THE CONCEPT OF SYNTHESIS OF MOBILE ROBOTS

КОНЦЕПЦИЯ СИНТЕЗА МОБИЛЬНЫХ РОБОТОВ

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Abstract: The paper proposes three basic principles for the synthesis of mobile robots: the accumulation and conversion of energy, the integration of motion drives and the use of a generator of reactive pneumatic traction. These technical solutions allow robots to navigate on surfaces of arbitrary orientation in different coordinate systems. The implementation of these principles contributes to reducing the total power of the drives and increasing the reliability of holding robots on the surface of arbitrary orientation in the technological space. The results of mathematical modelling of constructive and technological parameters of mobile robots are described.
KEYWORDS: *MOBILE ROBOTS, WALKING MECHANISMS, ROBOTS OF VERTICAL MOVEMENT, CLIMBING ROBOTS*

1. Introduction

The evolution of technical systems in the field of engineering science, as a rule, led to the emergence of new means of production. In the twentieth century scientific and technical thought created sufficiently reliable means of overcoming the gravitational force in the form of flying and reactive equipment. These funds are used as a reliable transport. However, up to the present time there are no industrial samples of equipment for performing contact technological operations while simultaneously overcoming the forces of gravity.

Mobile robots of arbitrary orientation are known in publications as robots of vertical movement or in international publications – under the term Climber Robot, are a new modification of mobile robots. These robots are equipped with means of fixation on the surface of arbitrary orientation relative to the horizon of the technological space. The creation of this kind of robotics is at the initial stage and is dictated by the need to perform technological operations in such areas of industrial activity as monitoring of industrial facilities, installation and dismantling of building structures, repair and prevention of their components. In the context of the fourth industrial revolution, "Industry 4.0" [1], with the focus on the use of robotic systems, information and communication tools, and the use of these robots becomes especially urgent in the extreme conditions of man-made disasters that are dangerous and even unacceptable for human presence.

2. Prerequisites and means for solving the problem

The problem of creating this type of robots is the lack of a methodology for synthesizing the robot subsystems that compensate or overcome the gravitational load in order to ensure that the robot is held on an arbitrarily oriented surface during the execution of technological operations. Therefore, the purpose of this research is to develop principles for the synthesis of mobile robots and the introduction of modern computer modeling tools for the transition to the design and manufacture of prototypes of mobile robots.

Theoretical and experimental studies on the creation of robots of arbitrary orientation in the technological space began in the last decade of the twentieth century in the countries of Western Europe, Japan, the United States, Korea, China and Russia. To date, there are mainly experimental samples of such robots.

Mobile works [2-5] are equipped with devices to fix the robot on surfaces of arbitrary orientation, and in studies [6, 7] hybrid drives are proposed that can improve the energy efficiency of mobile robots. Technical solutions [8-11] allow the robot to move on surfaces oriented at different angles to the horizon, but only in 2D space, that is, in a plane. In the general case, the variations of the constructions of the above-mentioned robots restrict their movement only in the Cartesian coordinate system.

Unlike the aforementioned technical solutions, the robot model [12] allows servicing objects in the cylindrical coordinate system, in particular, objects such as trees, but with a soft porous surface for the movement of the robot, which limits the technological capabilities of mobile robots. At a time when there are objects facilities that are also close to the cylindrical coordinate system, for example, electric grid posts, columns, pipes of thermal power plants and the like. In addition, the mobile robot should also work in a system of angular coordinates, which is typical for humans. The development of systems for connecting the robot to the surface of motion is a technical solution [13], which uses adhesion technology. However, current implementations of this technology are characterized by an extremely low speed of movement of the robot due to the effect of slow adhesion. This property still prevents the industrial use of adhesion as a method of fixing the robot to a surface of arbitrary orientation.

Thus, the problem of synthesizing mobile robots capable of performing technological operations in a space of arbitrary orientation is topical.

3. Solution of the problem under consideration

In contrast to the above, the concept of improving robots of arbitrary orientation based on three fundamental principles of the synthesis of mobile robot designs is proposed:

1. Accumulation of potential energy at each previous step of the robot's movement and subsequent conversion to kinetic energy at the next step of the movement.

2. Integration of drives of longitudinal, vertical displacement, and also drives of change of orientation of the robot according to the set route.

3. The use of traction generators (aerodynamic lift forces) as a means of counteracting the gravitational force to increase the technological load while simultaneously reducing the power of clutch drives and the movement of robots.

As technical means of implementing these principles of synthesis, consider the corresponding models of robots of arbitrary orientation. In Fig. 1 shows a mobile robot [14] realizing the first of the above mentioned principles, namely having the ability to accumulate potential energy at each previous step and converting it into kinetic energy of motion at each subsequent step of displacement.

On the robot body 1 are mounted rotary pneumatic actuators 2 connected through a gear train 10 with running mechanisms 3. When the elastic members 4 are compressed due to the rotation of the legs of the robot, the potential energy is accumulated during the first half of the step, and in the second half of the step, these elements convert the potential compression energy in the kinetic energy of the robot's motion [15, 16]. To implement a plane-parallel motion along the vertical, the robot is equipped with parallelograms 5. The latter connect pedipulators with vacuum grippers 6 that hold the robot on a surface of arbitrary orientation. Also, the robot is equipped with a control unit 7 and a power supply module 8. To overcome obstacles on the moving surface, the robot is additionally equipped with rolling bearings 9.

Volumes of the potential and kinetic energy of the robot motion at different stages of displacement can be determined using Lagrangian equations of the second kind.

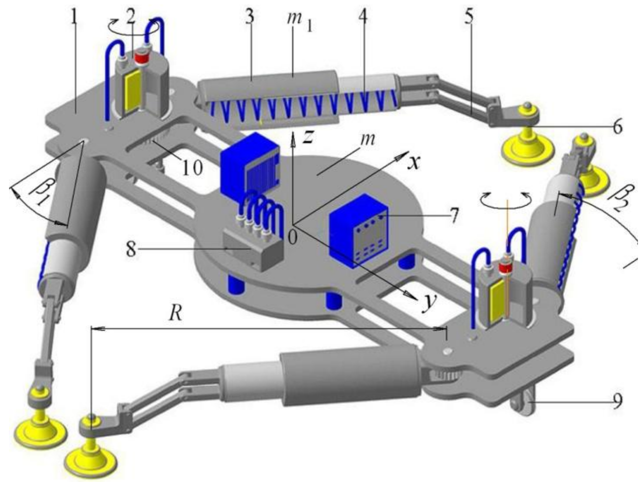

Fig.1. *The robot model of arbitrary orientation with the accumulation and transformation of energy*

The kinetic energy T_1 of the robot's foot free from adhesion to the moving surface will be

$$T_1 = \frac{1}{2}\int (V_{x1}^2 + V_{y_1}^2)dm\,, \qquad (1)$$

where: V_{x1}, V_{y1} – the velocity projections on the coordinate axis 0xyz; m – the mass of the robot.

Pedipulator of the robot, whose grips are engaged with the surface, performs a rotary motion with angular velocity $\dot{\beta}_1$. The expression for the kinetic energy of a supporting leg of mass m_1 and radius R can be obtained from expression (1) after integrating it, substituting the velocity of the translational motion of the robot $V = 0$ and the angular velocities of the pedipulators $\dot{\beta}_2 = \dot{\beta}_1$:

$$T_2 = \frac{m_1 R^2}{6}(\dot{\beta}_1)^2\ . \qquad (2)$$

Thus, the movement of the robot at each second half of the cycle occurs due to the energy accumulated at each first half of the travel step. This allows 40% ... 45% to reduce energy costs for the movement of the robot and to direct the resulting energy reserve for the execution of technological operations.

Pedipulators work with elastic elements (Fig.1, pos.4), which perform the function of accumulation of potential energy during the first half of the cycle of displacement.

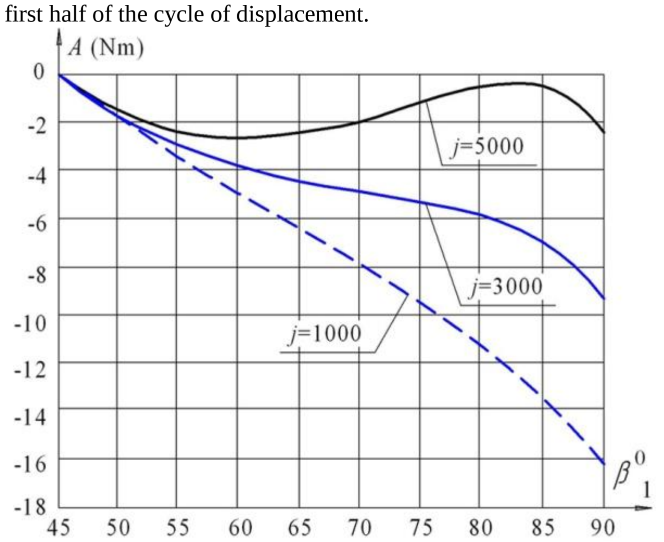

Fig.2. *The effect of the elastic element j (N/m) on the work performed in the step $\beta_1 > 45^o$ of the robot movement*

The main characteristic of elastic elements is their rigidity j – parameter, which determines the force of compression of these elements, and hence the value of the accumulated potential energy in the first half of the step of the pedipulator. In Fig. 2 shows the dependence of the variation of work "A" on the stiffness of the elastic element ***j*** (N/m) and the forces of weight in the second stage $\beta_{1,2} > 45^o$ of displacement, that is, during the transformation of the potential energy into the kinetic energy of the robot's motion. At the second stage of displacement $45^0 \le \beta_{1,2} \le 90^0$ drive the of pedipulator is turned off to save energy resources of the robot, and it moves only due to kinetic energy. Analysis of these graphs shows that to increase the kinetic energy of the robot movement, it is advisable to increase the rigidity, despite the fact that in this case the counteraction to the drive increases in the first half of the step, that is, the efficiency of the drive decreases. However, this negative manifestation can be compensated for by an increase in the transmission ratio (see item 10, figure 1) of pedipulators.

The second principle, as noted above, involves the integration of displacement drives [17] with the aim of reducing them, and hence of reducing the mass of the robot. It is known that in the Cartesian space we have six degrees of freedom – three translational movements and three rotational, each of which according to the classical solutions corresponds to an autonomous drive. The method of Fig. 3 – technical implementation of this principle eliminates the need for drives for each of the coordinate axes. To do this, the robot is equipped with flexible running mechanisms 2 mounted on the body 1. Each pair of legs of the robot through the transmissions 3 is provided with electric drives 4. The grippers 5 keep the robot on the surface moving, and the rotary actuators 6 change the position of the grippers relative to the displacement surface. The robot platform has a power supply unit 7, a hydraulic or pneumatic valve unit 8 and a gas or liquid pressure generator and a controller 9 for controlling the robot. Due to the fact that each foot of the robot is made in the form of a compressed set of hemispherical rings inside which corrugated pipes are placed under different pressures, the robot has the ability to work in different coordinate systems: rectangular Cartesian, spherical and cylindrical without additional drives on each axis of coordinates.

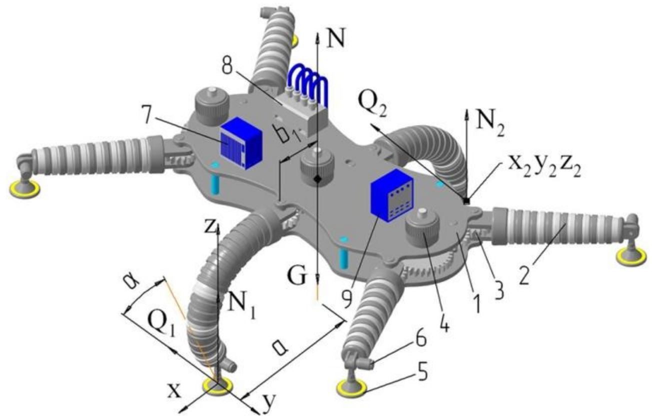

Fig.3. *Model of the robot with flexible pedipulators*

In each leg of the robot there are four corrugated pipes. Two pipelines with pressure p_1 p_2 are placed in a vertical plane and two other pipelines – in a horizontal plane with pressure p_3 and p_4. Due to the action of these pressures, forces appear that, while bending the robot's leg, orient the robot in the technological space:

$$F_1 = p_1\frac{\pi d^2}{4}; F_2 = p_2\frac{\pi d^2}{4}; F_3 = p_3\frac{\pi d^2}{4}; F_4 = p_4\frac{\pi d^2}{4}, \qquad (3)$$

where d – the internal diameter of the corrugated tubes. Since the axes of the pipelines are offset from the pedipulator axis by the eccentricity e, there are moments M_1 and M_2 that flex the robot's leg:

$$M_1 = \frac{\pi d^2}{4}(p_1 - p_2)e;\ M_2 = \frac{\pi d^2}{4}(p_3 - p_4)e \qquad (4)$$

where: e – eccentricity of placement of corrugated pipelines in the plane of the coordinate system.

To develop a robot, it is necessary to establish a connection between the forces of adhesion of its legs to the displacement surface and the permissible technological load to ensure the reliability of its industrial operation. Having formulated the system of equilibrium equations on the basis of the Herman–Euler–D`Alambert principle (here we omit the record for brevity), we find the corresponding reaction forces $N_{1,2}$ and the frictional forces $Q_{1,2}$ by the robot foot to the displacement surface and then compare them with the technological load N in depending on the angle $\boldsymbol{\alpha}$ of the robot inclination to the horizon.

The reaction forces of N_2 and the frictional forces Q_{2y} of the robot supports with the displacement surface are determined as follows (the designation of the parameters, see Fig.3):

$$N_2 = Q_2 + a_3G - b_3N; \quad Q_{2y} = d_3G + h_3N \,, \qquad (5)$$

where for the compactness of the incoming values of variables is denoted:

$a_3 = d_1b_2 - b_1d_2/\Delta$; $b_3 = b_2h_1 + b_1h_2/\Delta$; $d_1 = y_c\cos\alpha - z_c\sin\alpha$;

$b_2 = x_2\cos(\varphi-\alpha)$; $d_3 = d_2a_1 - d_1a_2/\Delta$; $h_3 = h_2a_1 + a_2h/\Delta$;

$a_1 = y_2\cos(\varphi-\alpha) + z_2\sin(\varphi-\alpha)$; $a_2 = -x_2\sin(\varphi-\alpha)$;

$d_2 = x_c\sin\alpha$; $b_1 = y_2\sin(\varphi-\alpha) - z_2\cos(\varphi-\alpha)$;

$h_1 = y_c\cos\psi + z_c\sin\psi$; $h_2 = x_c\sin\psi$; $\Delta = a_1b_2 - b_1a_2$; x_2, y_2, z_2 – coordinates of the contact point of the second leg of the robot with the displacement surface; x_c, y_c, z_c are the coordinates of the center of gravity of the robot; α, φ – angles of inclination to the horizon of surfaces on which the robot's legs rest; ψ is the angle of inclination of the central axis of the robot passing through its center of gravity G (see Fig.3). Then, from the same system of equilibrium equations, we find the remaining unknown reactions N_1 and the frictional forces Q_{1y}:

$$N_1 = Q_1 + Ga_4 - Nh_4; \quad Q_{1y} = Gh_5 + Nh_6, \qquad (6)$$

where also for the compactness of writing variables is defined:

$a_4 = \cos\alpha - a_3\cos(\varphi-\alpha) - d_3\sin(\varphi-\alpha)$;

$h_4 = \cos\psi - b_3\cos(\varphi-\alpha) + h_3\sin(\varphi-\alpha)$;

$h_5 = \sin\alpha - d_3\cos(\varphi-\alpha) + a_3\sin(\varphi-\alpha)$;

$h_6 = \sin\psi - h_3\cos(\varphi-\alpha) - b_3\sin(\varphi-\alpha)$.

For the stability of the robot, the frictional forces of each of its legs must not exceed the boundary values:

$$Q_{1y} < \mu N_1; \quad Q_{2y} < \mu N_2; \quad N_1 > 0; \; N_2 > 0, \qquad (7)$$

where μ – the coefficient of friction of the grip of the robot's leg with the surface along which the robot moves. Substituting in expression (7) the expressions above the found reactions of forces (5) and (6), we find limitations for the technological load of the robot taking into account the forces acting on it:

$$N_1 > 0 \Rightarrow N < \frac{Q_1 + Ga_4}{h_4}; \; N_2 > 0 \Rightarrow N < \frac{Q_2 + Ga_3}{b_3};$$
$$N < \frac{\mu Q_2 + G(\mu a_3 - d_3)}{h_3 + \mu b_3}; \; N < \frac{\mu Q_1 + G(\mu a_4 - h_5)}{h_6 + \mu h_4}. \qquad (8)$$

Among the values of the reaction N of the technological load calculated in accordance with conditions (8), we choose the largest, which simultaneously satisfies all inequalities, which allows to determine the maximum technological load of the robot, for example, for drilling, rivets, dowels, etc. technological operations.

As a result of the simulation, the limiting values of the technological load are obtained (Fig.4): curves 1 and 2, respectively, determine the separation states from the displacement surface of the first and second legs of the robot, and curves 3 and 4 are the beginning of slippage of the said robot legs, respectively.

The robot of arbitrary orientation can be on such surfaces as a floor, a wall or a ceiling. Accordingly, if the robot is on the floor, then in the above dependences it is necessary to substitute the value $\varphi = 0^o$, $\alpha = 0^o$; if on a vertical wall, then $\varphi = 90^o$, $\alpha = 90^o$ and if on the ceiling, then $\varphi = 180^o$, $\alpha = 180^o$ and so on.

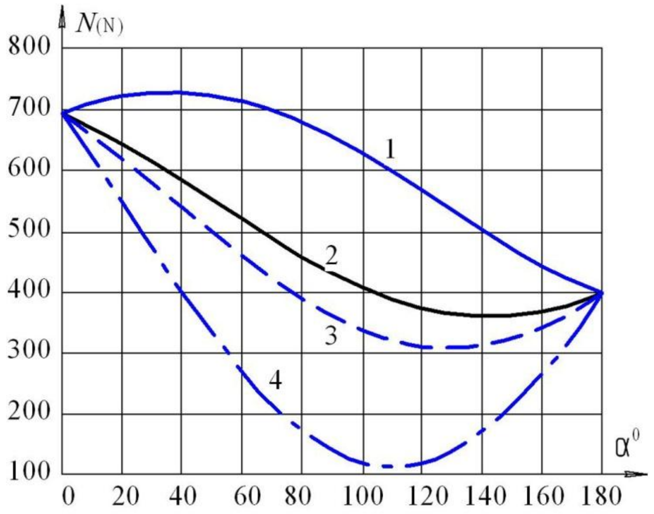

Fig.4. *Graphs of the boundary values of the technological force N of the robot as a function of the angle* $\boldsymbol{\alpha}$ *of the inclination to the horizon*

And, finally, the third principle – the use of traction generators as a means of counteracting the gravitational force is realized by the robot [18], shown in Fig. 5. Like the previous one, it also has flexible pedipulators 2, grippers 3, gear 4 and electric drives 5 on the body 1. The main difference of this robot is the installation in the center of its masses suspension Cardan 6 with three degrees of freedom and a pneumatic generator of traction 7. The location of the thrust generator on the Cardan suspension allows the thrust generator to maintain the coincidence of the lines of action of opposing forces: the rise of G_1 and the gravitational force G, regardless of the position of the robot in the XYZ space. This principle allows us to differentiate the approach to regulating the lifting force of the robot, depending on its orientation in space.

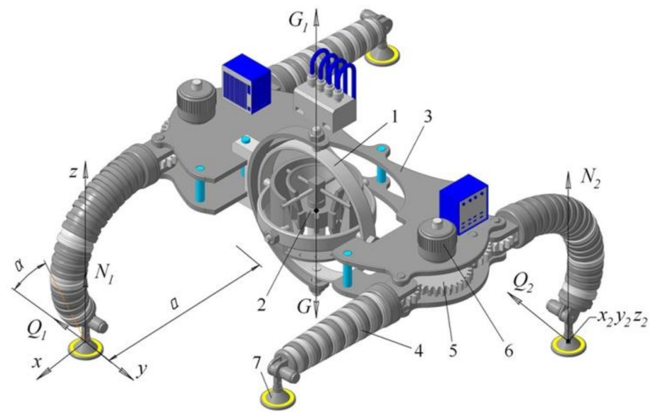

Fig.5. *Mobile robot with pneumatic generator of aerodynamic lift*

Similarly to the previous case, from the system of equilibrium equations of the robot determine the forces of normal reactions N_i of the legs of the robot and the corresponding frictional forces Q_i (see Fig.5):

$$N_2 = b_{12}(G - G_1)\,, \qquad (9)$$

where: G – the weight of the robot; G_1 – traction force; α - angle of inclination of the plane of movement of the robot to the horizon $b_{12} = \cos\alpha y_c - \sin\alpha z_c/2y_2$; y_c, z_c – coordinates of the center of gravity of the robot; y2 – coordinate of contact with the moving surface of the second part of the robot.

The frictional force Q_{1y} and the normal reaction N_1 are determined as

$$Q_{1y} = (G - G_1)(-\mu b_{12} + \frac{1}{2}\sin\alpha); N_1 = (G - G_1)(-b_{12} + \frac{1}{2}\cos\alpha).$$

As can be seen from the graphs of Fig. 6 with positive reactions N_1 and N_2 with the angle of inclination of the displacement surface $\alpha \leq 54^0$, the weight of the robot increases the technological load. This means that the inclusion of the jet engine is more suitable for the values of the angle of inclination of the robot to the horizon at $\alpha \geq 54^0$. Of course, the critical angle of inclination depends on the other centrifugal characteristics of the robot. However, using the generator of aerodynamic forces ensures reliable retention of the robot on surfaces of arbitrary orientation with any structural and technological parameters of the robots. To calculate the critical angle of inclination to the horizon and, accordingly, to regulate the force of the reactive thrust, that is, the aerodynamic force of the pneumatic generator, it is necessary to take into account other characteristics of the robot.

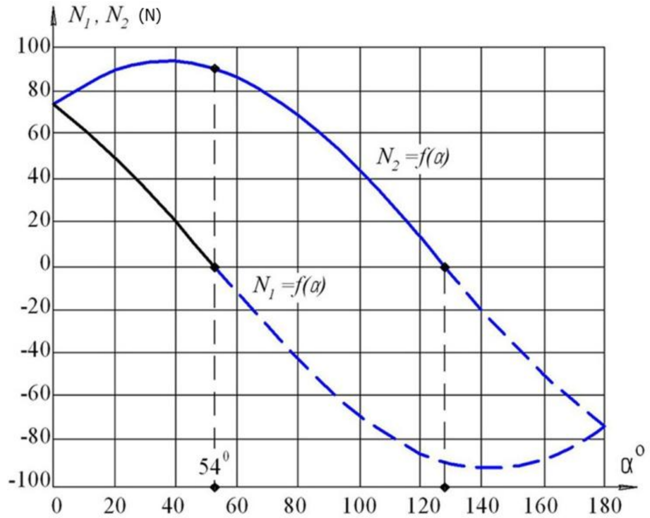

Fig.6. *Graphs of the dependence of the normal reactions N_1, N_2 of the robot on the angle α of its inclination to the horizon*

4. Results and discussion

The creation of means for accumulating the potential energy of the drives, and then transforming them into kinetic energy of the robot's motion, and also the integration of drives for longitudinal and vertical movement, can significantly reduce the total power that is of fundamental importance for mobile robots of arbitrary orientation in space, since reduces the gravitational load.

The use of a pneumatic motor as a means of counteracting the gravitational force makes it possible, when adjusting the traction force, depending on the angle of the robot's inclination to the horizon, to increase the reliability of holding the robot on the surface of an arbitrary orientation, which in turn makes it possible to reduce the power of the clutch actuators of the robot with the surface.

A fundamentally new realization of the legs of mobile robots in the form of a set of hemispherical rings and corrugated pipelines at different gas or liquid pressures makes it possible to achieve an arbitrary orientation of the mobile robot in different working spaces: a rectangular Cartesian, spherical and cylindrical coordinate system. This effect ensures the expansion of technological capabilities of mobile robots of arbitrary orientation in the technological space.

5. Conclusion

The concept of the synthesis of mobile robots is based on three principles of constructing their designs. These principles can be used autonomously and in combination, depending on the technological purpose of the robot and its profitability, which, in turn, is determined by the area of industrial operation. The proposed approach to the synthesis of mobile robots can reduce the weight of structures by reducing the total number of drives. This increases the energy resource for improving the efficiency of both transport and technological operations performed by the robot in various areas of industry. The next stage of the research is the experimental approbation of this concept of the synthesis of mobile robots.

References

1. Kuznetsov Yu.N. Challenges of the fourth industrial revolution "Industry 4.0" in front of scientists of Ukraine. – Vestnik KhNTU, Kherson. 2 (61), 2017, p. 67-75.

2. Raju D.D. Developments in wall climbing robots: a review.– International journal of engineering research and general science. 2 (3), 2014, p. 37 (Raju D.D., Jaju S.B).

3. Gradetskii V.G. Controlled movement of mobile robots over arbitrarily oriented surfaces in space. – Moscow: Nauka, 2001, 360p. (Gradetskii V.G.,Veshnikov V.B., Kalinichenko S.V.).

4. Chernous'ko F.L. Mobile robots: research, development, prospects. http://www.ras.ru/news/shownews.aspx?id=f5c75bcf-2fa5-40e6-b067-4492c5ab22&print=1. Last accessed 20 iyulya 2018. (Chernous'ko F.L. Bolotnik N.N. and Gradetskii V.G.)

5. Polishchuk M.N. Modernization of the vacuum gripper of the mobile walking robot.– Mechanics and Advanced Technologies, vol. 2 (80), 2017, p. 59–64.

6. Kuznjecov Ju.M. Robotic systems complexes of pharmaceutical and biotechnological productions. Kiev, GhNOZIS, 2012, 335 p. (Kuznjecov Ju.M., Shybecjkyj V.Ju.).

7. Pavlenko I.I.. Industrial work: calculation basics and design. KNTU. Kirovoghrad, 2007, 420 p.

8. Sinev A.V. The vehicle for moving along the surfaces arbitrarily oriented in space. State Register of Patents of Russia, Pat. № 2262461, 2005, 6 p. (Gradetskii V.G., Kravchuk L.N., Popovich V.A., Lebedenko I.B., Kochetov O.S.).

9. Baranov V. E. Vehicle for moving on inclined and vertical surfaces. State Register of Patents of Russia Pat. № 2267434, 2006, 8 p.(Baranov V. E., Vagin S.G., Zatsepin V. A., Kokorin A. G.)

10. Chashchukhin V.G. Investigation of the movement parameters of a robot with a sliding seal.–Vestnik Nizhegorodskogo universiteta im. N.I. Lobachevskogo, vol 4 (2), 2011, pp. 347–349.

11. Shamim Hasan. Smartphone Controlled Spy Robot with Video Transmission and Object Collector, International Journal of Engineering and Manufacturing (IJEM), Vol.7, No.6, 2017, p.50-58. (Shamim Hasan, Khalid Hossain Jewel, Niaz Mostakim, Nabil Hossain Bhuiyan, M.K. Rahman, Sheikh Dobir Hossain and Khalid Hossain).

12. Tin Lun Lam. Tree Climbing Robot: Design, Kinematics and Motion Planning. New York: Springer Heidelberg. 2012, p. 37–46. (Tin Lun Lam, Yangsheng Xu).

13. Yehya M. Unipolar Electroadhesion Pad Technology for Adhesion Mechanism of Wall Climbing Robot. – International Journal of Robotics and Mechatronics, vol. 2 (1), 2014, p. 1–10. (Yehya M, Hussain S, Wasim A, Jahanzaib M, Abdalla H A.).

14. Yampolskiy L.S. Method and device for movement of pedipulators of walking robot. State Register of Patents of Ukraine, Pat. 111021, 2016, 11p. (Yampolskiy L.S., Polishchuk M.N., Persikov V. K.).

15. Polishchuk M. Mobile climbing robot with elastic energy accumulators. – Mechanics and Advanced Technologies, vol. 1 (82), 2018, p. 116 – 122 (Polishchuk M., Oliinyk V.).

16. Kuznetsov Yu.M.. Walking mobile robot Kuznetsova – Polishchuka. Ukrainian Institute of Intellectual Property, Ukraine, application for a patent № a2018079762018, p.16 (Kuznetsov Yu.M., Polishchuk M.M.).

17. Polishchuk M. Walking Mobile Robot of Arbitrary Orientation, International Journal of Engineering and Manufacturing (IJEM), vol.8, No.3, 2018, p.1-11 (Polishchuk M., Opashnianskyi M., Suyazov N.).

18. Polishchuk M.N. Antigravity mobile robot Polishchuk. Ukrainian Institute of Intellectual Property, application for a patent № a201805661, 2018, p. 8–10.