SYNTHESIS AND STUDY OF THE MATHEMATICAL MODEL OF A CATERPILLAR MOBILE ROBOT FOR VERTICAL MOVEMENT

UDC 681.5

Oleksandr Serhiiovych GERASIN
lecturer, Admiral Makarov National University of Shipbuilding, Ukraine
Research interests: computer control systems, modeling, fuzzy logic, intelligent robotics, automation.
e-mail: oleksandr.gerasin@nuos.edu.ua

Oleksiy Valeriiovych KOZLOV
Ph.D., associate professor, Admiral Makarov National University of Shipbuilding, Ukraine
Research interests: automation, intelligent control systems, robotics, fuzzy logic, elements and devices of computing systems.
e-mail: oleksiy.kozlov@nuos.edu.ua

Galyna Volodymyrivna KONDRATENKO
Ph.D., associate professor, Admiral Makarov National University of Shipbuilding, Ukraine
Research interests: automation, intelligent decision support systems, fuzzy logic.
e-mail: galvlad09@rambler.ru

Huang MINGXIN
lecturer, Yancheng Polytechnic College, China
Research interests: robotics, automation, computer control systems, modeling.

Introduction and problem statement. Mobile robots (MRs) and robotic systems are becoming more and more widespread in various industries: from transportation and assembly operations to high-tech processing [1-5]. For a successful creation of the systems, the stage of their development commonly implements the means and approaches of mathematical and simulation modeling. In such a way, major mass-size, economic and environmental parameters are optimized, compliance of the control system with the given quality indicators is verified, and so on. This approach allows specifying the structure and parameters of control devices of the robot control system in due time (that is before the development of an experimental sample), as well as checking its main dimensions and the feasibility of choosing particular structural elements (driving wheels, motors, caterpillar tracks, etc.). In addition, it enables pre-estimating the time of the robot's response (change in control coordinates) to the setting action for the tasks of automatic control, which is crucial for ensuring a high accuracy of the MR's technological operations [5].

Under present-day conditions, of great interest is the possibility of realizing one or more technological operations on inclined and vertical surfaces with the help of MRs [5]. The robots with such a function are complex multicomponent technical objects; their operation requires special computer-aided monitoring and control systems [2]. An important phase in the development of such systems is mathematical and simulation modeling of the future designs [6]. In order to test the algorithms controlling the MR's spatial motion along inclined surfaces and study the effectiveness of the MR's control system, it makes sense to develop models of the whole MR and its individual components taking into account their design features and employing mathematical and computer simulation methods, which are quite effective and cheap in comparison with experimental and other approaches [6].

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. A mathematical description of the main types of mobile robots (wheeled, tracked and walking) is given in [9-16]. Development of mathematical models and transfer functions for DC and AC motors, gear units, driving wheels and other elements for the tasks of automated control is considered separately, for instance, in papers [17-19]. Besides, there is a certain number of publications concerning the synthesis of mathematical models of wheeled [12], tracked [13, 14] and walking [15-16] mobile robots. Meanwhile, the problem of development of the mathematical model of a wheeled MR moving vertically along inclined ferromagnetic surfaces, which would suitable for further synthesis of its automatic control system, is still unresolved. Analysis of the physical properties and technical characteristics of the MR as an object of control of a spatial position with respective control coordinates [20] proves the feasibility of development of its mathematical model with the use of the principles and algorithms based on the theory of vehicle movement and phased inclusion of the loads on the robot's drive motors work generated by the components of forces and moments of resistance [19].

The article aim is to develop a mathematical model of a vertically moving MR based on the theory of vehicle movement as well as to study its behavior in terms of the impact of the MR's individual components on its spatial position and the rate of response to various specified input actions and disturbances with account for the angle of inclination of the working surface and direction of the MR's movement.

Basic material. Synthesis of the mathematical model of a vertically moving MR. The principal scheme and basic properties of a vertically moving MR capable of performing specified technological operations on large inclined ferromagnetic surfaces are discussed in publications [20, 21]. The MR has a solid frame, two caterpillar tracks and two drive DC motors (DCM), one for each track. The whole structure of the MR holds onto the inclined or vertical ferromagnetic surface with the help of two separate flat permanent magnets, which are hinged to the frame, providing orientation of the resultant vector of the clamping force with regard to the ferromagnetic surface [15, 21, 22]. The MR is moving as the left-hand and right-hand tracks are rotated by the driving wheels. In turn, the driving wheels are actuated by the drive DCMs, which are connected to the wheels through gear units.

The process of modeling of the MR requires a thorough consideration of its main units and components [10, 11]. Let us render the mathematical models of the main elements of the MR below.

Drive motor model. The required rotational speed of the driving wheels is ensured by direct control of the MR's drive motors. In the design shown in [21], such are DCM, although they can be substituted with AC motors as well. Let us describe the DCM model.

An important property of a separately excited DCM is that the resulting moment of the forces from all the armature conductors [17-18] (dubbed as the electromagnetic moment of the motor M_{EM}) is proportional to the current of the armature I_A supplied to the motor from the power source:

$$M_{EM} = c_M I_A , \qquad (1)$$

where c_M is the coefficient of proportionality. According to the laws of electromagnetic induction in a conductor moving in a magnetic field there arises an electromotive force (EMF). The total EMF of the armature coils E is applied through the commutator and brushes to the external terminals of the motor. At the motor operation the EMF is directed against the external voltage U_A supplied to the armature from the power source. The EMF is directly proportional to the angular speed of the motor's shaft rotation ω_E:

$$E = c_E \omega_E , \qquad (2)$$

where c_E is the coefficient of proportionality of the motor's constant EMF. Due to the nature of electromagnetic phenomena in the DC motor, the coefficients c_E and c_M are to have approximately equal numerical values if the SI system is used.

In the motor's armature circuit the current I_A flows under the impact of the DC voltage U_A of the power source and the counter-EMF of the motor. This circuit is characterized by the active resistance R_A and the inductance L_A of the armature winding. Having the moment of inertia J_A, the rotating rotor is driven by the simultaneous action of the electromagnetic moment of the motor M_{EM} and the moment of resistance to external forces M_{SM} applied to the motor shaft.

The output differential equations for the DCM are drawn up on the basis of the laws of physics. The Kirchhoff's second law is applied for the electric circuit to compose the following equation:

$$U_A - E = R_A I_A + L_A \frac{dI_A}{dt}, \tag{3}$$

where $R_A I_A$ characterizes the voltage drop on the active resistance of the armature circuit in accordance with the Ohm's law, and $L_A(dI_A/dt)$ indicates the self-induced EMF that occurs in the winding when changing the armature current. This equation does not take into account the voltage drop on the brushes, which depends on the armature current nonlinearly but commonly has a relatively small value compared to the voltage U_A.

The differential equation describing the processes in the mechanical part of the motor is composed using the Newton's second law:

$$J_A \frac{d\omega_E}{dt} = M_{EM} - M_{SM}. \tag{4}$$

This equation ignores the impact of frictional forces that emerge during the rotor's rotation but have a relatively weak effect on the DCM shaft acceleration.

Using the above formulas and reducing the differential equations to the Cauchy normal form, we obtain the following description of the DCM:

$$\begin{cases} \dfrac{dI_A}{dt} = \dfrac{U_A - R_A I_A - c_E \omega_E}{L_A}; \\ \dfrac{d\omega_E}{dt} = \dfrac{c_M I_A - M_{SM}}{J_A}. \end{cases} \tag{5}$$

When studying the processes with the help of a personal computer (PC), it is convenient to use a structural representation of the DCM's mathematical model. For that end, let us subject the previously obtained system of linear differential equations to Laplace transformation under zero initial conditions. The resulting system of algebraic equations is as follows:

$$\begin{cases} pI_A(p) = \dfrac{U_A(p) - R_A I_A(p) - c_E \omega_E(p)}{L_A}; \\ p\omega_E(p) = \dfrac{c_M I_A(p) - M_{SM}(p)}{J_A}, \end{cases} \tag{6}$$

where p is the Laplace operator, while the quantities $I_A(p)$, $\omega_E(p)$, $U_A(p)$, $M_{SM}(p)$ are Laplace representations of the variables I_A, ω_E, U_A and M_{SM}, respectively. After equivalent transformations, these equations acquire the following form:

$$I_A(p) = \frac{U_A(p) - c_E \omega_E(p)}{R_A(T_E p + 1)}; \tag{7}$$

$$\omega_E(p) = \frac{c_M I_A(p) - M_{SM}(p)}{J_A p}, \tag{8}$$

where $T_E = L_A/R_A$ is the electromagnetic time constant of the motor's armature circuit.

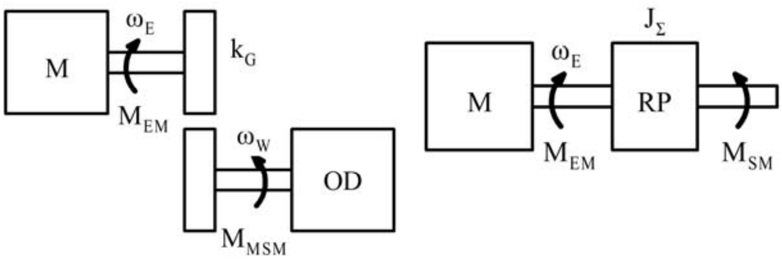
Gear unit model. If the operating device (OD) of the system is directly connected to the motor's shaft, analysis of the motion of the electromechanical system "motor – operating device" can utilize equation (4). Such a kinematic diagram is typical for fans, pumps and a number of other machines [17]. However, in our case, the operating device of the system (driving wheel) is connected to the motor's shaft through the gear system, namely, through the gear unit. Therefore, an immediate use of equation (4) is impossible, since the moments M_{EM} and M_{SM} are applied to different shafts, and inertial masses rotate at different speeds.

To enable the use of the equation of motion, one has to solve the problem of reducing all the moments of resistance and inertia of individual kinematic links to one shaft, usually to the shaft of the electric motor. This reduction is only a calculating operation and does not require any physical changes in the system. The principle of moment reduction is to preserve the equivalence of power. The reduction of the moments of inertia follows the principle of kinetic energy conservation [17].

As a rule, if the machine's OD is connected to the motor's shaft via a gear unit (Fig. 1, a) with the gear ratio k_G, reducing the actual moment of resistance M_{SM} applied to the driving wheel to the motor shaft requires compliance with the equivalence of power [17]:

$$M_{MSM}\omega_W = M_{SM}\omega_E, \tag{9}$$

where M_{MSM} is the moment of resistance to motion (hereinafter referred to as its static moment); ω_W is the angular speed of the driving wheel.



a) b)

Fig. 1. Reduction of the moments of resistance to the shaft of the motor (M): a – actual kinematic diagram of the motor's connection to the operating device (OD) through the gear unit; b – computational diagram with the reduced part (RP)

Therefore, if one knows the static moment on the shaft of the operating device, one can calculate the static moment applied to the motor's shaft using the following formula (not accounting for the losses in the gear unit):

$$M_{SM} = \frac{M_{MSM}}{\omega_E / \omega_W} = \frac{M_{MSM}}{k_G}. \tag{10}$$

The general rule here is that in order to reduce a static moment to the motor's shaft, one divides the actual static moment on the OD's shaft by the gear ratio. If it is necessary to take into account the losses in the gear unit, the coefficient of transmission efficiency should also be included to the denominator (10).

Thus, the first transfer function of the gear unit takes the following form:

$$W_{G1}(p) = \frac{\omega_E(p)}{\omega_W(p)} = k_G. \tag{11}$$

To reduce the moment of inertia of the driving wheel J_W to the motor's shaft, it is necessary to preserve the equality of kinetic energies

$$\frac{J_W\omega_W^2}{2} = \frac{J_{RM}\omega_E^2}{2}, \tag{12}$$

where J_{RM} is the moment of inertia reduced to the motor's shaft.

Consequently, the OD's moment of inertia reduced to the motor's shaft is calculated according to the formula:

$$J_{RM} = \frac{J_W}{k_G^2}. \tag{13}$$

The general rule here is that in order to reduce the moment of inertia to the motor's shaft, the actual moment of inertia of the kinematic link is to be divided by the squared gear ratio.

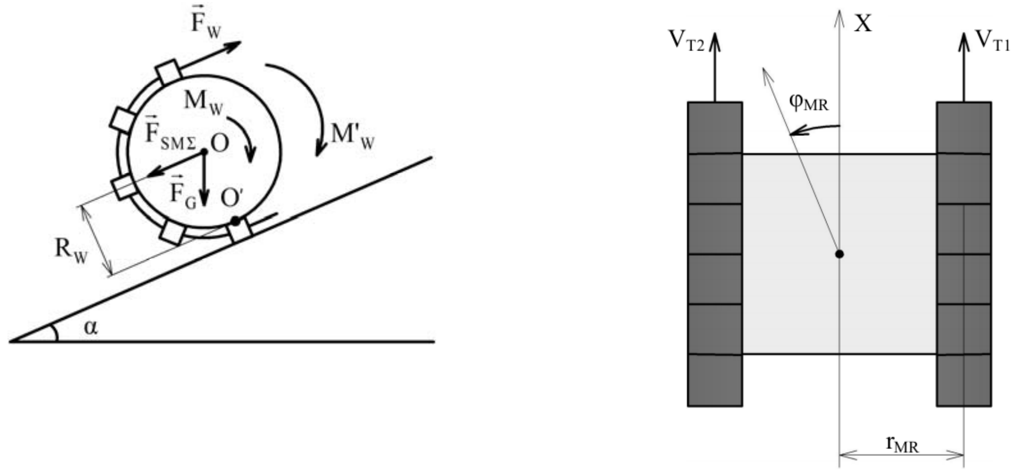
Hence, the second transfer function of the gear unit is as follows:

$$W_{G2}(p) = \frac{J_W(p)}{J_{RM}(p)} = k_P^2. \tag{14}$$

As a result of reducing the static moment and the moment of inertia to the motor's shaft, the actual kinematic diagram transforms into the computational one (Fig. 1, b), which enables using the modified equation of motion of the electric drive:

$$M_{EM} - M_{SM} = J_\Sigma \frac{d\omega_E}{dt} = \left(J_A + J_{RM}\right)\frac{d\omega_E}{dt}. \tag{15}$$

MR model. Development of MRs' models which would fit various designs usually considers its main operating device [17]. In our case, the main operating device of the MR is its driving wheels (gears) rotating the caterpillar tracks, which leads to the movement of the entire MR along the inclined surface (Fig. 2, a).



a) b)

Fig. 2. Schematic design of the MR: the driving wheel with a part of the caterpillar track at its movement along an inclined surface (a) and a generalized diagram of the tracked MR movement (b)

Let us compose the equation of moments on the DCM's shaft:

$$M_{EM} = M_{DE} + M_{MSE} + M_{WE}, \tag{16}$$

where M_{DE} is the dynamic moment of the DCM, $M_{DE} = J_{\Sigma E}d\omega_E/dt$, with $J_{\Sigma E}$ being the total moment of inertia of the motor; M_{WE} is the motor's operating moment (torque) transmitted to the gear unit; M_{MSE} is the moment of friction forces in the motor's bearings, $M_{MSE} = k_{MSE}\omega_E$, with k_{MSE} being the coefficient of friction in the motor's bearings.

The equation of moments on the wheel at its rotational motion can be drawn up as follows:

$$M_W = M_{DW} + M_{MSW} + M_W, \tag{17}$$

where M_W is the total mechanical moment on the driving wheel, $M_W = M_{WE}k_G$, with k_G being the gear ratio; M_{DW} is the dynamic moment of the wheel, $M_{DW} = J_{\Sigma W}d\omega_W/dt$, with $J_{\Sigma W}$ being the total moment of inertia of the wheel and caterpillar track and ω_W being the angular speed of the wheel's rotation; M_W is the wheel's operating moment (torque) transmitted to the caterpillar track; M_{MSW} is the moment of friction forces in the wheel's bearings, $M_{MSW} = k_{MSW}\omega_W$, with k_{MSW} being the coefficient of friction in the wheel's bearings.

Let us consider the rotational-translational motion of the MR's driving wheel (Fig. 2). The mechanical moment on the operating wheel M_W can be described as

$$M_W = F_W R_W, \tag{18}$$

where R_W is the radius of the operating wheel; F_W is the force that is applied at the top of the wheel to rotate it around the point 0' of its contact with the working surface (Fig. 2, a), $F_W = M_W/R_W$.

Fig. 2, a also allows determining the operating moment of the wheel M'_W created by the force F_W relative to the point 0':

$$M'_W = F_W \cdot 2R_W = 2M_W. \tag{19}$$

Let us compose an equation of moments on the wheel at its progressive rotation:

$$M'_W = M_{SM\Sigma}, \tag{20}$$

where $M_{SM\Sigma}$ is the total mechanical moment of the MR's motion resistance force, $M_{SM\Sigma} = F_{SM\Sigma}R_W$, with $F_{SM\Sigma}$ being the MR's motion resistance force.

The latter ($F_{SM\Sigma}$) is calculated as follows for each caterpillar track:

$$F_{SM\Sigma} = F_{SMG} + \frac{F_{DMR}}{2} + \frac{F_{SMMR}}{2} + \frac{F_L}{2}, \qquad (21)$$

where F_{SMG} is the resistance force generated by the force by gravity, F_{DMR} is the dynamic resistance force; F_{SMMR} is the MR's rotation resistance force; F_L is the force of the loading arising when a technological operation is performed, $F_L = \text{var}$.

Next, let us compose the expressions for each component of the MR's motion resistance force:

$$F_{SMG} = \frac{F_G}{2}\sin\alpha\cos\varphi_{MR} = \frac{m_{MR}g}{2}\sin\alpha\cos\varphi_{MR}, \qquad (22)$$

$$F_{DMR} = m_{MR}\frac{dV_{MR}}{dt}, \qquad (23)$$

$$F_{SMMR} = \frac{M_{SMMR}}{r_{MR}}, \qquad (24)$$

where m_{MR} is the mass of the MR; M_{SMMR} is the moment of the MR's resistance to rotation; r_{MR} is the arm of the force F_{SMMR} relative to the MR's center; V_{MR} is the MR's linear speed; α is the angle of the inclined surface; φ_{MR} is the route (course) of the MR (it is assumed that at $\varphi_{MR} = 0$, the robot is moving upward along the inclined plane); g is the acceleration of gravity.

In turn, the moment of the MR's resistance to rotation M_{SMMR} can be expressed as follows:

$$M_{SMMR} = M_{DR} + M_{FR}, \qquad (25)$$

where M_{DR} is the dynamic moment of resistance to rotation; M_{FR} is the moment of friction forces.

Let us consider each component of M_{SMMR} separately:

$$M_{DR} = J_{MR}\frac{d\omega_{MR}}{dt}, \qquad (26)$$

$$M_{FR} = k_{FR}\omega_{MR}, \qquad (27)$$

where J_{MR} is the moment of inertia of the MR; ω_{MR} is the angular speed of the MR; k_{FR} is the coefficient of friction at rotation.

Let us compile the equation of interrelation of the kinematic parameters of the MR, taking into account [13, 22] and Fig. 2, b:

$$\omega_W = \frac{\omega_E}{k_G}, \qquad (28)$$

$$V_{T1} = \omega_{W1}R_W, \qquad (29)$$

$$V_{T2} = \omega_{W2}R_W, \qquad (30)$$

$$V_{MR} = \frac{V_{T1} + V_{T2}}{2}, \qquad (31)$$

$$\omega_{MR} = \frac{V_{T1} - V_{T2}}{r_{MR}}, \qquad (32)$$

$$\omega_{MR} = \frac{d\varphi_{MR}}{dt}, \qquad (33)$$

where V_{T1} and V_{T2} are the linear speeds of the lefthand and righthand caterpillar tracks of the MR; ω_{W1} and ω_{W2} are the angular speeds of the driving wheels of the MR.

Accordingly, taking into account expressions (16) – (27), let us compose the equation of the mathematical model for the MR's first caterpillar track:

$$\begin{aligned} M_{EM1} &= J_{\Sigma E}\frac{d\omega_{E1}}{dt} + k_{MSE}\omega_{E1} + \frac{1}{k_G}\left(J_{\Sigma W}\frac{d\omega_{W1}}{dt} + k_{MSW}\omega_{W1} + \right. \\ &\left. + \frac{R_W}{4}\left(m_{MR}(g\sin\alpha\cos\varphi_{MR} + \frac{dV_{MR}}{dt}) + F_L + (J_{MR}\frac{d\omega_{MR}}{dt} + k_{FR}\omega_{MR})\frac{1}{r_{MR}}\right)\right). \end{aligned} \qquad (34)$$

The equation for the second track has the same form:

$$\begin{aligned} M_{EM2} &= J_{\Sigma E}\frac{d\omega_{E2}}{dt} + k_{MSE}\omega_{E2} + \frac{1}{k_G}\left(J_{\Sigma W}\frac{d\omega_{W2}}{dt} + k_{MSW}\omega_{W2} + \right. \\ &\left. + \frac{R_W}{4}\left(m_{MR}(g\sin\alpha\cos\varphi_{MR} + \frac{dV_{MR}}{dt}) + F_L + (J_{MR}\frac{d\omega_{MR}}{dt} + k_{FR}\omega_{MR})\frac{1}{r_{MR}}\right)\right). \end{aligned} \qquad (35)$$

The obtained mathematical dependencies (34) - (35) represent the mathematical model of the MR for moving over inclined surfaces.

Simulation results. Simulation of the obtained equations of the MR's individual elements and the whole MR employs the structural modeling method. Within this framework, the MR (equations (28) – (35)), the DCM (equations (7) and (8)), and the gear unit (equations (11) and (14)) are regarded as individual elements combined into a single reference structural scheme for the simulation of the MR's spatial motion. Table 1 provides a list of the MR's basic parameters which have been set in order to perform the simulation and obtain the initial dependencies of the MR's essential technological parameters on time.

Table 1.

Basic parameters of the MR

Loaded weight, m_{MR}, kg	300
Length, L_{MR}, m	1
Width, S_{MR}, m	0.7
Wheel radius, R_W, m	0.3
Wheel weight, m_W, kg	10
Caterpillar track weight, m_T, kg	30
Height (thickness) of the caterpillar tape, h_T , м	0.015
Linear speed, V_{MR}, m/s	0.3

Calculation of motor parameters for modeling. As noted above, each track is equipped with a motor 2PB132MG; parameters of the DC motors are given in [18]. The quantities indicated there are as follows: P_N is the nominal (rated) power of the DCM, 1.1 kW; n is the nominal rotational speed, 800 rpm; U_N is the nominal supply voltage, 220 V; I_N – is the nominal current of the armature, 7.46 A; R_A is the resistance of the armature winding, 2.44 Ohm; R_{AP} is the resistance of the additional poles winding, 1.53 Ohm; J is the moment of inertia of the armature, 0.038 kg·m^2; L_A is the inductance of the armature circuit, 0.055 H. The electric motor's parameters shall be calculated using the approximate methodology described in papers [18, 23].

Taking into account the technical characteristics, the nominal electromagnetic moment of each motor M_{EMN} is calculated as follows:

$$M_{EMN} = \frac{P_N}{\omega_N}, \tag{36}$$

where ω_N is the nominal angular speed of the motor's shaft rotation, $\omega_N = 2\pi n/60$, rad/s.

Hence, the coefficient of proportionality c_M can be calculated from expression (1):

$$c_M = \frac{M_{EMN}}{I_N}. \tag{37}$$

Next, let us compose the equation of the coefficient of proportionality of the constant EMF of the motor using (2) and (3):

$$c_E = \frac{E}{\omega_N} = \frac{U_N - (R_A + R_{AP})I_N}{\omega_N}. \tag{38}$$

The electromagnetic time constant of the motor's armature circuit T_E can be determined as follows:

$$T_E = \frac{L_A}{R_A + R_{AP}}. \tag{39}$$

The gear unit parameters. In order to decrease the load on the motor's shaft and reduce the rotational speed of the driving wheel, each DCM is equipped with an identical gear unit. The main parameters of the latter (1Ts3U — 160) are the following: k_G is the gear ratio, $k_G = 80$; T_2 is the permissible torque (rotating moment) on the output shaft, $T_2 = 1250$ Nm.

Calculation of the moments of inertia for the MR's rotating parts. Specification of the moments of inertia of geometrically complex bodies (the driving wheels, caterpillar tracks and the MR in general) is associated with a high complexity of the required calculation procedures and the need for experimental measurements [18, 23]. Thus, we shall determine these values approximatively, using the formulas for calculating the moments of inertia for geometrically simple bodies, particularly: a disk and a ring with a rectangular cross section.

On that account, the moment of inertia of the driving wheel J_W is calculated as follows:

$$J_W = \frac{m_W R_W^2}{2}, \tag{40}$$

where m_W is the driving wheel's mass, R_W is the driving wheel's radius.

Using the known value of the MR's length L_{MR}, one can estimate the caterpillar track's total length L_T in the following way:

$$L_T = 2(L_{MR} - 2R_W) + 2\pi R_W. \tag{41}$$

Next, let us calculate the moment of inertia for one caterpillar track, J_T:

$$J_T = m_{TR}\left(R_W^2 + \frac{h_T^2}{2} + R_W h_T\right) + m_{TT}\left(\frac{V_T}{\omega_W}\right)^2, \tag{42}$$

where m_{TR} is the mass of the track's rotating part, $m_{TR} = (2\pi R_W/L_T)m_T$; m_{TT} is the mass of the track's linearly moving part, $m_{TT} = m_T - m_{TR}$; m_T is the mass of the whole track; V_T is the linear speed of the track, assuming that $V_T = V_{MR}$; ω_W is the angular speed of the wheel, $\omega_W = V_T / R_W$.

Finally, the total moment of inertia of the wheel and the caterpillar tracks $J_{\Sigma W}$ can be calculated as follows:

$$J_{\Sigma W} = 2J_W + J_T. \tag{43}$$

The moment of inertia of the MR relative to its center axis shall be approximately calculated with the help of formula (44):

$$J_{MR} = \frac{m_{MR} r_{MR}^2}{2}, \tag{44}$$

where r_{MR} is the minimum radius of the MR's rotation (with opposite connection of back-to-back running motors), assuming that $r_{MR} = S_{MR}/2$.

Using the obtained parameters of the MR, a simulation model has been compiled for computer modeling of the transient processes of the MR's essential technological parameters, which are shown in Fig. 3-6 (in this case, the transient process is the system's response to the input stepwise signal by the corresponding parameter).

Fig. 3 clearly indicates how the MR's linear velocity at the supply voltage of 220 V on both actuators depends on the angle of inclination of the working ferromagnetic surface. When the angle increases from 0 to 90°, the resulting speed decreases due to the load increase generated by gravity. When α = 270°, the robot moves downwards, respectively, the gravitational force facilitates the MR's movement, thus making its resulting speed higher than in the previous cases (line 4 in Fig. 3).

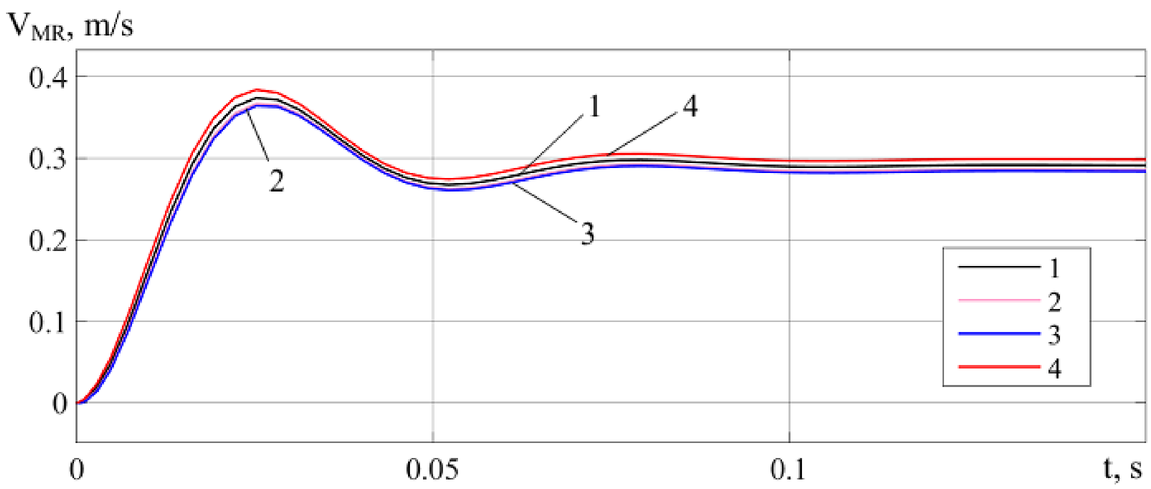


Fig. 3. Change in the MR's linear speed for different values of the angle α:
1 – α = 0°; 2 – α = 45°; 3 – α = 90°; 4 – α = 270°

Fig. 4 shows that for α = 60° and DCM supply voltage of 220 V, with introduction of the load (such as that generated by the technological operation of cleaning at the simulation time of 1 second), the steady-state speed decreases after the transient process and does not return to the previous value.

The robot's rotation to change its course – the φ_{MR} angle – is carried out by changing the supply voltage on each of the drive motors. At that, the linear speed of the whole MR's movement also changes. The changes in the φ_{MR} and V_{MR} coordinates for different values of DCM supply voltage are shown in Fig. 5 and 6, respectively.

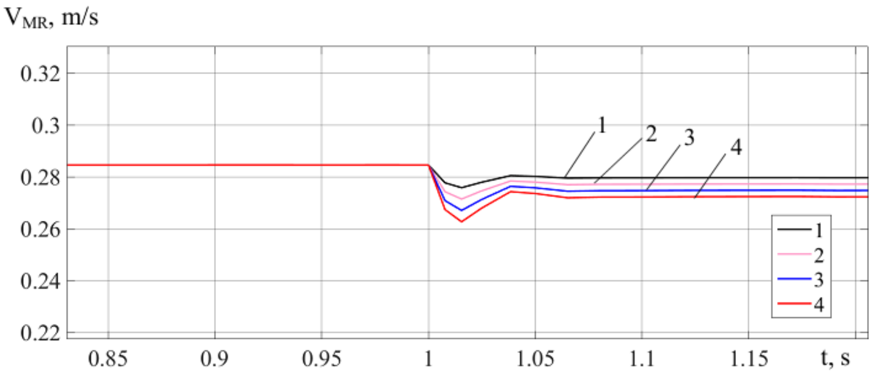


Fig. 4. Change in the linear speed of movement for different values of load: 1 – 2 kN; 2 – 3 kN; 3 – 4 kN; 4 – 5 kN

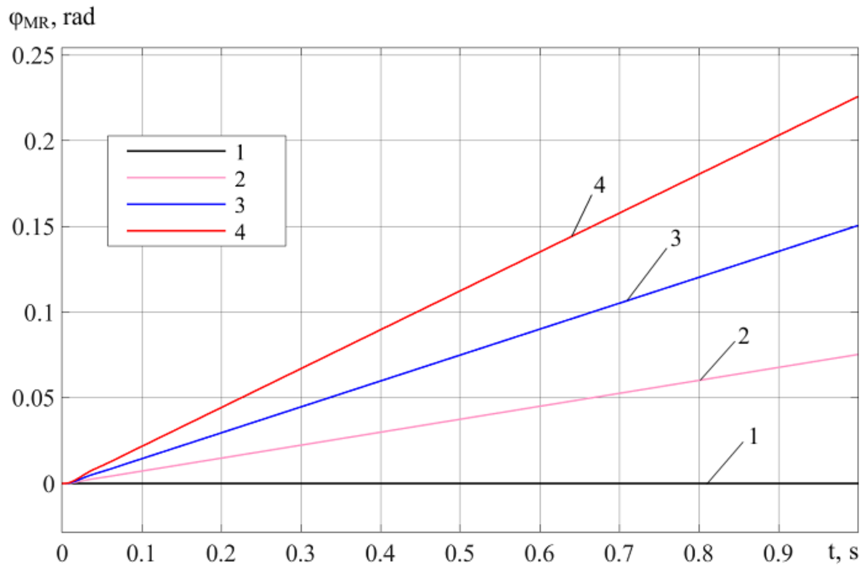


Fig. 5. Change in the MR's angle of rotation at the following modulus difference in the DCM supply voltages ΔU_{12}: 1 – ΔU_{12} = 0 V; 2 – ΔU_{12} = 20 V; 3 – ΔU_{12} = 40 V; 4 – ΔU_{12} = 60 V

Fig. 5 attests to the linearity of the dependencies of the MR's angle of rotation on the difference between the DCM supply voltages for $\alpha = 60°$, simulation time of 0.5 seconds and the load of 2 kN generated by the technological equipment. In this case, the latter does not affect the dependency.

Fig. 6 shows the effect of the difference in the supply voltages of the two DC motors on the MR's linear speed at $\alpha = 60°$, the load of 2 kN, generated by the technological equipment, and the simulation time of 0.5 seconds. Namely, as this difference increases, the MR's speed decreases. Introduction of the load does not alter the nature of the speed's decrease.

Fig. 3-6 prove that the results obtained for the nature of the change of the MR's essential technological parameters under these conditions correspond to the actual ones. In future, it is appropriate to consider the synthesis of the system for monitoring and automatic control of the MR's spatial movement along an inclined working surface.

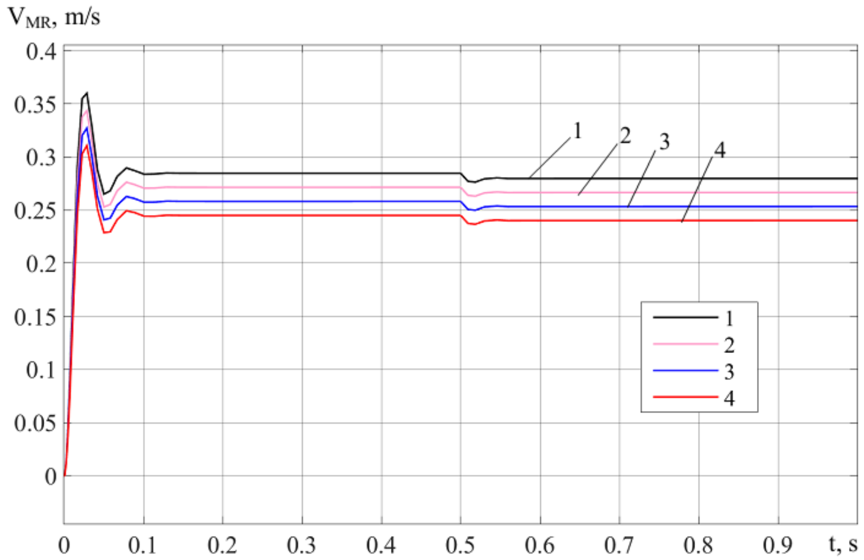


Fig. 6. Change in the MR's linear speed at the following modulus difference in the DCM supply voltages ΔU_{12}: 1 – ΔU_{12} = 0 V; 2 – ΔU_{12} = 20 V; 3 – ΔU_{12} = 40 V; 4 – ΔU_{12} = 60 V

CONCLUSION

The article presents the procedure of synthesis of the mathematical models of the entire MR and its individual components taking into account the special features of the MR's structural design. Also, the results of MR's model study via computer modeling in terms of the influence of the MR's individual components on its spatial position and the rate of response to particular input actions are shown with account for the angle of inclination of the working surface and the direction of the MR's movement.

The mathematical model has been developed with the application of the mathematical apparatus of the theory of vehicle movement and load reduction to drive motor's shafts. The model enables studying the behavior of the object of spatial movement control under various production conditions and transient modes, in particular, calculating the MR's speed of movement and angle of rotation at specified and disturbing actions (caused by the load from the working tool). The study results display the major properties of the MR as a complex control object with substantial dependence of MR's spatial motion parameters from surface and acting load features.

The obtained mathematical model can be further applied in the development and study of the effectiveness of a multi-circuit system for monitoring and automatic control of the MR's spatial movement, as well as its software and algorithms operating in real time.

REFERENCES:

1. Tosun O. Mobile robotics: solutions and challenges / O. Tosun, H.L. Akin, M.O. Tokhi, G.S. Virk (ed.). // Proceedings of the Twelfth International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines. Istanbul. – 2009.
2. Yurevich Ye. I. Osnovy robototekhniki: Uchebnoe posobiye. – Saint-Petersburg, BKhV-Peterburg, 2005. – 416 s.
3. Siciliano B., Khatib O. (ed.). Springer handbook of robotics / B. Siciliano, O. Khatib (ed.). // Springer. – 2016.
4. Niku S.B. Introduction to robotics: analysis, systems, applications, New Jersey: Publisher Prentice Hall. – 2001.
5. Gerasin O.S. Analiz osoblyvostei mobilnykh robotiv bahatotsilovoho pryznachennia // Naukovi pratsi: Naukovo-metodychnyi zhurnal. Seriia "Compiuterni tekhnolohii". – 2014. – vol. 250, no. 238. – S. 25-32.
6. Kustovska O.V. Metodolohiia systemnoho pidkhodu ta naukovykh doslidzhen: Kurs lektsii. – Ternopil: Ekonomichna dumka, 2005. – 124 s.
7. Usov A.V., Dubrov A.V., Dmitrishin D.V. Modelirovaniye sistem s raspredelennymi parametrami. – Odessa: Astroprint, 2002. – 664 s.
8. Sharuda V.H. Praktykum z teorii avtomatychnoho upravlinnia. – Dnipropetrovsk: NHU, 2002. – 414 s.
9. Kurfess T.R. (ed.). Robotics and automation handbook. CRC press. – 2004.
10. Spong M.W. Robot modeling and control / M.W. Spong, S. Hutchinson, M. Vidyasagar M. // New York: Publisher Wiley. – 2006.

11. Chernousko F.L. Printsipy dvizheniya i problemy dinamiki mobilnykh robotov // Sbornik materialov Mezhdunarodnoy Vystavki-kongressa Mekhatronika i robototekhnika, 2007. – S. 89-90.
12. Kondratenko Y.P. Synthesis and research of neuro-fuzzy observer of clamping force for mobile robot automatic control system / Y.P. Kondratenko, O.V. Kozlov, O.S. Gerasin, Y.M. Zaporozhets // Proceedings of the 2016 IEEE First International Conference on Data Stream Mining & Processing (DSMP), Lviv, Ukraine, August 23 – 27, 2016. – P. 90-95.
13. Kabanov A.A. Modelirovaniye i upravleniye dvizheniem gusenichnogo mobilnogo robota // Upravleniye v tekhnicheskikh, ergaticheskikh, organizatsionnykh i setevykh sistemakh. – Saint Petersburg, 2012. – S. 740-743.
14. Koloskov S.S. Razrabotka mobilnogo robota i vizualiatsiya ego dvizheniya // Molodezhnyy nauchno-tekhnicheskiy vestnik. Available at: http://sntbul.bmstu.ru/doc/602336.html.
15. Kondratenko Y. Modeling of clamping magnets interaction with ferromagnetic surface for wheel mobile robots / Y. Kondratenko, Y. Zaporozhets, J. Rudolph, O. Gerasin, A. Topalov, O. Kozlov // International Journal of Computing. – 2018. – 17(1). – P. 33-46.
16. Souto D. A Robot for the Unsupervised Grit-Blasting of Ship Hulls / D. Souto, A. Faiña, A. Deibe, F. Lopez-Peña, R.J. Duro // International Journal of Advanced Robotic Systems. – 2012. – vol. 9. – P. 1–16.
17. Onishchenko G.B. et al. Avtomatizirovannyy elektroprivod promyshlennykh ustanovok. – Moscow: RASKhN, 2001. – 520 s.
18. Pitsan R.M., Bardachevskyi V.T., Boichuk B.H. Zbirnyk zadach do kursu "Elektropryvid". Persha chastyna "Rozimkneni systemy elektropryvoda". – Lviv, Vydavnytstvo Derzhavnoho universytetu "Lvivska politekhnika", 1999. – 425 s.
19. Vikovych I.A. Teoriia rukhu transportnykh zasobiv. – Lviv, Vydavnytstvo Lvivskoi politekhniky, 2013. – 672 s.
20. Kozlov O.V. Complex of tasks of monitoring and automatic control of mobile robots for vertical movement / O.V. Kozlov, O.S. Gerasin, G.V. Kondratenko // Shipbuilding & Marine Infrastructure. – 2017. – no. 2 (8). – P. 77-87. (http://smi.nuos.edu.ua/article/view/120596/116517) DOI: https://doi.org/10.15589/SMI20170215
21. Kushnir V.O., Kondratenko Y.P., Topalov A.M., Gerasin O.S. Mobilnyi robot dlia mekhanichnoho ochyshchennia korpusu sudna [Mobile robot for mechanical cleaning of a ship hull]. Patent UA, no. u201500063, 2015.
22. Kondratenko Y.P. Neiro-nechitki sposterihachi dlia identyfikatsii prytysknoho zusyllia mahnitokerovanykh rushiiv mobilnykh robotiv / Y.P. Kondratenko, J. Rudolph, O.V. Kozlov, Y.M. Zaporozhets, O.S. Gerasin // Tekhnichna elektrodynamika. – 2017. – no. 5. – S. 53-61.
23. Sew-eurodrive. Praktika privodnoy tekhniki. Proektirovanie privodov [Sew-eurodrive. Practice of drive engineering. Designing of drives]. Available at: www.sew-eurodrive.ru/files/pdf/11322853.pdf.

Рецензент: д.т.н., проф. Рябенький В.М.,
завідувач кафедри теоретичної електротехніки
та електронних систем НУК ім. адм. Макарова