\delta \operatorname{sign}(x_3), & |x_3| > 10^{-7}, \\ \frac{1}{2}\left(\left|2B_e|x_4| - mg\delta\right| + 2B_e|x_4| - mg\delta\right)\operatorname{sign}(x_4), & |x_3| < 10^{-7}. \end{cases} \quad (9)$$

The use of software for computer modeling of processes in a shuttle vehicle necessarily requires substantiation of the results obtained in the future in order to confirm the absence of errors in the software used, in the developed computer models, and to show the correct use of the software.

To determine the values of the constants $x_3^{(\infty)}$ and $x_4^{(\infty)}$, we have a system of two linear algebraic equations, the solution is represented by Cramer's rule:

$$x_3^{(\infty)} = \frac{\begin{vmatrix} mg\delta & 2B_e \\ U_e & R_e \end{vmatrix}}{\begin{vmatrix} -B & 2B_e \\ B_e & R_e \end{vmatrix}}, \quad x_4^{(\infty)} = \frac{\begin{vmatrix} -B & mg\delta \\ B_e & U_e \end{vmatrix}}{\begin{vmatrix} -B & 2B_e \\ B_e & R_e \end{vmatrix}}. \quad (10)$$

Calculating the determinants will lead to this result: $x_3^{(\infty)} = \frac{2B_e U_e - R_e mg\delta}{R_e B + 2B_e^2}$, $x_4^{(\infty)} = \frac{BU_e + B_e mg\delta}{R_e B + 2B_e^2}$

Taking into account the inequality $x_3 > 0$, we will have the corresponding inequality $x_3^{(\infty)} > 0$, which will lead to the inequality: $2B_e U_e - R_e mg\delta > 0 \Rightarrow U_e > \frac{R_e}{2B_e} mg\delta$. This inequality determines the value of the electric supply voltage of the driving electric motors of the shuttle vehicle, which ensures overcoming the rolling friction forces of the wheels for moving from a stationary state and will take the form:

Moving from a stationary state of the shuttle vehicle requires the value of the supply voltage of the driving electric motors. Taking into account the calculated inequalities for computer modeling of processes in the shuttle vehicle, we will use the following value: $U_e = 24\,\text{B}$.

The change in time of the linear coordinate is clearly consistent with the constant speed, which is established with time. Then, the speed of a fully loaded shuttle vehicle is limited by a value of about 2 m/s, and the maximum acceleration is about 0,7m/s^2.

RESULTS RELIABILITY ASSESSMENT THROUGH FIELD TESTS. Conducting full-scale tests to assess the reliability of mathematical models can be quite a difficult task due to the need to reproduce the studied processes and organize the necessary measurements. Reproducing the processes occurring in an automatic shuttle vehicle is quite a difficult task, since the studied processes are the movements of the shuttle vehicle, which can be carried out over fairly large displacements.

A drawing of the test wheel for modeling viscous resistance, which is provided for in the test scheme (Fig. 2), is presented in Fig. 3; the wheel was manufactured in the 3D printing laboratory of the Department of Computer-Integrated Technologies, Automation and Robotics at the Kharkiv National University of Radio Electronics.

A general view of the equivalent electromechanical system of the experimental setup created for full-scale tests is shown in Fig. 4.

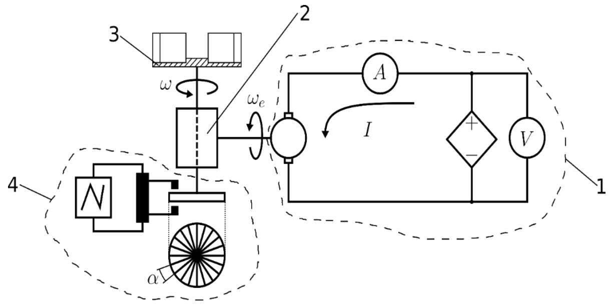


Fig. 2. Testing and measurements organization scheme for assessing the reliability of mathematical modeling results 1 – electric motor with power supply; 2 – gearbox; 3 – test wheel for viscous drag simulation; 4 – angular velocity measurement system

The following equipment and devices were provided for the tests:

– PINTEK PW-3033R DC power supply with smooth voltage regulation and built-in voltmeter and ammeter;

– a test wheel for modeling viscous resistance, which is specially designed so that it can be easily installed on the output shaft of the electric motor reducer and removed from this output shaft;

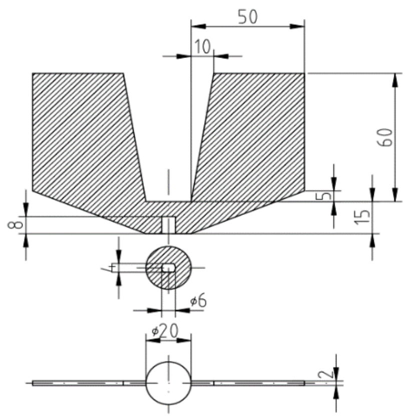


Fig. 3. Test wheel for viscous drag simulation

– TT Motor-2 Shafts gear motor with a DC electric motor, a disk with radial cutouts for measuring the angular velocity of the output shaft of the reducer and a breadboard;

– a photoelectric device – an INFRARED-SPEED-SENSOR sensor, which, when rotating the shaft of the gear motor with the disk fixed on it behind the radial cutouts, generates an electric voltage with jumps at the moments of passing the radial cutouts in the disk;

– a tablet PC with software specially designed for processing the measurement results;

– DT-838 digital multimeter for measuring electric voltage with greater accuracy than the built-in voltmeter of the power supply;

– SAIONW YX-360TRE-L-B analog multimeter for measuring current with greater accuracy than the built-in voltmeter of the power supply, and ensuring filtering of current fluctuations during testing;

– RIGOL DS5102C digital oscilloscope for measuring the time interval between electric voltage pulses at the moments of passing radial notches in the disk during rotation of the motor-gearbox shaft

– auxiliary analog oscilloscope C1-101 for additional visual control of electric voltage on the electric motor;

– PINTEK FG-32 signal generator for checking the accuracy of measuring time intervals by oscilloscopes.

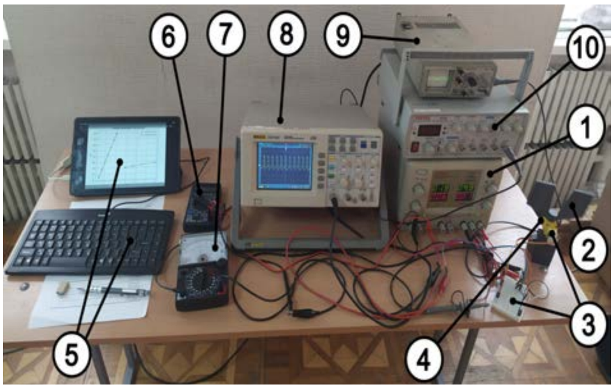


Fig. 4. General view of the experimental setup with the installed test wheel for modeling viscous resistance 1 – controlled power supply; 2 – test wheel for modeling viscous resistance; 3 – gear motor with disk and breadboard; 4 – optical sensor; 5 – tablet with keyboard; 6, 7 – digital and analog multimeter; 8, 9 – digital and analog oscilloscope; 10 – signal generator

Tests were conducted for different values of current, which are measured by an analog multimeter, which has the lowest accuracy of the measuring instruments used. Such an organization of the study allows us to reliably separate different test conditions and use the capabilities of the available measuring instruments, which allowed us to obtain the results shown in Table 1 and Table 2.

The results obtained (Table 1 and Table 2) indicate that the magnitude U_{ef} of the supply voltage, which leads to the displacement: $2\,\text{B} < U_{ef} < 3\,\text{B}$.

Table 1

Measurement results for the case of an equivalent system without a test wheel installed for viscous drag simulation

№	Voltage, V	Current, mA	Interval between pulses, ms
1	0.45	50	∞
2	0.72	75	∞
3	0.98	100	∞
4	1.25	125	∞
5	1.5	150	∞
6	1.75	175	∞
7	2.02	200	∞
8	2.95	80	29.20
9	3.65	85	22.29
10	4.56	90	17.11
11	5.85	95	13.00

Table 2

Measurement results for the case of an equivalent system with an installed wheel for modeling viscous resistance

№	Voltage, V	Current, mA	Interval between pulses, ms
1	0.44	50	∞
2	0.71	75	∞
3	0.97	100	∞
4	1.24	125	∞
5	1.48	150	∞
6	1.73	175	∞
7	2.00	200	∞
8	2.77	80	32.00
9	3.45	85	24.29
10	4.37	90	18.22
11	5.19	95	14.83

The possibilities of saving electrical energy by choosing the speed of the shuttle vehicle were theoretically shown earlier. To assess the savings in electrical energy, we will perform tests of an equivalent electromechanical system without a wheel for modeling viscous resistance and with such a wheel. Let us present the expressions corresponding to the equivalent electromechanical system:

$$\omega_L^{(opt)} = \left(1 + \sqrt{\frac{b_E}{b_L}}\right)\frac{\varphi}{t},\; \omega_E^{(opt)} = \left(1 + \sqrt{\frac{b_L}{b_E}}\right)\frac{\varphi}{t}, \quad (12)$$

where $\omega_L^{(opt)}$ and $\omega_E^{(opt)}$ – optimal values of the angular velocity of the output shaft of the gearbox of an equivalent electromechanical system with and without a wheel installed for viscous drag simulation; b_L and b_E the viscous drag parameters of an equivalent electromechanical system with and without a wheel installed for viscous drag simulation; φ and t half of the rotation angle that must be completed, and the time during which the entire rotation angle must be completed.

The optimal mode of motion is compared with motion at a constant speed:

$$\omega = 2\frac{\varphi}{t}, \tag{13}$$

where ω – constant angular velocity, which ensures the required rotation angle is achieved in the required time.

Energy consumption during an equivalent electromechanical system movement:

$$A^{(opt)} = U_L^{(opt)} I_L^{(opt)} \frac{\varphi}{\omega_L^{(opt)}} + U_E^{(opt)} I_E^{(opt)} \frac{\varphi}{\omega_E^{(opt)}}, \tag{14}$$

$$A = U_L I_L \frac{\varphi}{\omega} + U_E I_E \frac{\varphi}{\omega}, \tag{15}$$

where $A^{(opt)}$ and A – electric energy consumption at optimal speeds (12) and at constant speed (13) of the equivalent electromechanical system; $U_L^{(opt)}$ and $I_L^{(opt)}$ – voltage and current when moving at optimal speed (14) of the equivalent electromechanical system with a wheel installed for viscous resistance modeling; $U_E^{(opt)}$ and $I_E^{(opt)}$ – voltage and current when moving at optimal speed (15) of the equivalent electromechanical system without a wheel installed for viscous resistance modeling; U_L and I_L – voltage and current when moving at constant speed (15) of the equivalent electromechanical system with a wheel installed for viscous resistance modeling; I_E and I_E – voltage and current when moving at constant speed (15) of the equivalent electromechanical system without a wheel installed for viscous resistance modeling.

The savings in electric energy can be estimated as follows:

$$E = \left(1 - \frac{A^{(opt)}}{A}\right) 100\%, \tag{16}$$

where E – percentage relative savings of electrical energy.

Substituting expressions (14) and (15) into formula (16) will lead to the following result:

$$E = \left(1 - \frac{U_L^{(opt)} I_L^{(opt)} / \omega_L^{(opt)} + U_E^{(opt)} I_E^{(opt)} / \omega_E^{(opt)}}{U_L I_L / \omega + U_E I_E / \omega}\right) 100\% \tag{17}$$

Taking into account the ratio, we have the following:

$$\omega_L^{(opt)} = \frac{2\pi}{A\tau_L^{(opt)}},\ \omega_E^{(opt)} = \frac{2\pi}{A\tau_E^{(opt)}},\ \omega = \frac{2\pi}{A\tau}, \tag{18}$$

where $\tau_L^{(opt)}$, $\tau_E^{(opt)}$ and τ – time intervals between pulses corresponding to angular velocities $\omega_L^{(opt)}$, $\omega_E^{(opt)}$ and ω.

Thanks to relations (16), the result (18) will take the form:

$$E = \left(1 - \frac{U_L^{(opt)} I_L^{(opt)} \tau_L^{(opt)} + U_E^{(opt)} I_E^{(opt)} \tau_E^{(opt)}}{\left(U_L I_L + U_E I_E\right)\tau}\right) 100\%. \tag{18}$$

The electric voltages and currents should be measured using appropriate instruments – voltmeters and ammeters, and the values of $\tau_L^{(opt)}$, $\tau_E^{(opt)}$ and τ should be provided using an oscilloscope. To determine the values of $\tau_L^{(opt)}$, $\tau_E^{(opt)}$ and τ, we introduce the following notation:

$$\tau_{\frac{1}{2}} = \frac{2\pi}{A\varphi/t}, \tag{19}$$

where $\tau_{\frac{1}{2}}$ – numerical parameter.

Thanks to the introduced parameter (19), we will have the following values:

$$\tau_L^{(opt)} = \frac{\tau_{\frac{1}{2}}}{1 + \sqrt{b_E/b_L}},\ \tau_E^{(opt)} = \frac{\tau_{\frac{1}{2}}}{1 + \sqrt{b_L/b_E}},\ \tau = \frac{\tau_{\frac{1}{2}}}{2}. \tag{20}$$

Therefore, the study of saving electric energy effect by choosing the speed of movement is reduced to choosing the values of the parameter $\tau_{\frac{1}{2}}$, determining the values (18), and performing tests to measure the electrical voltages and currents that

Table 4

Calculated intervals between pulses

Parameter $\tau_{\frac{1}{2}}$, ms	**Corresponding parameter values, ms**		
	$\tau_L^{(opt)}$	$\tau_E^{(opt)}$	τ
50	26.001748220345807	23.998251779654193	25.0
44	22.88153843390431	21.118461566095693	22.0
40	20.801398576276647	19.198601423723357	20.0
35	18.201223754242065	16.798776245757935	17.5

Table 5

Measurement results of parameters that determine electricity savings

Measured quantity	**Measured quantities values corresponding to the parameter $\tau_{\frac{1}{2}}$, ms**			
	50	**44**	**40**	**35**
$U_L^{(opt)}$. V	3.14	3.49	3.85	4.51
$I_L^{(opt)}$. mA	80	84	85	91
$\tau_L^{(opt)}$. ms	26	22.75	20.77	18.2
$U_E^{(opt)}$. V	3.47	3.79	4.1	4.81
$I_E^{(opt)}$. mA	80	81	84	87
$\tau_E^{(opt)}$. ms	24	21.11	19.2	16.8
U_L. V	3.31	3.6	3.99	4.75
I_L. mA	81	85	86	92
U_E. V	3.38	3.7	4.01	4.78
I_E. mA	79	83	84	92
τ. ms	25	22	20	17.5

Table 6

Results of calculations of relative electricity savings

Parameter	**Measured quantities values corresponding to the parameter $\tau_{\frac{1}{2}}$, ms**			
	50	**44**	**40**	**35**
E, %	1.380225366	2.507755668	1.398110974	3.390979898

are necessary to perform calculations according to formula (20).

It is clear that the parameter τ must be consistent with the characteristics of the studied equivalent electromechanical system, and as such values, it is recommended to multiply by two the corresponding values given in Table 1 and Table 2.

It is clear that the value τ occupies an intermediate value between the optimal values $\tau_E^{(opt)}$ and $\tau_L^{(opt)}$. The measurement results when conducting tests corresponding to the values $\tau_L^{(opt)}$, $\tau_E^{(opt)}$ and τ from Table 4 are given in Table 5. The results obtained for the relative percentage of electricity savings according to Table 5 and Table 6 clearly indicate the effect of saving electric energy.

CONCLUSIONS. The paper presents the results of a study on increasing the energy efficiency of automated warehouse logistics systems by selecting the optimal speeds of a mobile automatic transport vehicle-shuttle on an experimental setup that reproduces an equivalent electromechanical system. The corresponding field tests were conducted. The measurement results obtained during such field tests indicate the savings of electrical energy by selecting the optimal speeds of a mobile automatic transport vehicle-shuttle (mobile transport robot) in the range from 1.4% to 3.4% depending on its average speed. Such results confirm the possibility of increasing energy efficiency by selecting the optimal speeds of an automatic transport vehicle-shuttle during operation.

The authors express their gratitude to the employees of the "Student Design and Technology Bureau for "Robotics and Mechatronics" of the Department of Computer-Integrated Technologies.

Automation and Robotics (CITAR) of the Kharkiv National University of Radioelectronics [11]. as well as personally to Prof. Nevlyudov I. Sh. (Head of the CITAR Department) and Prof. Romashov Y. V. (Prof. CITAR Department) for comprehensive support in conducting the experiment and consulting.

REFERENCES

1. Nevliudov. I., Vzhesnievskyi. M., Romashov. Y., & Chala. O. (2023). Matematychne modeliuvannia mekhatronnykh shatliv yak obiektiv avtomatyzatsii dlia bahatorivnevykh syctem vnutrishnoskladskoi lohistyky [Mathematical modeling of mechatronic shuttles as an objective of automation for complex intra-warehouse logistics systems]. *Suchasnyi stan naukovykh doslidzhen ta tekhnolohii v promyslovosti*, 4 (26), 135–144. DOI: 10.30837/ITSSI.2023.26.135 [in Ukrainian].

2. Vzhesnievskyi, M.O., Chala, O.O. Romashov, Yu.V. (2024). Rozrobka kinematychnoi skhemy transportuvalnoho shatla dlia vnutrishnoskladskoi vyrobnychoi lohistyky [Development of a kinematic scheme of a transport shuttle for internal warehouse production logistics]. *Kompiuterno-intehrovani tekhnolohii: avtomatyzatsiia ta robototekhnika: materialy I Vseukr. konf. Kharkiv*. 16–17 travnia: tezy dopovidei. Kharkiv. 6–10 [in Ukrainian].

3. Vzhesnievskyi, M. & Chala, O. (2024). Avtomatyzatsiia vnutrishno-skladskykh vyrobnychykh lohistychnykh protsesiv dlia vprovadzhennia kontseptsii Industry 4.0: enerhooshchadlyvist, produktyvnist, mobilnist, modulnist, avtonomnist [Automation of intra-warehouse production logistics processes to implement the Industry 4.0 concept: energy efficiency, productivity, mobility, modularity, autonomy]. *Systemy upravlinnia. navihatsii ta zviazku. Zbirnyk naukovykh prats,* 2 (76), 34–38. DOI: https://doi.org/10.26906/SUNZ.2024.2.034 [in Ukrainian].

4. Liashenko, O., Starodubtsev, M., Makarenko, H., & Pashchenko, O. (2024). Keruvannia elektromekhanichnymy systemamy konveiernykh linii [Control of electromechanical systems of conveyor lines]. *Suchasnyi stan naukovykh doslidzhen ta tekhnolohii v promyslovosti*, 4 (30), 85–96. DOI: 10.30837/2522-9818.2024.4.085 [in Ukrainian].

5. Nevliudov, I., Maksymova, S., Chala, O., Bronnikov, A., & Vzhesnievskyi., M. (2023). Automated Logistics Processes Improvement in Logistics Facilities. *Multidisciplinary Journal of Science and Technology*, 3 (3), 157–170. Retrieved from https://mjstjournal.com/index.php/mjst/article/view/202.

6. Yevsieiev, V.V., Nevliudov, I.S., Maksymova, S.S., Omarov, M.A.O., Klymenko, O.M. (2023). Conveyor Belt Object Identification: Mathematical. Algorithmic. and Software Support. *Applied Mathematics and Information Sciences,* 17 (6), 1073–1088. https://doi.org/10.18576/AMIS/170615.

7. Nevliudov, A., & Bronnikov, O., & Chala, R. (2023). Allakhveranov. “Improvement and Optimization of Automated Logistics Processes in Logistics Premises.” *2023 IEEE 5th International Conference on Modern Electrical and Energy System (MEES)*. Kremenchuk. Ukraine. P. 1–6. DOI: 10.1109/MEES61502.2023.10402386.

8. Perekrest, A., Konokh, I., & Kushch-Zhyrko, M. (2019). “Administrative Buildings Heating Automatic Control Based on Maximum Efficiency Criterion.” *2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES)*. Kremenchuk. Ukraine. P. 202–205. DOI: 10.1109/MEES.2019.8896517.

9. Zavalieiev, A. et al. (2024). Information and Analytical System for Collecting. Processing and Analyzing Data on air Pollution. *Automation of technological and business processes*, 16 (1), 72–82.

10. Alyokhina, S., Nevliudov, I., & Romashov, Y. (2021). Safe Transportation of Nuclear Fuel Assemblies by Means of Wheeled Robotic Platforms. *Nuclear and radiation safety*, 3 (91), 43–50. DOI: 10.32918/nrs.2021.3(91).05.

11. Beskorovainyi, V., & Draz, O. (2021). Mathematical models of decision support in the problems of logistics networks optimization. *Innovative Tech-nologies and Scientific Solutions for Industries*, 4 (18), 5–14. Retrieved from: https://doi.org/10.30837/ITSSI.2021.18.005.

12. Student Design – Technological Bureau for “Robotics and mechatronics” [Electronic resource]. Title from the screen. Access mode. https://nure.ua/department/kafedra-komp-yuterno-integrovanih-tehnologiy-avtomatizatsiyi-ta-mehatroniki-kitam/laboratorii-kafedri/studentske-konstruktorsko-tehnologichne-bjuro-z-robototehniki-ta-mehatroniki.

ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ АВТОМАТИЗОВАНИХ СИСТЕМ СКЛАДСЬКОЇ ЛОГІСТИКИ

Максим Вжеснєвський
здобувач третього (освітньо-наукового) рівня вищої освіти кафедри комп'ютерно-інтегрованих технологій. автоматизації та робототехніки,
Харківський національний університет радіоелектроніки, просп. Науки, 14, Харків, Україна, 61166,
maksym.vzhesnievskyi@nure.ua
ORCID: 0000-0002-7585-628X

Олена Чала
кандидат технічних наук. доцент. доцент кафедри комп'ютерно-інтегрованих технологій автоматизації та робототехніки,
Харківський національний університет радіоелектроніки, просп. Науки, 14, Харків, Україна, 61166,
olena.chala@nure.ua
ORCID: 0000-0003-2454-3774

У роботі представлено шляхи підвищення енергоефективності автоматизованих складських логістичних систем завдяки вибору оптимальних швидкостей автоматичного транспортувального засобу-шатла.

Досліджено задачу автоматичного керування рухом транспортувального засобу-шатла у внутрішньоскладських системах в умовах невизначеності, що використовує математичні моделі для вибору параметрів найкращого варіанта рішень керування – для підвищення енергоефективності та продуктивності технологічних систем у межах концепції INDUSTRY 5.0. Об'єктом дослідження є процес автоматичного керування човниковими транспортними засобами в автоматизованих внутрішньоскладських системах. Предметом дослідження є сукупність математичних моделей і методів, що описують процес автоматичного керування човниковими транспортними засобами.

Удосконалено математичну модель керованого технологічного процесу функціонування транспортувального засобу-шатла в автоматизованих внутрішньоскладських системах, що базується на використанні регуляторів з інтелектуальними системами, з обґрунтуванням поточних параметрів виробничих процесів з використанням комп'ютерно-інтегрованих технологій, що дало змогу забезпечити економію електричної енергії інтелектуальних транспортних засобів-шатлів завдяки оптимізації швидкості. Для перевірки достовірності побудованих диференціальних рівнянь математичної моделі електромеханічних процесів у транспортувальному засобі-шатлі запропоновано побудову експериментальної установки для дослідження еквівалентної за виглядом диференціальних рівнянь електромеханічної системи у вигляді електричного двигуна постійного струму з редуктором і колесом випробувальним для моделювання в'язкого опору. Було здійснено відповідні натурні випробування за різних середніх швидкостей руху. Результати вимірювань, що отримані під час проведення таких натурних випробувань, свідчать про економію електричної енергії ззавдяки вибору оптимальних швидкостей у межах приблизно від 1,4 до 3,4% залежно від середньої швидкості.

Ключові слова: автоматизація, логістика, енергоефективність, мобільний транспортувальний робот, ПІД-регулятор, швидкість.

ЛІТЕРАТУРА

1. Невлюдов І., Вжеснєвський М., Ромашов Ю., Чала О. Математичне моделювання мехатронних шатлів як об'єктів автоматизації для багаторівневих систем внутрішньоскладської логістики. *Сучасний стан наукових досліджень та технологій в промисловості.* 2023. № 4 (26). С. 135–144. DOI: 10.30837/ITSSI.2023.26.135.

2. Вжеснєвський М. О., Чала О. О., Ромашов Ю. В. Розробка кінематичної схеми транспортувального шатла для внутрішньоскладської виробничої логістики. *Комп'ютерно-інтегровані технології: автоматизація та робототехніка : матеріали I Всеукр. конф.* Харків. 16–17 травня : тези доповідей. Харків. 2024. С. 6–10.

3. Вжеснєвський М., Чала О. Автоматизація внутрішньо-складських виробничих логістичних процесів для впровадження концепції Industry 4.0: енергоощадливість, продуктивність, мобільність, модульність, автономність. *Системи управління, навігації та зв'язку. Збірник наукових праць*. 2024. № 2 (76). С. 34–38. DOI: https://doi.org/10.26906/SUNZ.2024.2.034.

4. Ляшенко О., Стародубцев М., Макаренко Г., Пащенко О. Керування електромеханічними системами конвеєрних ліній. *Сучасний стан наукових досліджень та технологій в промисловості*. 2024. № 4 (30). С. 85–96. DOI: 10.30837/2522-9818.2024.4.085.

5. Nevliudov I., Maksymova S., Chala O., Bronnikov A. Vzhesnievskyi Maksym. Automated Logistics Processes Improvement in Logistics Facilities. Multidisciplinary Journal of Science and Technology. 2023. Vol. 3 (3). P. 157–170. URL: https://mjstjournal.com/index.php/mjst/article/view/202.

6. Yevsieiev V.V., Nevliudov I.S., Maksymova S.S., Omarov M.A.O.., Klymenko O.M. Conveyor Belt Object Identification: Mathematical. Algorithmic. and Software Support. *Applied Mathematics and Information Sciences*. 2023. Vol. 17 (6). P. 1073–1088. https://doi.org/10.18576/AMIS/170615.

7. Nevliudov A., Bronnikov O., Chala R. Allakhveranov. "Improvement and Optimization of Automated Logistics Processes in Logistics Premises." *2023 IEEE 5th International Conference on Modern Electrical and Energy System (MEES)*. Kremenchuk. Ukraine. 2023. P. 1–6. DOI: 10.1109/MEES61502.2023.10402386.

8. Perekrest A., Konokh I., Kushch-Zhyrko M. "Administrative Buildings Heating Automatic Control Based on Maximum Efficiency Criterion." *2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES)*. Kremenchuk. Ukraine. 2019. P. 202–205. DOI: 10.1109/MEES.2019.8896517.

9. Zavalieiev A. et al. Information and Analytical System for Collecting. Processing AND Analyzing Data on Air Pollution. *Automation of technological and business processes*. 2024. Vol. 16 (1). P. 72–82.

10. Alyokhina S., Nevliudov I., Romashov Y. Safe Transportation of Nuclear Fuel Assemblies by Means of Wheeled Robotic Platforms. *Ядерна та радіаційна безпека*. 2021. № 3(91). P. 43–50. DOI: 10.32918/nrs.2021.3(91).05.

11. Beskorovainyi V., Draz O. Mathematical models of decision support in the problems of logistics networks optimization. *Innovative Technologies and Scientific Solutions for Industries*. 2021. Vol. 4 (18). P. 5–14. https://doi.org/10.30837/ITSSI.2021.18.005.

12. Студентське конструкторсько-технологічне бюро з «Робототехніки та мехатроніки» [Електронний ресурс]. Назва з екрана. URL: https://nure.ua/department/kafedra-komp-yuterno-integrovanih-tehnologiy-avtomatizatsiyi-ta-mehatroniki-kitam/laboratorii-kafedri/studentske-konstruktorsko-tehnologichne-bjuro-z-robototehniki-ta-mehatroniki.

Стаття надійшла 17.11.2024