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MOBILE ROBOT FOR AUTOMATIC MOVEMENT AND SPRAYING COATINGS ON FERROMAGNETIC SURFACES IN SHIP REPAIR

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INTRODUCTION

There is a special need for mobile robots (MRs) able to move along horizontal, inclined or vertical surfaces using different types of movers and clamping devices (CDs), in particular for cleaning external ferromagnetic surfaces (FSs) of ships and other structures afloat or dry dock at automation of technological processes in shipbuilding and ship repair[1]. Such MRs are able to perform time-consuming and dangerous to human life and health work[2], such as cleaning of vertical large surfaces and in tight areas[3,4,5]; deactivation in radiation conditions; mounting of dowels and explosive devices; firefighting; dyeing; inspection and diagnostics; welding, cutting and polishing; desalination of the ship hulls and more to. The main requirement for any automatic control system (ACS) of similar robots is to provide reliable adhesion of MR with working surface at a given position and it holding without slippage[6].

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[2] Christensen L., Fischer N., Kroffke S., Lemburg J., Ahlers R. Cost-Effective Autonomous Robots for Ballast Water Tank Inspection. Journal of Ship Production and Design. 2011. 27 (3). P. 127-136.

[3] Souto D., Faica A., Lypez-Peca F., Duro R.J. Lappa: a New Type of Robot for Underwater Non-magnetic and Complex Hull Cleaning. Robotics and Automation : Proceedings of IEEE International Conference (Karlsruhe, Germany, May 6-10, 2013). Germany, 2013. P. 3394-3399.

[4] Ross B., Bares J., Fromme C. A Semi-Autonomous Robot for Stripping Paint from Large Vessels. The International Journal of Robotics Research. July-August, 2008. P. 617-626.

[5] Souto, D., Faiña, A., Deibe, A., Lopez-Peña, F., Duro, R. J. A Robot for the Unsupervised Grit-Blasting of Ship Hulls. International Journal of Advanced Robotic Systems. 2012. Vol. 9. P. 1-16.

[6] Kondratenko Y., Gerasin O., Topalov A. A simulation model for robot's slip displacement sensors. International Journal of Computing. 2016. V. 15, № 4. P. 224–236.

Automated spraying of various types of coatings on ship hulls and other large-sized FSs by means of robotics is of great practical importance, which will allow to significantly increase the service life of various work surfaces, to ensure a higher technical level of physic-mechanical and operational properties of steel parts of ships without the influence of different external factors[7].

1. Analysis of the current state of the problem of development of MRs for movement on complex surfaces in ship repair

The world experience of creating the new and modernizing existing technological equipment points to the rapid development of the controlled electric drives, the computer automation tools and the expansion of the spheres of use of the information tools. The share of the production of complete solutions increases, when executive mechanisms are coordinated with appropriate computer automation tools in the form of flexibly programmable systems intended for wide use due to the high rate of payback[8].

A characteristic feature of ship repair processes is their high labor intensity and large areas for processing with appropriate technological equipment during the implementation of individual technological operations. At the same time, the working technological process must ensure: the realization of the values of the basic indicators of the manufacturability of the performed operations; compliance with the rules of safety and industrial sanitation, standards for typical technological processes, instructions and other normative documents on safety and industrial sanitation. Accordingly, the individual technological operations and working methods must also meet these requirements. Given that the basis of process automation is the partial or complete removal of a person from direct participation in the production process (usually in areas with dangerous, harmful to health, difficult or monotonous working conditions)[9], we will consider in more detail the main means of extreme robotics for performing tasks on inclined FSs of ship hulls.

[7] Hui W., Ben N., Ryzhkov S., Topalov A., Gerasin O., Vyzhol Y. Improving the efficiency of an eddy current sensor measuring the thickness of a heat-resistant metal film of turbine blades during its deposition in vacuum. Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia, 2022, Iss. 88, P. 86 – 97.

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[9] Выжигин А. Ю. Гибкие производственные системы : учеб. пособие. М. : Машиностроение, 2009. 288 с.

To ensure movement on the external surfaces of structures and constructions MRs can be equipped with various types of CDs: mechanical, magnetic, adhesive, pneumatic, vacuum and magneto-operated[10,11]. Features of existing CDs limit the use of most types of such robots due to the inability to overcome complex surfaces, so we will consider control systems of the MRs by type of CDs.

MRs with vacuum CDs[12,13] are poorly controlled, move slowly, jerkily, which often leads to the necessary re-cleaning of missed areas. In addition, vacuum clamps are unreliable when passing through non-uniform surfaces (such as welds) that deform the vacuum seal and can cause it to fall, requiring significant maintenance and replacement costs. An alternative to vacuum CDs can be CDs based on propeller screws placed in a closed suction chamber, which do not depend on the material of the working surface[14]. Thanks to their multifunctionality, they can adjust the direction and speed of movement of the MR under water, allow it to come to the surface in case of loss of adhesion with the ship's hull. However, such pressure-driving devices have large weight and dimensions due to the presence of a gear motor and require careful sealing of the shafts for underwater works. The control system of such an MR is hierarchical and contains three levels. The main top-level module calculates the path the robot must follow along the hull to adequately clean it. The configuration of this module can vary depending on the strategy being used (random or based on the hull layout). The mid-level system is responsible for autonomously overcoming obstacles and performing local maneuvers (on the basis of sensor information). The low-level controller is implemented

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[10] Taranov M., Rudolph J., Wolf C., Kondratenko Y., Gerasin O. Advanced Approaches to Reduce Number of Actors in a Magnetically-Operated Wheel-Mover of a Mobile Robot. Perspective Technologies and Methods in MEMS Design (MEMSTECH) : Proceedings of the 2017 13th International Conference (Polyana, Ukraine, April 20–23, 2017). Polyana, 2017. P. 96–100.

[11] Запорожец Ю. М., Кондратенко Ю. П. Задачи и особенности управления магнитными движителями колесного мобильного робота. Электронное моделирование. 2013. Т. 35, № 5. С. 109-122.

[12] Градецкий В. Г., Вешников В. Б., Калиниченко С. В., Кравчук Л. Н. Управляемое движение мобильных роботов по произвольно ориентированным в пространстве поверхностям. Москва : Наука, 2001. 369 с.

[13] Мобільний робот для переміщення по довільно орієнтованим у робочому просторі поверхням: пат. 104113 Україна: МПК B25J9/00,B25J15/00. № u2015 06969; заявл.13.07.2015; опубл.12.01.2016, бюл. №1. 8 с.

[14] Мобільний робот для очищення підводних поверхонь суден: пат. 104222 Україна: МПК B25J 19/00, B25J 21/00. № а 2015 06778; заявл. 08.07.2015; опубл. 25.01.2016, бюл. № 2. 8 с.

using a Simatic S7-300 PLC, and for which an operator GUI is developed (it is responsible for the operation of the motors). This low-level controller may be available for operational monitoring by the operator.

One of the methods of adhesion of robots to the surface is chemical and molecular adhesion, which is implemented by adhesive CDs. Such MRs can be used only for inspection tasks, artistic decoration of vertical walls and facades, or transportation of small loads[15].

To perform specified technological operations on FSs, typical in ship repair, shipbuilding, and some other applications, a natural alternative to the ones already discussed is CD based on permanent magnets, electromagnets, or their combinations[16]. Examples of such structures are ferromagnetic ship hulls, tank walls, bridge supports, pipeline structures, etc.

The wheeled MRs with permanent magnets on wheels are widely used for work in hard-to-reach places for diagnostic and inspection tasks (MINOAS Crawler, Magnetbike, HR-MP20[17]). The MINOAS Crawler and Magnetbike robots use roughness sensors, thickness and instrumental means for measuring oxygen concentration and high-resolution wide-angle CCD cameras. A miniature IRU XSENS MTi gyroscope and a directional coordinate system are integrated into it to ensure the orientation of the inspection robot. An internal low-power signal processor provides drift 3D orientation of the MR without significant power consumption, and also calibrates 3D graphics acceleration, 3D yaw and 3D magnetic field data of the ground. Such robots are high-passability, can work autonomously, but they have low carrying capacity.

An underwater cleaning-inspection MR of a tracked type with permanent magnets on tracks («Fugro», Aberdeen, GB[18]) is shown in Fig. 1, a, b. Such robot contains a hydraulic drive and is controlled remotely from the surface using a laptop. Cleaning occurs with the help of a combined effect on the working surface of water jets and rotating brushes.

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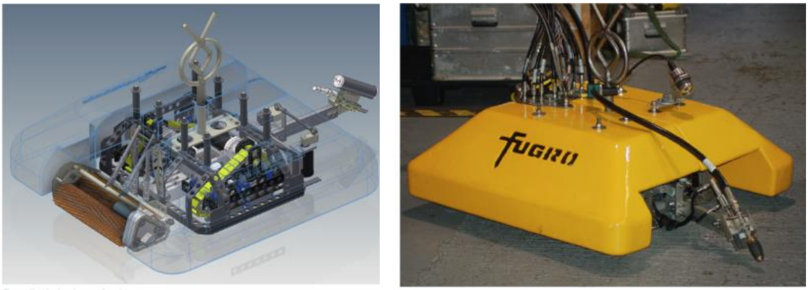
[15] Kozlov O. V., Gerasin O. S., Kondratenko G. V. Complex of tasks of monitoring and automatic control of mobile robots for vertical movement. «SHIPBUILDING & MARINE INFRASTRUCTURE». 2017. № 2(8). P. 77-87.

[16] Кондратенко Ю. П., Рудольф Й., Козлов О. В., Запорожець Ю. М., Герасін О. С. Нейро-нечіткі спостерігачі для ідентифікації притискного зусилля магнітокерованих рушіїв мобільних роботів. Технічна електродинаміка. 2017. № 5. С. 53–61.

[17] Робот-верхолаз HR-MP значно спростить процедуру діагностики конструкцій турбін вітрогенераторів. URL: https://goo.gl/iXlvty

[18] Герасін О. С. Аналіз особливостей мобільних роботів багатоцільового призначення. Наукові праці. Науково-методичний журнал, Серія «Комп’ютерні технології». Миколаїв : ЧДУ ім. П. Могили, 2014. Т. 50, № 238. С. 25–32.

The quality of control of the cleaning and diagnostic processes is increased with the help of various control methods: HD cameras, ultrasonic thickness gauge measurement, cathodic protection monitoring, coating thickness measurement, crack detection, 3D Sonar visualization and laser scanning. The advantage of such an MR is high speed, mobility and passability due to a large area of adhesion to the working surface.



a) b)

Fig. 1. Cleaning MR with permanent magnets on tracks:
a – 3D model; b – general view

The disadvantages of such MR are:

– low reliability and a short service life due to the continuous shock mechanical collisions of the permanent magnets with the operating surface during the caterpillar tracks movement, which leads to demagnetization and gradual destruction of the magnets;

– low energy efficiency and speed of the MR movement, since each subsequent elementary (singular) displacement of the device equivalent to the width of a track's permanent magnet is accompanied by separation of the latter in the opposite direction, which leads to the emergence of additional resistance to the robot's movement and extra energy loss; it requires using high-power engines with high torque and load capacity[19];

– limited scope of application and low reliability of cleaning and movement when the MR operates on an uneven working surface due to the possible separation of one of the tracks from the surface, which will lead to the separation of the second track from the plane of the ship hull.

[19] Пристрій для механічного очищення корпусу судна: пат. 63172 Україна: МПК B63B 59/00. № u 2011 04125; заявл. 05.04.2011; опубл. 26.09.2011, Бюл. № 18. 3 с.

Marine wheeled MR Octopus[20] is able to move on vertical, horizontal or inclined steel surfaces with the help of powerful electromagnets. The control system can be pre-programmed to follow a predetermined path or controlled remotely in real-time using a joystick. Such a robot has low speed and passability due to a small area of coupling with the FS.

The cycle of works is devoted to the analysis of other types of MRs, which in general confirms the feasibility of choosing CDs based on electromagnets or their combination with permanent magnets, which are able to provide greater speed and reliability when moving along inclined and vertical FSs when performing specified technological operations, unlike other types of CDs[21]. For the high-quality and reliable performance of technological operations in extreme conditions, the transport systems of robots are provided with a high-pass crawler mover, sensors of position and pressure force, built into the CDs. Regardless of the design and type of control system, small and universal built-in controllers that each robot carries on board are widely used in modern MRs. At the same time, the peculiarities of the control object in the form of MR for movement and spraying coatings on inclined FSs add specific tasks to be solved, therefore adaptive and intelligent systems are the most promising.

Adaptive and intelligent control involves the formation of models of the external environment; decision-making and planning of further actions; traffic management; creating an intelligent interface between the operator and the robot. However, such control methods are not common due to the complexity of developing and implementation of the control systems. Thus, as a result of the analysis of the features and prospects for the development of MRs for the automation of the processes of movement and spraying coatings, it was found that research in this field is mainly carried out by foreign scientists, and the tasks of developing functional structures, mathematical models, software and technical means of systems for the monitoring and control of the MRs, to increase the energy efficiency, reliability and economic indicators of the robot remain the subject of research by a number of scientific teams both in Ukraine and abroad.

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[20] Robot strips marine growth at sea. JOTUN. Solving the maintenance puzzle. Corrosion Protection Systems for Offshore Structures, Subsea Structures, FPSOs. Number 224. URL: https://cutt.ly/ONewK6R

[21] Faina A., Orjales F., Souto D., Bellas F., Duro R. A Modular Architecture for Developing Robots for Industrial Applications. Advances in Intelligent Robotics and Collaborative Automation / Y. Kondratenko, R. Duro, Eds. River Publishers Series in Automation, Control and Robotics, 2015.

2. Design of the advanced MR for movement and spraying coatings and formalization of its major tasks of monitoring and automatic control

Development of an effective design for the MR has resulted in the decision to improve it through introducing additional components and modifying its construction, namely, the tracked undercarriage and the elements holding the MR on the working surface. This will reduce energy consumption, increase the robot's speed, reliability and passability during various technological operations, and generally adapt it to the effective functioning on large FSs.

Fig. 2 presents a layout of the MR for the technological operations performing on a ship hull. In particular, the dashed lines in Fig. 2, a (top view) indicate the elements that are not visible from this angle. The robot is built on a solid flat frame (Fig. 2, a). Rectangular part of the frame 1 is equipped with a tracked mechanism[22]. Each caterpillar track 2 is equipped with a driving and a driven wheels, tape 3 made of a friction material is stretched in between. Each driven wheel is connected to drive motor 4 and gear unit 5. The rectangular part of the frame also accommodates zero buoyancy tank 6 and spherical hinges 7 (on the lower surface) securing the main permanent magnets 8 between the left and right caterpillar tracks with a proper gap δ to the operating FS 9 (Fig. 2, b).

The MR for movement and spraying coatings on complex surfaces of a ship hull equipped with specialized tools (not-shown in Fig. 2) operates as follows. First, the MR is installed on the ship hull in such a way that the main permanent magnets are oriented through the gap δ along the FS to provide the required clamping force. Afterwards, the spraying equipment is launched, and the spraying procedure begins.

Next, electric motors 4 are powered to rotate the driving wheels together with caterpillar tracks 3 through the gear units 5. Thus, the MR starts moving along the surface of the ship hull and spraying protective coating (the FS must first be cleaned of algae and other aquatic organisms). Spraying can be performed in a floating or dry dock.

[22] Мобільний робот для механічного очищення корпусу судна: пат. 100341 Україна: МПК B25J 19/00. № u 2015 00063; заявл. 05.01.2015; опубл. 27.07.2015, Бюл. № 14. 8 с.

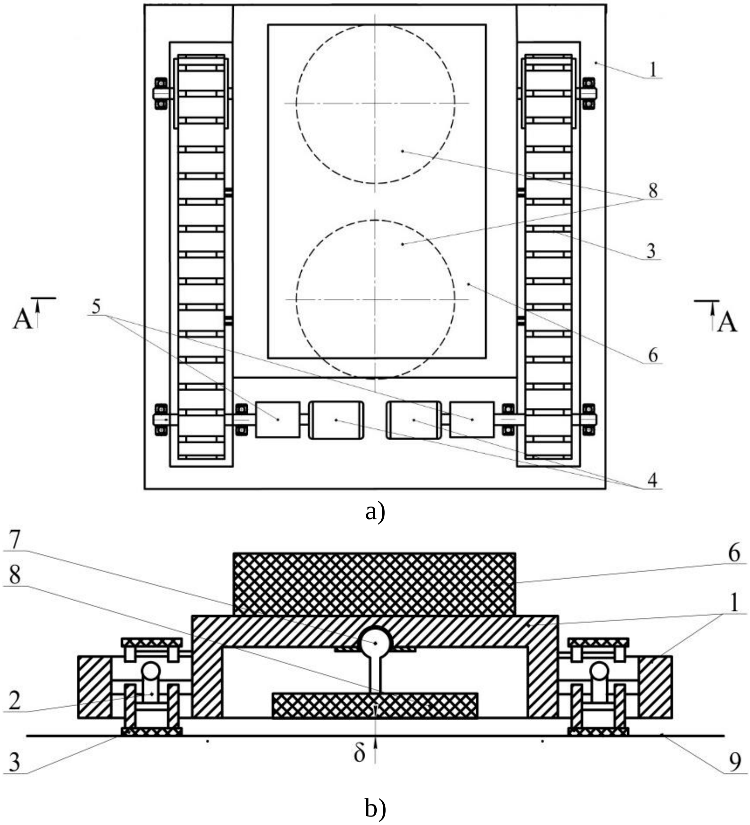

Fig. 2. Layout of the MR for movement on complex FSs of a ship hull equipped with cleaning tools: a – top view; b – cross-section A-A

The MR moves automatically on the surface of the ship hull in the direction specified by the program at a speed appropriate for the execution of a particular technological operation. The speed of spraying can be controlled by a human operator or a specialized computer system according to the quality of processing of the operating FS. Apart from that, two twin motors 4 with gear units 5 operate autonomously, independently of each other, which allows the robot to make any turn from 0° to 360° or move backwards. When the robot is moving along a rough FS, permanent magnets 8 secured with spherical hinges 7 deviate from the vertical axis of the hinge within the gap δ, and thus set the holding force vector perpendicular to the FS of the ship hull. In this way, the uniform distribution of the maximum clamping force between the magnets and the ship's FS is ensured along the entire operating plane of the magnets.

The use of separate holding magnets to create a clamping force and the installation of spherical hinge joints securing the magnets between the tracks on the underside of the MR frame improve the reliability of adhesion of the device to the operating surface by increasing the magnetic holding force of the robot. The main vector of the clamping force generally acting on the polar magnet facet and its components are calculated by the different methods[23,24].

The presence of an appropriate gap between the main permanent magnets and the surface allows increasing the speed and passability of the robot, since it provides the possibility of orienting the outer plane of the main clamping magnets in relation to the ship hull. The proposed tracked MR consumes less power because there is no additional resistance to movement, which means that there is no need for a cyclic separation of the permanent magnets from the FS during movement.

Besides, the tracked undercarriage can be additionally equipped with carrier rollers, as well as support rollers mounted on dampers to improve the adhesion of the caterpillar tracks with the working surface. At various technological operations (not only spraying), it increases the passability, maneuverability and speed of movement of the MR along the working surface with any angle of inclination.

In order to ensure reliability of the MR movement and continuity of the high-quality spraying protective coatings of the ship's hull surfaces (or other technological operations), these processes should be automatically controlled with the appropriate level of precision, all the operating parameters of ongoing operations should be monitored and checked for compliance with the declared level of quality. In addition, it is necessary to keep track of the current operational parameters of the robot and its technical equipment (TE).

The generalized robotic complex capable to move on large FSs may be considered as a multi-coordinate control and monitoring object. Then, there can be formulated the following major tasks for its monitoring and automatic control:

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[23] Пристрій для механічного очищення корпусу судна: пат. 63172 Україна: МПК B63B 59/00. № u 2011 04125; заявл. 05.04.2011; опубл. 26.09.2011, Бюл. № 18. 3 с.

[24] Kondratenko Y., Zaporozhets Y., Rudolph J., Gerasin O., Topalov A., Kozlov O. Modeling of clamping magnets interaction with ferromagnetic surface for wheel mobile robots. International Journal of Computing. 2018. № 17 (1). P. 33–46.

– monitoring and automatic control of the YMR vector of the MR spatial motion parameters;

– monitoring and automatic control of the FMP value of the clamping force of created by the MR clamping magnets;

– monitoring and automatic control of the XYMP vector of the operating parameters of the TE of the MR propulsor;

– monitoring and automatic control of the XFMP vector of the operating parameters of the TE of the MR CD.

The functional structure of the MR, capable to move and spray on large FSs, as a multi-coordinate control object is shown in Fig. 3. In the diagram, TE stands for the TE of the MR (spraying device), which is used for the implementation of specified technological operations; UTE is the vector of the signals of the MR TE control; UP is the vector of the signals of the MR propulsor control; UCD is the vector of the signals of the MR CD control; ZP, ZCD, ZTE, and ZMR indicate the vectors of the disturbing impacts acting on the MR propulsor, CD, TE, and main body, respectively.

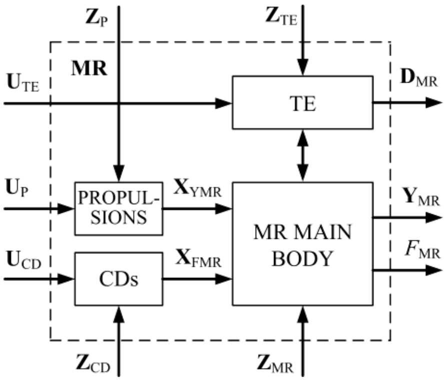

Fig. 3. Functional structure of the MR as a multi-coordinate control object

Thus, the given MR, capable to move on large FS, is a complex multicoordinate control object, and its effective functioning necessitates a developed multi-coordinate monitoring and ACS of positioning on large FSs based on intelligent techniques.

3. A mathematical model of spraying MR as a motion control object

With the effective development of the MR, it is not enough just to choose the most successful design, which should generally ensure its reliable, accident-free movement and execution of technological operations. Of great importance is its ACS, which provides the specified indicators of quality and efficiency on complex FSs. The ACS should receive information about the state of the environment, in particular the operating FS, and about the main parameters of the robot. Based on these data and according to the built-in control algorithm, the system should produce the necessary control influences, changing the current state of the executors, control the quality of operations performed by the robot[25].

Relatively low-cost (compared to experimental and other approaches) modeling methods, which are based on the principle of analogy to a real robot, have virtually unlimited possibilities for describing the features of a functionally complex system such as the MR and its control system.

The caterpillar MRs able to move on inclined and vertical FS are very effective instrument for moving different working tools along given trajectories and automation of painting and coatings spraying on ship hulls. However, to implement the operations the caterpillar MRs have to be able to move along pre-set trajectories and operate under uncertainty of the working surface caused by their technological features, presence of obstacles, structural damage, etc. Thus, automatic control of the spatial motion under the action of various disturbances is one of the most important and complicated automation tasks of MRs of such type. This task involves the simultaneous control of two interrelated MR's variables: linear speed and steering angle. The given interrelation of variables as well as a number of features of the robot as a non-linear multicoordinate interrelated plant don't allow achieving high control efficiency at using separate conventional controllers in the MR's two-channel ACS[26]. Thus, it is expedient to use the intelligent approaches to design the ACS for the spatial motion of the MR.

The mathematical model of the MR consists of the following equations[25]:

$$F = \frac{F_{\text{TO}} + G\left(f\cos\gamma + \sin\gamma - \xi\cos\gamma\right) + m_{\text{MR}} c\lambda}{\xi - f};$$

[25] Kondratenko Y., Kozlov O., Gerasin O. Neuroevolutionary approach to control of complex multicoordinate interrelated plants. International Journal of Computing, 2019. № 18(4), P. 502-514.

[26] Gerasin, O.S., Kozlov, O.V., Kondratenko, G.V., Rudolph, J., Kondratenko, Y.P. Neural Controller for Mobile Multipurpose Caterpillar Robot. 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Vol. 1. – Metz, France. – 2019. – P. 222-227.

$$\omega_{\mathrm{MR}} = V_{\mathrm{MR}} / R_{\mathrm{T}} = \left(V_{\mathrm{C2}} - V_{\mathrm{C1}}\right) / B;$$
$$V_{\mathrm{MR}} = \left(V_{\mathrm{C2}} + V_{\mathrm{C1}}\right)/2;$$
$$V_{\mathrm{C1}} = \omega_{\mathrm{MR}}\left(R_{\mathrm{T}} - 0.5B\right) = \omega_{\mathrm{W1}} R_{\mathrm{W}};$$
$$V_{\mathrm{C2}} = \omega_{\mathrm{MR}}\left(R_{\mathrm{T}} + 0.5B\right) = \omega_{\mathrm{W2}} R_{\mathrm{W}};$$
$$R_{\mathrm{T}} = \frac{0.5B(V_{\mathrm{C2}} + V_{\mathrm{C1}})}{(V_{\mathrm{C2}} - V_{\mathrm{C1}})};$$
$$M_{\mathrm{EM}a} = \frac{D_{\mathrm{M}}}{\eta_{\mathrm{M}}}\frac{d\omega_{\mathrm{M}}}{dt} + \frac{1}{k_{\mathrm{R}}\eta_{\mathrm{MR}}}\left[D_{\Sigma\mathrm{W}}\frac{d\omega_{\mathrm{W}}}{dt} + R_{\mathrm{W}}\left(f\frac{G\cos\gamma + F}{2} + G\sin\gamma\left(\frac{\cos\varphi_{\mathrm{MR}}}{2} + \right.\right.\right.$$
$$\left. + b\frac{x_O}{B}\sin\varphi_{\mathrm{MR}} + bf\frac{h_{\mathrm{C}}}{B}\sin\varphi_{\mathrm{MR}}\right) - b\frac{\mu_{\mathrm{T}} L\left(G\cos\gamma + F\right)}{4B}\left(1 + \frac{4x_O^2}{L^2}\right) +$$
$$+ F_{\mathrm{TO}}\left(\frac{1}{2}\cos\beta - \frac{\left(x_1 - x_O\right)}{B}\sin\beta\right) + \left(\frac{G\cos\gamma + F}{2g} + bG\sin\gamma\sin\varphi_{\mathrm{MR}}\frac{h_{\mathrm{C}}}{\mathrm{g}B}\right)\frac{dV_{\mathrm{C}a}}{dt} +$$
$$\left.\left. + \left(m_{\mathrm{MR}} + \frac{F}{g}\right)\frac{L^2 + B^2}{12B}\frac{d\omega_{\mathrm{MR}}}{dt}\right)\right],$$

where F_{TO} and F are the values of the specific forces of technological operation and the clamping magnets; G is the total weight of the robot and process equipment; γ is the surface inclination angle; f is the coefficient of rolling friction; ξ is the coefficient of adhesion; m_{MR} is the robot mass; λ is a combined mass ratio, $\lambda = 1{,}15 + 0{,}001\,k_{\mathrm{R}}^2$; k_{R} is the gear ratio; c is the robot acceleration; V_{C1}, V_{C2} are the current linear velocity of lagging and running caterpillars; R_{T} is the robot turning radius; V_{MR}, φ_{MR} are the current linear speed and course of robot, ω_{MR} is the rotation speed of the MR, $\omega_{\mathrm{MR}} = d\varphi_{\mathrm{MR}}/dt$; B is the distance between the centers of caterpillars; ω_{W1}, ω_{W2} – angular velocity of lagging and running wheels; R_{W} is the radius of the driving wheel; a and b are the coefficients, that take into account direction of rotation of the robot, a = 1, b = 1 – for a lagging caterpillar; a = 2, b = – 1 – for a running caterpillar; $M_{\mathrm{EM}a}$ are the electromagnetic torques of drive motors; η_{M}, η_{MR} are the efficiency of the motor and MR; D_{M} is the moment of inertia of the motor anchor; $D_{\Sigma\mathrm{W}}$ is the total moment of inertia of two wheels and caterpillar; L, h_{C} are the length of robot and height of center of gravity; x_O, x_1 are the distances from the transverse axis of the robot to the turning centers of the caterpillars and to the point of fixing the technological equipment; β is the angle of deviation of the force F_{TO} from the longitudinal axis of the robot; μ_{T} is the cornering resistance, which depends on the turning radius.

4. Automatic control system of the MR for spraying coatings on FSs

The functional structure of the two-channels ACS of the spraying MR's spatial motion on the basis of complex neural controller is presented in the Fig. 4[26]. The following designations are used: U_S and U_A are the setting signals corresponding to the given values of the MR's speed V_{MRG} and angular coordinate φ_{MRG}, which come from the upper control level; ε_S and ε_A are the error signals in speed and angle channels accordingly, which arrive to the motion neural controller (MNC); U_{CTC1} and U_{CTC2} are the voltages supplied to the MR's model for the each thyristor converter, which supply MR's drive motors of rotating tracks; U_{AS} and U_{SS} are the feedback signals from the speed (SS) and angle (AS) sensors; φ_{MR} and V_{MR} are the MR's current angular coordinate (robot's course) and linear speed.

The proposed MNC considers simultaneous control of two interdependent MR's variables – V_{MR} and φ_{MR}, as well as a number of features of the robot as a non-linear control object. The input variables of this controller are: ε_S, $\frac{d\varepsilon_S}{dt}$, $\int \varepsilon_S dt$, ε_A and $\frac{d\varepsilon_A}{dt}$. The outputs of MNC are, in turn, U_{CTC1} and U_{CTC2}. In fact, MNC allows to replace two separate conventional speed and angle controllers which usually used in the MR's two-channels ACS. So, combination of separate speed and angle controllers in a single complex controller look like very promising as a way for improving control quality indicators. Taking into account the need to use five inputs and two outputs in the resulting MNC it is advisable to apply neural networks tools for its development.

The stage of structural synthesis of the intellectual neurocontroller is a rather important task, because at this stage the topology of the neural network links is formed, neuronal activation functions are selected, which further determine the principle of the network functioning and its efficiency for solving the control problem. Choosing the excess amount of hidden layers and the number of neurons can lead to over-training or loss of approximation properties of the network. Therefore, it is advisable to use a constructive method for finding the optimal structure of the neural network, which begins to search from the minimum possible architecture of the network (neural network with a minimum number of layers, neurons and interneuronal connections) and consistently add new layers, neurons and interneuronal connections in each iteration. When looking for the optimal structure of a connectionist model, it is important to set parameters such as the number of neurons in each layer, the matrix of connections between neurons of the network, and also the choice of parameters of the neurons (parametric synthesis) that form the network.

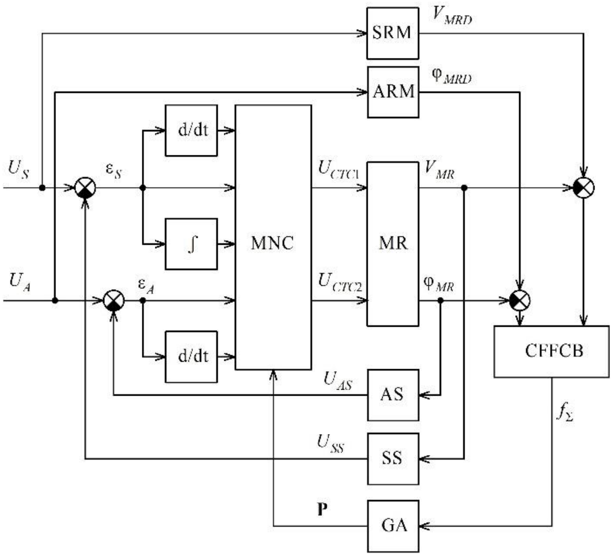

Fig. 4. The structure of MR's ACS with blocks for the neural controller tuning

Connectionist model of the intelligent MNC can be presented as a multidimensional function, which depends on the structure and parameters of the model:

$$y = f(w, x),$$

where *w* is the set of weight and correction coefficients values of the neural network; *x* is the vector of arguments belonging to the space of attributes[27,28].

[27] Xiao Z., Guo J., Zeng H., Zhou P., Wang S. Application of Fuzzy Neural Network Controller in Hydropower Generator Unit. *Kybernetes*, 2009. Vol. 38, No. 10. P. 1709–1717.

[28] Xu B., Yang Ch., Pan Y. Global Neural Dynamic Surface Tracking Control of Strict-Feedback Systems With Application to Hypersonic Flight Vehicle. *IEEE Transactions on Neural Networks and Learning Systems*. 2015. Vol. 26 (10). P. 2563–2575.

So, for the proper use of MNC at controlling MR, it is necessary to apply effective methods and algorithms of its training[29,30]. The genetic algorithm (GA) is an evolutionary approach that has proven itself well at training, synthesis and optimization of neural networks and other intelligent systems. GA is an universal method of optimization and can be used as the basis of the synthesis method of the complex MNC.

The general scheme of adjustment of the MNC with the help of GA is also shown in Fig. 4. In our case it assumes that there are two reference models (RMs) unlike the traditional description of GA. SRM and ARM are speed and angle reference models that describes the desired reaction of MR for speed $V_{MRD}(t)$ and angle $\varphi_{MRD}(t)$ in a near description to any inputs $U_S(t)$ and $U_A(t)$. Mentioned RMs can be much simpler than a MR's model for each control channel and can be represented by the transfer functions $W_{SRM}(s)$ and $W_{ARM}(s)$ accordingly:

$$W_{SRM}(p) = \frac{U_S(s)}{V_{MRD}(s)} = \frac{1}{(T_{SRM}s + 1)^{\gamma}};$$
$$W_{ARM}(p) = \frac{U_A(s)}{\varphi_{MRD}(s)} = \frac{1}{(T_{ARM}s + 1)^{\lambda}},$$

where T_{SRM} and T_{ARM}, γ, λ are the time constants and the orders of the transfer functions of SRM and ARM, s is the Laplace operator.

Alternative variants of the parameters of the MNC **P** (Fig. 4) are coded using chromosomes. To evaluate the suitability of each chromosome, it is necessary to perform a modelling of the transient process with the **P** parameters of the MNC for the given $U_S(t)$ and $U_A(t)$. In accordance with two control channels presence input parameter of GA is a complex fitness function f_Σ that consider control quality of both channels whether its mutual influence:

$$f_\Sigma = f_V + k_f f_A = \sum_{i=1}^{N}\left(V_{MRD_i} - V_{MR_i}\right)^2 + k_f \sum_{i=1}^{N}\left(\phi_{MRD_i} - \phi_{MR_i}\right)^2 \to \min, \quad (1)$$

where f_V and f_A are the fitness functions from two channels, k_f is the normalization factor. Therefore, it is proposed to combine two fitness

[29] Molina J.K., Dominguez M.J., Onate C.U., Salamea H.T. Development of a neural controller applied in a 5 DOF robot redundant. *IEEE Latin America Transactions*. 2014. Vol. 12 (2). P. 98–106.

[30] Zhang Y., Yingliu Ch., Song X., Yan Zh. Application of RBF Neural Network PID Controller in the Rectification Column Temperature Control System. *Proc. of Sixth Int. Symp. on Computational Intelligence and Design*. 2013, Vol. 2, P. 72–75.

functions (in channels of speed and angle) into common one f_Σ with considering weight coefficient k_f for f_A due to possible different order in f_V and f_A values. Complex fitness function f_Σ is calculated in the complex fitness function calculation block (CFFCB) in Fig. 4.

The control quality evaluations (the adaptabilities of each chromosome) are made on the basis of f_Σ value. The relative adaptability (RA) F of the chromosome can be calculated as $F=1/f_\Sigma$.

Thus, the control law is synthesized by means of proposed method based on GA as a result of multiple experiments with the MR's simulation model. With adequate work of the MNC, the outputs of the MR's model and RMs should be close, so the task of setting the neural controller is set as the task of minimizing the fitness function f_Σ. In addition to the criterion (1), the following traditional criteria for the quality of the transients can be used as a supply of stability, time of the transients, overshoot, etc. Thus, the proposed synthesis method of intellectual neural controller can be represented as follows.

Step 1. In accordance with the complexity and order of the control object, choose the inputs and outputs of the neural controller.

Step 2. Determination of boundary values of the parameters of the neural network structure (maximum number of hidden layers, neurons and interneuronal connections).

Step 3. Perform parametric optimization of synaptic weights of the neural network with the given architecture by means of GA.

Step 3.1. Encoding parameters by chromosome.

The chromosome consists of the genes, each of which is a MNC parameter. Binary or real numbers can be used to represent genes. For example, the synapse weight coefficient between the first input neuron and the first hidden layer neuron is encoded as w_{11}, between the second input and the third hidden neuron – w_{23}. In this case, all the synaptic weights between the input and the hidden layers become a vector W_1, between the hidden and the output layers – vector W_2.

Step 3.2. The choice of genetic operators.

The work of the GA is managed by three genetic operators: selection, crossing and mutation. There are various modifications of these operators, so the choice of a particular variant affects the speed and quality of the solution. Setting the probability of crossing P_C and the probability of mutation P_M.

Step 3.3. Perform initialization of the initial population by chromosomes, containing information on the values of the weighting coefficients of the given network structure, that is, the formation of the initial population P_0 (a finite set of admissible solutions to a problem)

$$P_0 = \left\{ H_1, H_2, \ldots, H_j, \ldots, H_L \right\},$$

where H_j is the population's *j-th* chromosome; L is a size of population.

Step 3.4. Rate the chromosomes of the current population.

Step 3.4.1. Decode each chromosome population into a set of weight coefficients of the neurocontroller.

Step 3.4.2. Build the neural networks that meet the estimated chromosomes. Simulate the system with current weighting factors of the neurocontroller.

Step 3.4.3. Calculate the value of the fitness function of the estimated chromosomes $f_\Sigma(H_j)$, taking into account the error and complexity of the network (j = 1,..,L).

Step 3.5. Check the search expiration criteria.

Condition 1. Achievement of an acceptable value of the target (fitness) function $f_{\Sigma\text{opt}}$ of the synthesized MNC. If the value of the target function f_Σ of some individual reaches a value $f_{\Sigma\text{opt}}$ with a predetermined accuracy ε in the process of functioning of the GA, then the criterion is considered achieved.

Condition 2. Exceeding the maximum allowed number of iterations $n_{\max}$ (50-100 iterations).

Condition 3. Degeneration of the population.

The iterations number n_p and the threshold of the coefficient of improvement of the values of the fitness functions of the best chromosome ρ_p are given. After that, the coefficient of improvement is calculated as

$$\rho = \frac{f_{best_t} - f_{best_{t-1}}}{f_{best_{t-1}}},$$

where f_{best_t} is the best value of the target function, $f_{best_{t-1}}$ is the best value of the target function from previous generations. If the value ρ is less than ρ_p, then the stopping criterion is considered reached.

Switching to step 3.10 in case one of the stopping condition is satisfied.

Step 3.6. Select individuals to generate new solutions based on the value of the fitness function. The proportional selection is used in this case.

Step 3.6.1. Find the average value of the fitness function $f_{\Sigma M}$ of the population as the average of the arithmetic values of the fitness functions.

$$f_{\Sigma M} = \frac{1}{L}\sum_{j=1}^{L} f_{\Sigma j}.$$

Step 3.6.2. For each individual calculate the ratio $P_S(j)=f_{\Sigma j}/f_{\Sigma M}$.

Step 3.6.3. Form an array of admitted to crossing individuals depending on the $P_S(j)$ value (if $P_S(j) > 1$, then, the individual is considered well adapted and allowed to crossing).

Step 3.7. Apply crossing operators for the chromosomes, selected in the previous step. Random selection of parent couples is applied in this case.

Step 3.7.1. Number all the representatives of the current population in an arbitrary manner.

Step 3.7.2. Choose the first parent.

To do this, starting with the first one, take over all the chromosomes of the population until the randomly chosen number on the interval [0; 1] will not be less than P_C. When this happens for one of the elements of the population, this element will become the first parent.

Step 3.7.3. Continue to browse the population starting from the decision following after the first parent, until the randomly chosen number again is less than P_C. The chromosome for which such a condition is fulfilled will be the second parent. Continue Step 3.7.3 until the required number of parent pairs is selected.

Step 3.7.4. For each parent pair use the one-point cross-operator.

Step 3.8. Apply mutation operators for chromosomes, selected in step 3.6 for the probability of mutation P_M.

Step 3.8.1. Copy the parent chromosome into a chromosome-heir.

Step 3.8.2. Choose the mutant gene randomly.

Step 3.8.3. Choose a new gene value that is not equal to the current one in a given range of permissible gene values.

Step 3.9. Form a new generation of elite chromosomes and chromosomes-heirs obtained by applying crossing and mutation. Go to step 3.4.

Step 3.10. Stopping the operation of the GA.

Step 4. Checking the criteria for stopping genetic search. If condition 1 is satisfied then proceed to step 7.

Step 5. Add the neuron to the last hidden layer. If the maximum number of neurons in the layer is reached, then proceed to the next step, otherwise – to step 3.

Step 6. Add a new hidden layer, consisting of one neuron before the output layers. If the maximum number of hidden layers have been reached, go to the step 1, otherwise go to step 3.

Step 7. The end.

For the successful synthesis of the control system, it is necessary to design the most appropriate simulation model of the control plant and the nature of the load, although for a substantially nonlinear system, this task is quite complex and does not always have a proper solution[31].

In order to perform simulation and obtain output characteristics, the following main parameters of the MR have been chosen: loaded weight of 300 kg, length of 1 m, width of 0.7 m, wheel radius of 0.15 m, linear speed of movement of 0.2 m/s, two DC drive motors and gear ratio of 80. The specified parameters of the MR's ACS (Fig. 4) and the mathematical model of the MR shall be used to obtain the MR's speed and the angle of rotation transient processes (response of the system to a step input), as well as the main control quality indicators.

As a result of the conducted training the optimal structure of the MNC network is found as follows: five input neurons, the first and the second hidden layers consist of four and three neurons, as well as two output neurons (5-4-3-2). For the given structure each GA chromosome consists of 38 genes and the total goal (fitness) function value J_{Σ} = 159.33 is achieved at the 87-th iteration. The characters of change of the total goal function (4) value in the process of neural controller training for the obtained structure are presented in Fig. 5.

The simulation of the designed spatial motion ACS with MNC of the caterpillar MR on the basis of the neuroevolutionary approach transients is conducted to study its efficiency. The comparison of the obtained simulation results is performed for two control coordinates V_{MR} and φ_{MR} at the output of MR's model (Fig. 4) with desired V_{MRD} and φ_{MRD} values formed at the output of their RMs as well as with traditional separate speed PID-controller and angle PD-controller in interrelated two-channels structure of MR's spatial motion ACS. In turn, the conventional speed PID-controller and angle PD-controller are tuned via parametric optimization of basic control quality indicators with the help of gradient method. The obtained coefficients values are as follows: k_{PV} = 6.5; k_{IV} = 422.4; k_{DV} = 0.23 – for the speed PID-controller and $k_{P\varphi}$ = 48.5; $k_{D\varphi}$ = 5.2 – for the angle PD-controller. In this case, the disturbance is simulated as the constantly acting on the MR maximum permissible load force from the spraying operation $F_{\mathrm{TO}} = 10^3$ N.

[31] Yaoyao W., Tianlin L., Yian D. Learning to Chase a Ball Efficiently and Smoothly for a Wheeled Robot. Proc. of 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP), Auckland, New Zealand, 2017, November 21-23, P. 36–41.

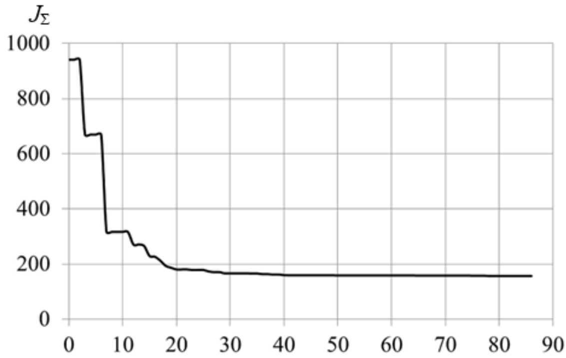

Fig. 5. The nature of the best goal function value change in the process of MNC training

The graphs of the ACS transients for step up changes of set points V_{MRS} = 0.3 m/s and $\varphi_{MRS} = \pi/3$ rad at the surface inclination angle $\gamma = 60^o$ are presented in Fig. 6 and 7 respectively.

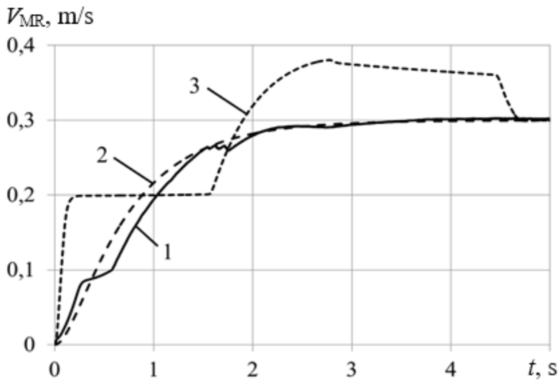

Fig. 6. ACS step up transients of MR's speed: 1 – with MNC of spatial movement; 2 – speed RM; 3 – with conventional PID-controller

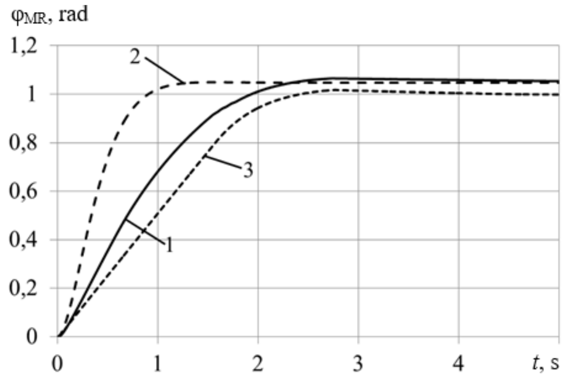

Fig. 7. ACS step up transients of MR's angle: 1 – with MNC of spatial movement; 2 – angle RM; 3 – with conventional PD-controller

The quality indicators comparative analysis of the spatial motion ACS of the MR with the developed MNC and optimally tuned conventional controllers is presented in Table 1, where t_t is the transient time; Δ is the static error.

Table 1

Comparative analysis of quality indicators of the ACS of the MR spatial motion (step up transients)

Model type	**ACS quality indicators**			
	t_t, s	**Δ,%**	**J_V**	**J_φ**
RM_V	2.11	0	0	-
Speed with PID-controller	4.6	1	22.7	-
Speed with MNC	2.09	0.7	0.8	-
RM_φ	0.89	0	-	0
Angle with PD-controller	2.36	4.8	-	292.4
Angle with MNC	1.91	0.6	-	138.1

As it can be seen in Table 1, Fig. 6 and Fig. 7 the developed ACS of the spraying MR spatial motion on the basis of the proposed neuroevolutionary approach has considerably higher quality indicators for speed and turning angle control compared with the use of conventional ACS with separate controllers of the given variables. In particular, the use of the multicoordinate interrelated ACS with the single complex MNC allows us to reduce the transients time of the speed and angle control by 55% and 19% respectively, to eliminate unwanted overshoot of 27% at speed control and significantly reduce (8 times) the static error at angle control. Wherein, the static error of the MR's speed control is less than 1% that isn't critical while performing various technological operations.

The graphs of the ACS transients for step down changes of set points V_{MRS} = 0.1 m/s and $\varphi_{MRS} = \pi/12$ rad (from 0.3 m/s and $\varphi_{MRS} = \pi/3$ rad respectively) at the same simulation conditions are presented in Fig. 8 and 9.

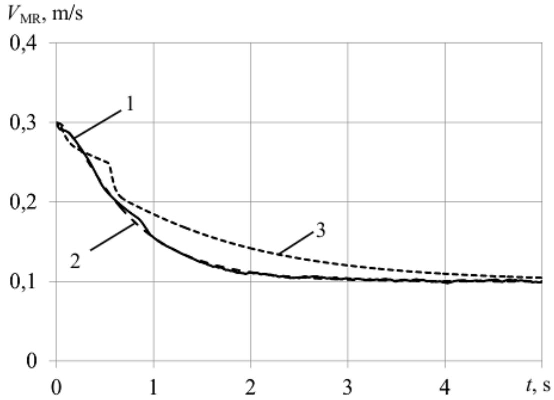

Fig. 8. ACS step down transients of MR's speed: 1 – with MNC of spatial movement; 2 – speed RM; 3 – with conventional PID-controller

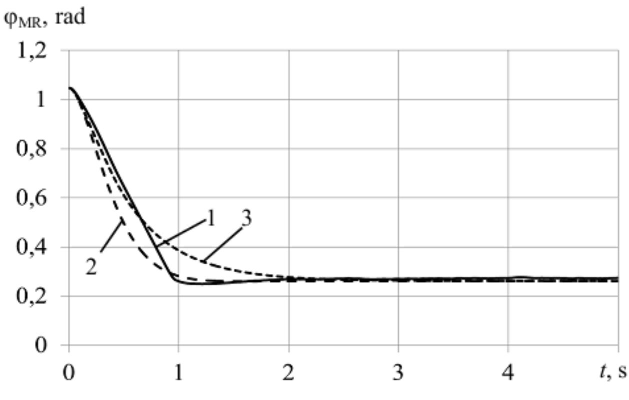

Fig. 9. ACS step down transients of MR's angle: 1 – with MNC of spatial movement; 2 – angle RM; 3 – with conventional PD-controller

As well, the quality indicators comparative analysis of these transients is presented in Table 2.

Table 2

Comparative analysis of quality indicators of the ACS of the MR spatial motion (step down transients)

Model type	ACS quality indicators			
	t_t, s	Δ,%	J_V	J_φ
RM_V	2.55	0	0	-
Speed with PID-controller	4.9	0	2.36	-
Speed with MNC	2.4	1	0.13	-
RM_φ	1.06	0	-	0
Angle with PD-controller	2.07	0	-	12.7
Angle with MNC	0.95	2.9	-	9.96

As it can be seen in Table 2, Fig. 8 and Fig. 9 the developed ACS of the spraying MR spatial motion on the basis of the neuroevolutionary approach also has higher quality indicators for speed and turning angle control compared with the use of conventional ACS with separate controllers of the given variables. In particular, the use of the multicoordinate interrelated ACS with the single complex MNC allows to reduce the transients time of the speed and angle control by 51% and 54% respectively for step down transients, wherein the static errors at speed (1%) and angle (2.9%) control are not critical while performing spraying operations. Besides, J_V and J_φ are less for developed system in both transients (step up and step down).

Thus, the synthesized ACS of the MR spatial motion with MNC shows higher quality of control, better takes into account the mutual influence of control channels of the angle and speed of the MR than separate conventional regulators, and, accordingly, allows increasing performance and quality of the operations.

Therefore, the above studies confirm the high efficiency of the proposed neuroevolution based approach to design of control systems for complex multicoordinate interrelated plants. The application of the developed approach at designing ACSs for MRs gives the opportunity to take into account the mutual influence of their control variables and, as a result, significantly improve the quality indicators of control and total effectiveness providing optimal operating modes.

CONCLUSIONS

The paper presents the design of the MR capable of automatic moving along inclined and vertical FSs in order to perform spraying coatings in ship repair industry.

Analysis of the features of most types of the modern ship repairing MRs able to move along FSs renders the complex of problems related to the development and operation of the CDs, control of the drives, as well as different ways of their solution for ship repair. Magnetic and magnetically operated CDs are most suitable for moving along the most common FSs due to providing the highest speed and insensitivity to changes in the structure of the surface; the permanent magnets in CDs improve the reliability of the robot in the event of the power system failure.

Analysis and formalization of the complex of tasks for monitoring and automatic control of the spraying MR are performed, and as the result course angle and speed are chosen as main control coordinates for its motion ACS.

The development of the structure and the synthesis method of the complex neural controller for spatial motion of the presented caterpillar MR able to move on FSs in accordance with pre-set parameters for increasing the quality indicators and efficiency of MR's two-channels ACS is presented. The obtained solution combines separate speed and angle controllers in the single complex neural controller in the interdependent two-channels structure of MR's control system. Developed controller takes into account the mutual influence of the MR motion parameters, namely, the value of speed and the course angle of movement on inclined FS. The proposed MNC is tuned by genetic algorithm using complex fitness function considering quality of control for both output coordinates (speed and angle) shows its high efficiency.

Further work is related to the practical implementation of the synthesized controller and the study of its functioning on the experimental MR's model.

SUMMARY

This work presents the design of a mobile robot (MR) able to automatically move along various ferromagnetic surfaces performing spraying coatings for ship repair industry. Analysis and formalization of the monitoring and automatic control tasks of the MR for the movement and execution of given technological operation on inclined and vertical surfaces are obtained. The corresponding MR's construction is chosen for reliable movement and spraying protective coatings on the ship hulls. A mathematical model of the MR for spatial motion is presented; it relates the movement speed, course angle and clamping force created by the robot's clamping devices. The structure and synthesis approach of the neural controller of the MR's spatial motion are proposed for chosen

robot’s construction and in accordance with its mathematical model. The peculiarity of the proposed structure lies in combination of separate speed and angle controllers in a single complex neural controller in interdependent two-channels structure of MR’s control system. The synthesis method of the proposed controller is developed on the basis of genetic algorithm using complex fitness function considering quality of control for both output coordinates (speed and angle). Simulation results confirm the high efficiency of the proposed MR and its control system.

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