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MODELING OF AN AUTOMATIC CONTROL SYSTEM FOR A MULTIPURPOSE MOBILE ROBOT’S SPATIAL MOTION

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Abstract. *The paper presents the simulation model of the automatic control system (ACS) for a caterpillar mobile robot (MR) with separate main clamping magnets intended for moving on ferromagnetic surfaces. The developed model accounts for the mutual influence of the MR positioning parameters, as well as the main properties of the ACS’s elements.*

Key words: *caterpillar mobile robot, spatial motion, simulation, automatic control system, linear speed, course angle, control error, PID-controller.*

Introduction and problem statement

Current trends of industrial development reveal that enterprises are greatly interested in maximum automation of production operations [1]. It is associated with the need to intensify production, increase productivity and reduce the cost of finished products while maintaining their quality for the company to be competitive in the world market. It should be noted that there are some high-cost technological operations, particularly, high-rise works or the works performed under difficult conditions of radioactivity, contamination with gas, high temperatures. The most effective solution for the automation of production technological operations under these conditions is application of unmanned robotic complexes, such as mobile robots (MRs) capable of moving along inclined and vertical surfaces [2-5]. So, the most important problem which has to be solved is replacing the monotonous human labor with MRs in life-threatening operating conditions. It can significantly improve the performance of technological operations and reduce the risks to human life and health. In addition, the MR has to be able to move along given trajectories and operate under the working surface uncertainty caused by the technological features of the surface, presence of obstacles, structural damage or shelling (for example, the ship’s hull or elevator constructions), etc. [4, 5].

In order to maximize the potential of the MR and similar robotic complexes and systems in agriculture, shipbuilding, ship repair, gas and oil refining, as well as in some other industries, it is necessary to provide an opportunity of obtaining mechanical work on the working tool moving and performing technological operations along given trajectories [5, 6]. Solution of this problem calls for creation of a specialized high-performance automatic spatial motion control system (ACS). Thereat, of particular interest is the possibility of a timely testing of the selected hardware and software means of the implementation of the ACS and control algorithms through mathematical and computer modeling.

1. Latest research and publications analysis

Publications [7-8] present and elaborate on the basic methods for mathematical modeling of control objects, which are used for the analysis and synthesis of an automatic control system. Research on the modeling and implementation of the MR’s ACS has a limited scope [2, 6, 9, 10]. Development of mathematical models and transfer functions for separate MR elements and their ACSs (controlled power converters, DC and AC motors, gear units, etc.) for the tasks of automated control is considered separately, for instance, in papers [11, 12]. Publication [9] presents a mathematical model of a tracked MR designed for moving over horizontal surfaces and the results of modeling of its movement along a given trajectory, but there are no data on its ACS. The authors of the study [10] model a wheeled MR, but do not provide any data on the special features of control of such robots. Meanwhile, the problem of synthesis of the ACS of a MR vertically moving and performing specified technological operations on inclined surfaces (particularly the ferromagnetic surfaces which are typical in shipbuilding, ship repair, oil and gas transportation), is still unresolved. Analysis of the physical properties and technical characteristics of a vertically moving MR as an object of spatial position control with respective control coordinates [20] proves the feasibility of development of its ACS based on the principles of optimization of control quality indicators [13].

The article aim is the development of the spatial motion ACS model of a multipurpose vertically moving MR based on the methods of the automatic control theory and the synthesis of control devices through optimizing the control quality indicators with further study of the MR's behavior at given input actions and disturbances.

2. Development of a functional structure of a multipurpose vertically moving MR

The principal diagram and main properties of a multipurpose tracked MR, which serves to perform at least two different technological operations and can move along inclined and vertical ferromagnetic surfaces, are in detail discussed in the papers [14, 15]. The mathematical model of such a robot, which takes into account the inclination angle of the working surface and the direction of the MR’s movement, has been developed in study [16]. It is noteworthy that the process of synthesis of the MR’s ACS model requires an in-depth consideration of its main components [17]. Hence, let us separately render the mathematical models of the main elements of the MR’s ACS.

The main elements of the ACS for MR positioning are a thyristor or transistor converter, sensors and control devices (regulators).

Thyristor converter. Drive motors have to be powered from the AC mains using contactors and a thyristor or transistor converter; if we use AC motors, a scalar or vector frequency converter should be used.

Generally, separately excited DC motors are powered with the help of regulated power sources [18, 19]: electric machinery – DC generator – AC motor (G-M system); controlled thyristor converters (rectifiers) with phase control (TC-DCM system); semiconductor rectifiers regulating the value of the rectified voltage via pulse-width modulation (PWM-DCM system).

The major system with a variable-speed electric drive and DC motors is the TC-DCM system. The circuit diagram of thyristor converters is based on semicontrolled power semiconductor devices – thyristors. Thereat, thyristor converters in the DC drive circuits perform two functions: rectification of the alternating supply voltage and regulation of the average value of the rectified voltage [19].

The generalized functional diagram (Fig. 1) shows the connection between the thyristor converter (TC), the DC motor (DCM) and the MR. At that, the TC is fed with a control signal in the form of the voltage U_{TC}, which regulates the angle of thyristor opening and, consequently, the voltage U_{DCM}, which is supplied to the electric motor. Further, the motor converts the electrical energy into the mechanical energy manifested through the rotor frequency ω_{DCM} and drives the driving wheel of the MR via the gear unit. The MR model output is the robot’s angle of rotation φ_{MR} and linear speed V_{MR}. The moments of load acting on the MR and thus on the motor are labeled as M_L. Let us elaborate upon the features of the DCM and TC for the formation of the structure of the ACS for the MR’s spatial motion.

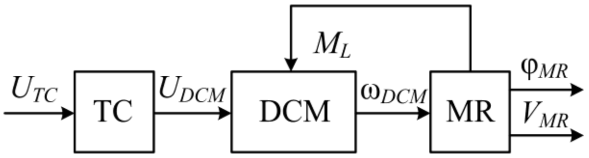

Fig. 1. Generalized functional diagram “thyristor converter – DC motor – mobile robot”

The equation of the phase control block (PCB) which directly generates the pulses opening the TC thyristors [19] has the following form:

$$\theta(t) = \arccos \frac{k_{PCB}}{1 + T_{PCB} \cdot p} u_{IN}(t),$$

where u_{IN} is the PCB input voltage; T_{PCB} is the time constant of the aperiodic link at the PCB input; k_{PCB} is the PCB amplification coefficient.

The arccosine dependence between the regulation angle and the control voltage at the PCB input is typical for the control devices utilizing the voltage of the supply network as the reference level. The aperiodic link with the time constant T_{PCB} is introduced at PCB input to limit dynamic equalizing current in a reversible TC with shared control of groups of thyristors, $T_{PCB} = 0.006 \div 0.01$ s.

Consequently, the simplified version of the transfer function of the TC is as follows:

$$W_{TC}(p) = \frac{k_{TC}}{T_{TC} p + 1},$$

where k_{TC} is the TC amplification coefficient, and T_{TC} is the TC time constant.

The thyristor converter’s gain is calculated via the following equation:

$$k_{TC} = \frac{U_N}{U_{RV.\max}},$$

where $U_{RV.\max}$ is the amplitude of the reference sinusoidal voltage ($U_{RV.\max} = 10$ V).

Sensors. For the monitoring and reliable control of the MR’s main parameters (speed of its movement and angle of its rotation, i.e. its route), the ACS should include an information-measuring part in the form of sensors or other computing identification devices which would be intended precisely for the accident-free control of the robot positioning [20,21].

The mobile robot’s position can be determined directly, through analyzing the rotary motion parameters (angle and speed of rotation). Using these parameters, one can calculate the distance covered by each driving wheel from the starting point and, accordingly, the MR coordinates. Most commonly, measurement of the angle and speed of rotation employs encoders, which are mounted on the motor’s shaft.

Therefore, for the case of encoder application, let us denote the transfer function of the angle and speed sensors of the driving wheels with a proportional link k_{AS} and k_{SS} being the coefficients of signal amplification in the angle and speed feedback).

$$W_{AS}(p)=\frac{U_{AS}(p)}{U_C(p)}=k_{AS};$$

$$W_{SS}(p)=\frac{U_{SS}(p)}{U_C(p)}=k_{SS},$$

where $U_{AS}(p)$ and $U_{SS}(p)$ are the output voltages of the angle sensor and the rotational speed sensor, respectively; $U_C(p)$ is the control voltage.

Control devices (regulators). Compliance with specified control quality indicators of various technological equipment is commonly achieved through implementation of typical control laws that underlie the synthesis of control devices, in particular, PID controllers [22, 23].

The regulators are adjusted sequentially. The speed circuit is tuned first, then the angle circuit, both with the help of the gradient method of parametric optimization of regulator coefficients.

The control object of the speed circuit covers a speed regulator (SR), thyristor converters, electric and mechanical parts of electric motors (DCM with armature windings and driving wheels). The circuit is closed by voltage feedback, with its value being determined by the speed sensor.

The control object of the angle circuit includes a regulator, thyristor converters, electric and mechanical parts of electric motors (DCM with armature windings and driving wheels). The circuit is also closed by voltage feedback with the voltage value being recorded by the angle sensor.

The transfer function of the PID speed controller is as follows [22]:

$$W_{SC}(p)=K_{PS}+\frac{K_{IS}}{p}+K_{DS}\,p\,,$$

where K_{PS} is the SR’s proportional gain, K_{IS} is the SR’s integral gain, and K_{DS} is the SR’s derivative gain; p is the Laplace operator.

In this case, we suggest using the quadratic integral deviation of the actual value of the MR’s speed from the given one as an objective function:

$$\min_{\mathbf{Q}} f(t,\mathbf{Q})=\min_{\mathbf{Q}}\left[\int e_V^2(t,\mathbf{Q})dt\right]=$$
$$=\min_{\mathbf{Q}}\left[\int (V_S(t)-V_R(t,\mathbf{Q}))^2\,dt\right],$$

where $f(t,\mathbf{Q})$ is the quadratic integral deviation of the actual value of speed in the speed circuit V_R from the given (preliminarily specified) value V_S; $\mathbf{Q}$ is the vector of optimization parameters; e_V is the control error regarding speed.

Accordingly, the vector of optimization parameters has the following form:

$$P=\{K_{PS},K_{IS},K_{DS}\}.$$

The initial values of the speed regulator’s coefficients before optimization are selected to be as follows: $K_{PS}=1$, $K_{IS}=1$, $K_{DS}=1$.

The following iterative procedures can be used to optimize the coefficients given above:

$$K_{PS}[n+1]=K_{PS}[n]-\gamma[n]\frac{\partial f(\mathbf{Q})}{\partial K_{PS}}\Big|_{K_{PS}[n]};$$

$$K_{IS}[n+1]=K_{IS}[n]-\gamma[n]\frac{\partial f(\mathbf{Q})}{\partial K_{IS}}\Big|_{K_{IS}[n]};$$

$$K_{DS}[n+1]=K_{DS}[n]-\gamma[n]\frac{\partial f(\mathbf{Q})}{\partial K_{DS}}\Big|_{K_{DS}[n]},$$

where γ is the gradient descent step, and n is the number of iteration.

The above parametric optimization procedures should be performed with the help of specialized software for mathematical, structural and simulation modeling. As a result of parametric optimization, the optimal values of the PID speed controller’s coefficients are obtained, which are as follows: $K_{PS}=5{,}92$; $K_{IS}=72{,}02$; $K_{DS}=-2{,}57$. In addition, the SR contains a voltage limiter ($0\le U_{SR}\le 10$ V).

After tuning the angle regulator, the following parameters of the PD controller were obtained: $K_{PA}=48{,}5$; $K_{DA}=5{,}2$. Additionally, the AR is equipped with a voltage limiter ($0\le U_{AR}\le 10$ V).

Thus, the automatic speed control system employs the PID regulator, while the automatic angle control system utilizes the PD regulator.

Fig. 2 demonstrates a functional diagram of the ACS for the MR’s spatial motion [24]. The following designations have been adopted: V_{MRG} and φ_{MRG} are the given values of the MR’s speed and angular coordinate; U_{SDS} and U_{SDA} are the signals at the setting device output; ε_S and ε_A are the error signals fed to the regulator of motion RM; U_{AR} and U_{SR} are the voltage values set by the interconnected angle (AR) and speed (SR) regulators; U_{RTC1} and U_{RTC2} are the voltages supplied to the thyristor converters TC1 and TC2; U_{TC1} and U_{TC2} are the power supply voltages for the drive motors M1 and M2; RT and LT are the MR’s right-hand and left-hand tracks; IB is the inverting block; ω_{E1} and ω_{E2} are the angular speeds of the M1 and M2 rotation; M_{L1} and M_{L2} are the moments of resistance acting on the drive wheels; U_{AS} and U_{SS} are the feedback signals from the angle (AS) and speed (SS) sensors; V_{MR} and φ_{MR} are the MR’s current linear speed and angular coordinate.

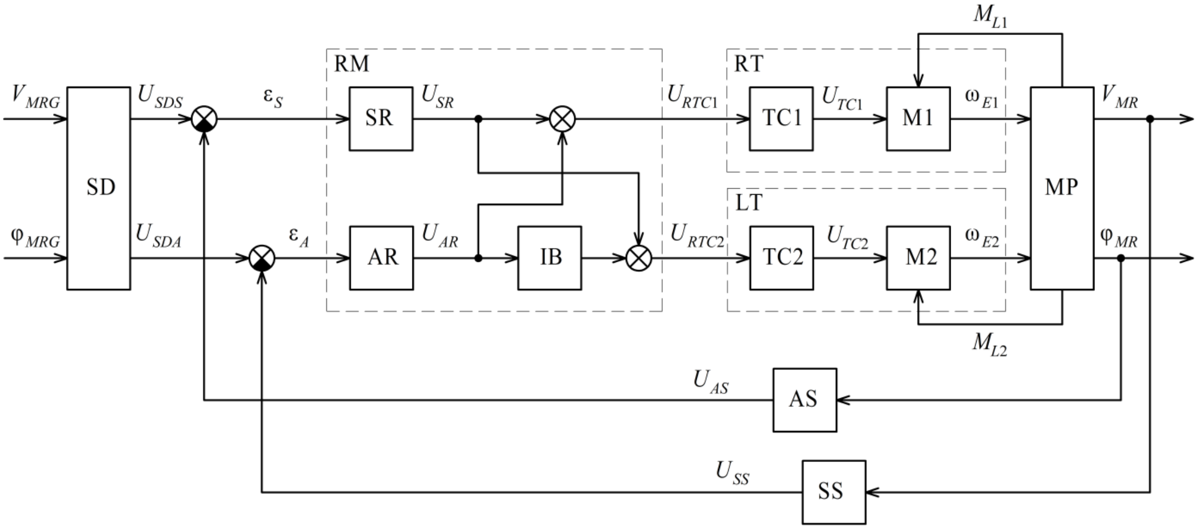

Fig. 2. Functional diagram of the system for automatic control of spatial motion of the multi-purpose mobile robot

The diagram works as follows. The operator specifies the φ_{MRG} and V_{MRG} values through the human-machine interface, and the setting device SD converts the analog signal into a signal to be perceived by the robot (U_{SDS} and U_{SDA}). After the adder, the ε_S and ε_A error signals are supplied to the AR and SR. They determine the U_{AR} and U_{SR} voltage values to be applied to each thyristor converter (TC1 and TC2), so that the latter generate the U_{TC1} and U_{TC2} voltages for the DCMs M1 and M2. Thereat, the RT and LT caterpillar tracks are equipped with the same TC and DCM, only the LT receives a negative signal from the angle regulator. Hence, after all the transformations, each TC receives some signal U_{RTC1} and U_{RTC2}. Next, the motors with the angular speeds of rotation being ω_{E1} and ω_{E2} drive the wheels of each caterpillar track (RT and LT) of the MR. The moments of resistance M_{L1} and M_{L2} on each track are created by the MR’s motion resistance forces. The robot’s angular displacement (the angular coordinate φ_{MR}) is monitored with the angle sensor AS, which generates a feedback signal U_{AS} in order to adjust further movement. Meanwhile, the robot’s speed (the coordinate V_{MR}) is tracked with the speed sensor SS, which generates the feedback signal U_{SS} to bring adjustments to further movement.

The functional diagram of the ACS for the MR’s spatial motion contains two converters that separately power two motors driving the robot’s caterpillar tracks. The MR’s mathematical model (discussed in [16]) includes the gear ratio, since each driving wheel is equipped with a gear unit to reduce the rotational speed and increase the rotating moment (torque) of the DCM. Calculation of the basic parameters of the ACS for the MR’s spatial motion for the purpose of its further modeling should follow the methods given in papers [25, 26].

In order to perform modeling and obtain output dependencies, the following basic parameters of the MR have been specified: loaded weight of 300 kg, length of 1 m, width of 0.7 m, driving wheel radius of 0.3 m, linear speed of movement of 0.3 m/s, two drive motors 2PB132MH [26], and gear ratio of 80.

3. Computer modeling results

The specified parameters of the MR and the developed model of the MR’s ACS (Fig. 2) shall be used to obtain the transient processes regarding the MR’s speed and angle of rotation, as well as the major control quality indicators. In this case, by the transient process we mean the system’s response to a step input. The ACS analysis involves identification of the quality indicators by which the system’s properties are assessed. Compliance of the ACS quality indicators with the required values is a sufficient condition for its serviceability [12].

Figures 3 and 4 render the transient processes of mobile robot control employing a PID speed controller and a PD angle controller accounting for the mutual influence of the MR’s speed and angle control systems. The results of computer modeling provide an opportunity to specify the quality indicators for the developed automatic control system intended for the MR’s linear speed and angle of rotation at the step input supply (the system launches from the initial position with φ_{MR} = 0 rad and V_{MR} = 0 m/s according to Figures 3 and 4). Major quality indicators of the ACS for the MR’s spatial motion with regard to the mutual influence of the speed and angle control systems are as follows: t_{TS} is the control time for speed, t_{TS} = 0.74; t_{TA} is the control time for angle, t_{TA} = 0.96; $\sigma_{\max}$ is the overshoot, μ is the oscillability index, and δ_S is the static error. In our case $\sigma_{\max}$, μ and δ_S are equal to zero for MR’s speed and angle control systems (taking into account the mutual influence of the speed and angle control systems).

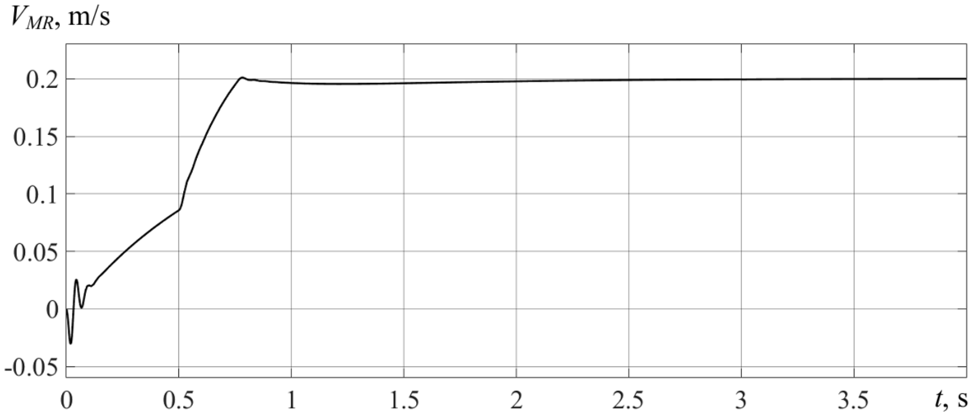

Fig. 3. Transient process of the MR’s speed control system taking into account the mutual influence of the speed and angle control systems

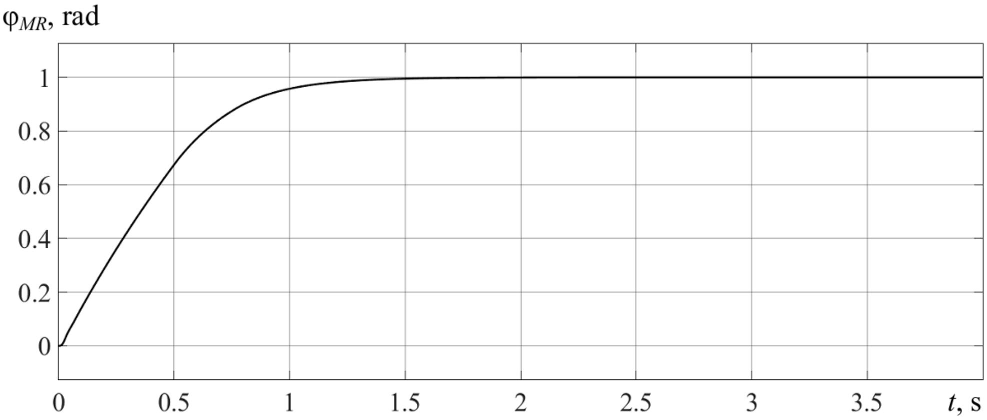

Fig. 4. Transient process of the MR’s angle control system taking into account the mutual influence of the speed and angle control systems

Next, let us consider the following transient processes:

- the transient process of speed control excluding the angle control system from the general diagram (in Fig. 2);
- the transient process of angle control excluding the speed control system from the general diagram (in Fig. 2).

Fig. 5 and 6 demonstrate the transient processes of the systems for automatic control of the MR’s speed and angle of rotation, both taking into account and disregarding the mutual influence of the speed and angle control systems with the MR’s PID speed and PD angle controllers.

It is clear from Fig. 5 that the ACS for the MR’s speed has a much shorter response time, a slight fluctuation at the beginning of the process and uneven growth of the controlled coordinate when taking into account the angle control system’s influence as compared to the ACS disregarding this impact.

Fig. 6 reveals that the ACS for the MR’s angle of rotation has a slightly longer response time when accounting for the speed control system’s influence as compared to the ACS ignoring this effect. The overshoot is zero in both cases.

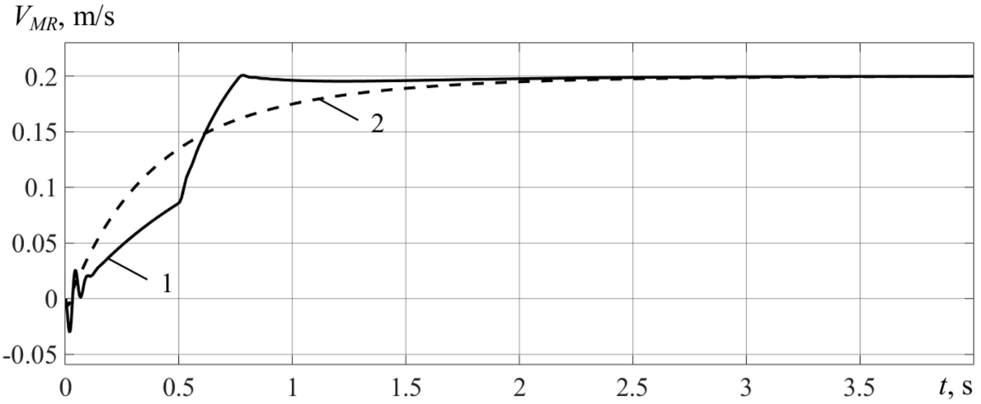

Fig. 5. Transient processes of the speed control system: 1 – with account for the mutual influence of the speed and angle control systems; 2 – disregarding the angle control system

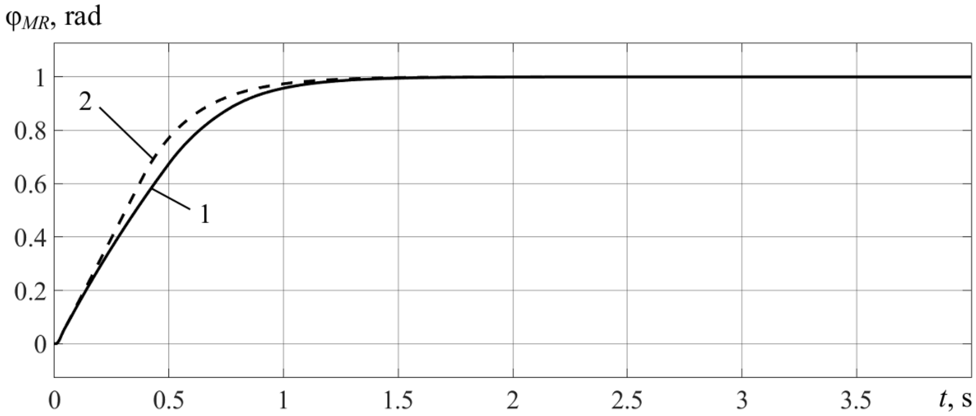

Fig. 6. Transient processes of the angle control system: 1 – with account for the mutual influence of the speed and angle control systems; 2 – disregarding the speed control system

In their essence, the obtained results are similar to the transient processes manifested in the real MRs, which testifies to their qualitative adequacy to actual characteristics [27]. In order to eliminate undesirable speed fluctuations at the beginning of the transient process, smooth out the graph of the controlled coordinate and improve the quality of control of the MR’s main coordinates, further research should consider the effectiveness of artificial intelligence methods and tools [28, 29] with the control algorithms being implemented on the basis of embedded and network technologies [30, 31].

Conclusions

The publication renders the development of the simulation model of the spatial motion ACS of the multipurpose MR intended for moving and performing specified technological operations on inclined and vertical ferromagnetic surfaces. The model, which has been developed with the help of the automatic control theory, takes into account the mutual influence of the MR positioning parameters, namely, the value of the course angle and speed of movement on an inclined surface. Synthesis of the regulators in the MR’s speed and angle channels is conducted through optimizing the control quality parameters. The study also considers the MR’s behavior under given input actions and disturbances. The results of computer modeling confirm that the behavior of the obtained model of the ACS for the MR’s spatial motion corresponds to that of actual samples of such equipment, and the control quality indicators are rather high.

References

1. Belov, M. P., Novikov, V. A., Rassudov, L. N. (2007). Automated electric drive of standard production mechanisms and technological complexes [“Avtomatizirovannyy elektroprivod tipovykh proizvodstvennykh mekhanizmov i tekhnologicheskikh kompleksov”] M., Izdatelskiy tsentr Akademiya.

2. Yurevich, Ye. I. (2005). Handbook on Basic Robotics [“Osnovy robototekhniki: Uchebnoye posobiye”] Saint-Petersburg, BKhV-Peterburg.

3. Siciliano, B., Khatib, O. (2016) (ed.). Springer handbook of robotics. Springer.

4. Niku, S. B. (2001). Introduction to robotics: analysis, systems, applications. New Jersey: Publisher Prentice Hall.

5. Gerasin, O. S. (2014). Analysis of the features of multi-purpose mobile robots [“Analiz osoblyvostei mobilnykh robotiv bahatotsilovoho pryznachennia”]. Scientific-methodical Journal “Proceedings”. Series “Computer Technologies” [“Naukovi pratsi: Naukovo-metodychnyi zhurnal. Seriia “Compiuterni tekhnolohii”], vol. 250, no. 238, pp. 25–32.

6. Spong, M. W., Hutchinson, S., Vidyasagar, M. (2006). Robot modeling and control. New York: Publisher Wiley.

7. Usov, A. V., Dubrov, A. V., Dmitrishin, D. V. (2002). Modeling of systems with distributed parameters [“Modelirovaniye sistem s raspredelennymi parametrami”]. Odessa: Astroprint Publisher.

8. Sharuda, V. H. (2002). Practical course on automatic control theory [“Praktykum z teorii avtomatychnoho upravlinnia”]. Dnipropetrovsk: National Mining University Publisher.

9. Kabanov, A. A. (2012). Modeling and control of the movement of a caterpillar mobile robot [Modelirovaniye i upravleniye dvizheniem gusenichnogo mobilnogo robota]. In Control in technical, ergatic, organizational and network systems [“Upravleniye v tekhnicheskikh, ergaticheskikh, organizatsionnykh i setevykh sistemakh”]. Saint Petersburg, pp. 740–743.

10. Koloskov, S. S. (2013). Development of a mobile robot and visualization of its movement [“Razrabotka mobilnogo robota i vizualiatsiya ego dvizheniya”]. Youth Scientific and Technical Bulletin [“Molodezhnyy nauchno-tekhnicheskiy vestnik”]. [online] Available at: http://sntbul.bmstu.ru/doc/602336.html.

11. Terekhov, V. M. (2006) Electric drive control systems [“Sistemy upravleniya elektroprivodov”]. Moscow: Izdatelskiy tsentr “Akademiya” Publisher.

12. Kondratenko, Y. P., Kozlov, O. V., Gerasin, O. S., Zaporozhets, Y. M. (2016). Synthesis and Research of Neuro-Fuzzy Observer of Clamping Force for Mobile Robot Automatic Control System In: Proceedings of the 2016 IEEE First International Conference on Data Stream Mining & Processing (DSMP). Lviv, Ukraine, August 23-27, pp. 90–95.

13. Balaguer, C. (2008). Robotics and automation in construction. Croatia: In-Teh, pp. 295–306.

14. Kushnir, V. O., Kondratenko, Y. P., Topalov, A. M., Gerasin, O. S. (2015). Mobile robot for mechanical cleaning of a ship hull [“Mobilnyi robot dlia mekhanichnoho ochyshchennia korpusu sudna”]. Patent UA, no. u201500063.

15. Kozlov, O. V., Gerasin, O. S., Kondratenko, G. V. (2017). Complex of tasks of monitoring and automatic control of mobile robots for vertical movement. Shipbuilding & Marine Infrastructure, no. 2 (8), pp. 77–87. Available at: http://smi.nuos.edu.ua/article/view/120596/116517.

16. Gerasin, O.S., Kozlov, O.V., Kondratenko, G.V., Mingxin, H. (2018). Synthesis and study of the mathematical model of a caterpillar mobile robot for vertical movement. Problems of information technologies, no. (). pp. [Unpublished]

17. Kurfess, T. R. (2004) (ed.). Robotics and automation handbook. CRC Press.

18. Onishchenko, G. B. et al. (2001). Automated electric drive in industrial installations [“Avtomatizirovannyy elektroprivod promyshlennykh ustanovok”]. Moscow: RASKhN Publisher.

19. Basharin, A. V., Novikov, V. A., Sokolovskiy, G. G. (1982). Electric drive control [“Upravleniye elektroprivodami”]. Leningrad: Energoizdat Publisher.

20. Franke, M., Rudolph, J., Woittennek, F. (2009). Motion planning and feedback control of a planar robotic unicycle model. Methods and Models in Automation and Robotics, vol. 14, no. 1, pp. 501–506.

21. Plakhotnyi, M. V., Hrychyna, A. Yu. Special features of the structure of the systems for remote monitoring of equipment parameters [“Osoblyvosti pobudovy system dystantsiinoho monitorynhu parametriv obladnannia”]. [online]. Available at: http://ena.lp.edu.ua.

22. Pyavchenko, T. A. (2006). Calculation of the parameters of the PID control law for objects with a transport delay [“Raschet parametrov PID zakona upravleniya dlya obektov s transportnym zapazdyvaniem”]. Bulletin of TREU [Izvestiya TRTU], no. 5 (60), pp. 83–88.

23. Smirnov, N. I., Sabanin, V. R., Repin, A. I. (2007). Structural realization and optimal tuning of a multiparameter PID controller with real derivation [“Strukturnaya realizatsiya i optimalnaya nastroyka mnogoparametricheskogo PID regulyatora s realnym differentsirovaniem”]. Industrial Automatic Control Systems and Controllers [Promyshlennye ASU i kontrollery], no. 11, pp. 34–39.

24. Gerasin, O. S., Kozlov, O. V. (2016). System of automatic control of a caterpillar mobile robot's spatial motion [“Systema avtomatychnoho keruvannia prostorovym rukhom husenychnoho mobilnoho robota”]. In Proceedings of the Third International Scientific and Practical Conference of

Young Scientists, Postgraduate and Undergraduate Students “Automation and Computer-Integrated Technologies (ACIT-2016)”. Kyiv: NTUU «KPI» Publisher, pp. 115–116.

25. Sew-eurodrive. Practice of drive engineering. Designing of drives [Sew-eurodrive. Praktika privodnoy tekhniki. Proektirovanie privodov]. [online]. Available at: www.sew-eurodrive.ru/files/pdf/11322853.pdf.

26. Pitsan, R. M., Bardachevskyi, V. T., Boichuk, B. H. (1999). Problem book in the course “Electric Drive”. Chapter 1 “Open-loop Electric Drive Systems” [“Zbirnyk zadach do kursu «Elektropryvid». Persha chastyna “Rozimkneni systemy elektropryvoda”]. Lviv: Vydavnytstvo Derzhavnoho universytetu “Lvivska politekhnika” Publisher.

27. Trunov, A. N. (2016). Criteria for the evaluation of model’s error for a hybrid architecture DSS in the underwater technology ACS. Eastern-European Journal of Enterprise Technologies, vol. 6, no. 9(84), pp. 55–62.

28. Lozovyy, P., Thomas, G., Simon, D. (2011). Biogeography-based optimization for robot controller tuning. Computational Modeling and Simulation of Intellect, pp. 162–181.

29. Ulyanov, S. V. (2011). Mobile intelligent systems with robots for vertical movement [Mobilnye intellektualnye sistemy s robotami vertikalnogo peremeshcheniya]. System Analysis in Science and Education, issue 2, pp. 1–20. [online]. Available at: http://sanse.ru/archive/20.

30. Kondratenko, Y. P., Rudolph, J., Kozlov, O. V., Zaporozhets, Y. M., Gerasin, O. S. (2017). Neuro-fuzzy observers of clamping force for magnetically operated movers of mobile robots [“Neyro-nechitki sposterigachi dlya identifikatsiyi pritisknogo zusillya magnitokerovanih rushiyiv mobilnih robotiv”] Technical Electrodynamics, no. 5, pp. 53–61.

31. Maykiv, I., Stepanenko, A., Wobschall, D., Kochan, R., Kochan, V., Sachenko, A. (2012). Software–hardware method of serial interface controller implementation. Elsevier Computer Standards & Interfaces, vol. 34, pp. 509–516.

32. Kondratenko, Y. P., Kozlov, O. V., Gerasin, O. S., Topalov, A. M., Korobko, O. V. (2017). Automation of control processes in specialized pyrolysis complexes based on web SCADA Systems. In: Proceedings of the 9th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS). Bucharest, Romania, vol. 1, pp. 107–112.

МОДЕЛЮВАННЯ СИСТЕМИ АВТОМАТИЧНОГО КЕРУВАННЯ ПРОСТОРОВИМ РУХОМ МОБІЛЬНОГО РОБОТА БАГАТОЦІЛЬОВОГО ПРИЗНАЧЕННЯ

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Анотація. *В роботі представлена імітаційна модель системи автоматичного керування багатоцільовим гусеничним мобільним роботом з окремими основними притискними магнітами для переміщення та виконання заданих різнотипних (двох і більше) технологічних операцій на похилих та вертикальних феромагнітних поверхнях в складних або небезпечних для людського життя та здоров’я умовах. Розроблена функціональна схема системи автоматичного керування, яка враховує взаємний вплив параметрів позиціонування мобільного робота, а саме: значення курсу (кута повороту) і лінійної швидкості переміщення по похилій поверхні. Крім того, розглянуті основні властивості керованого тиристорного перетворювача, сенсорної частини, регуляторів та мобільного робота в цілому для дослідження поведінки робота в різних умовах. Виконано налаштування регуляторів швидкості та кута повороту методом параметричної оптимізації основних показників якості керування за допомогою сучасного програмного забезпечення. Отримані перехідні процеси системи керування кутом та швидкістю мобільного робота з урахуванням взаємовпливу контурів управління швидкістю та кутом, а також без урахування їх взаємного впливу. Результати комп’ютерного моделювання показують наявність суттєвого впливу контуру керування курсом на характер перехідного процесу за швидкістю, в той же час, контур керування швидкістю має незначний вплив на характер перехідного процесу за курсом. Отримані характеристики показують високу адекватність поведінки розробленої моделі системи автоматичного керування просторовим рухом мобільного робота існуючим зразкам подібного обладнання та високі показники* *якості керування, зокрема для керованих координат проводиться аналіз часу перехідного процесу, перерегулювання, статичної помилки та коливальності.*

Ключові слова: *гусеничний мобільний робот, просторове переміщення, імітаційне моделювання, система автоматичного керування, лінійна швидкість, курс, помилка керування, ПІД-регулятор.*

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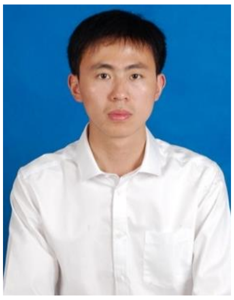

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