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Mobile climbing robot with elastic energy accumulators

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Abstract. *This paper presents a novel method of improving energy efficiency of climbing robot by implementing accumulation of motion energy and its further recycling. Patented construction and functional scheme of pedipulator – conceptual walking mechanism are provided as well as a method to integrate movement and surface attachment modules of the robot. Calculations of dynamic loads are provided followed by results of simulations that demonstrate effective approach implementation by changing kinematic or constructional parameters instead of dynamic.*

Keywords: Mobile robot, walking mechanism, pedipulator, vertical movement robot, climbing robot, wall climbing robot.

Introduction

The need for climbing robots is caused by emerging extreme situations and increasing requirements for the technological operations in conditions that are dangerous for human. Main objectives of the development of technological climbing robots are choosing a way to hold and simultaneously move on a vertical surface, calculation of robot's design parameters, taking into account the dynamic loads when driving on the arbitrary oriented surface.

Vertical moving robot is one of the new types of mobile robots. Robots of these types are equipped with grippers, that allow to stay in contact with surface.

The main problem of control for this type of robots is the need to take into account the gravity component in the combination of dynamic loads. It can be explained by the fact that for conventional mobile robots gravitational force contributes to the stabilization of their movement, and in case of climbing robots − on the contrary, it needs to be overcome in order to guarantee attachment of the robot to the movement surface.

Analysis of studies and publications

The fundamentals of climbing robots modeling are rather widely described in works [1, 2, 3], though without solving the problem of reusing energy of motion. Modeling of vertical moving robots is devoted to [4, 5, 6], however without solving the problem of energy consumption of motion. Studies [7, 8, 9] contain descriptions of various models of robots. But in these works there are no designs for the recuperation of energy of motion. Known technical solutions [10] promote partial energy saving, for example, by using pulsed lifting mechanism. However, described system increases weight of robot, so it leads to increasing energy consumption. Therefore, the task of reducing energy consumption of the mobile robot movement is still relevant.

Design of the walking climbing robot

Fig. 1 shows a general view of the walking climbing robot of a new type [11] based using elastic accumulator energy. The robot includes a body 1, containing a rotary pneumatic servomotor 2 that is connected via a transmission with walking mechanisms − pedipulators 3. These mechanisms are equipped with elastic elements 4 that perform the function of potential energy accumulation during the first half of the movement cycle (first half of the step). For performing plane parallel movement robot is equipped with parallel link mechanisms 5 that connect vacuum grippers 6 with the pedipulators 3.

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Vacuum grippers 6 keep the robot attached to vertical or any arbitrary oriented surface and can be replaced by other type of robot grippers, for example, mechanical, electromagnetic or adhesive. Selection of the actual type of the grippers depends on the type of movement surface and technology functions of the robot.

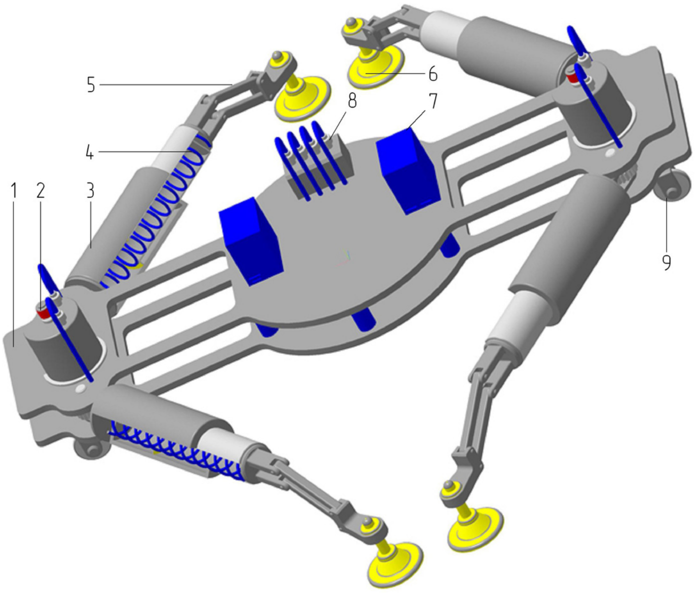

Fig. 1. Climbing robot with energy accumulation and recycling modules

In addition, the robot is equipped with a control unit 7 and power supply module 8. In order to overcome the obstacles on the movement surface the robot is additionally equipped with rolling bearings 9. These bearings have a kinematic connection through the differential roller screw with front and rear servomotors 2. It allows lifting the body 1 in order to overcome obstacles in the robot's path. The hardware implementation of the control system can be either a microcontroller or a dedicated computer.

The operating principle of the climbing robot with is following: during each half-step according to the instructions from the control system only one pair of grippers – rear or front is attached to the surface. Another pair of grippers is in a free state. After turning on servo 2 pedipulators 3 rotate around the axis of grippers 6 and thus move the body in the direction of the movement. Consequently, the elastic elements 4 compress, accumulating potential energy. During the second half of the step servomotor 2 turns off, the elastic elements 4 decompress, converting stored potential energy to the kinematic energy of motion.

Thereby, movement of the robot at each second half of the cycle (that is, half of a step) is done using energy accumulated in the first half of each movement step. This approach allows reducing energy consumption by 40 ... 45% and thus greatly improving the energy efficiency of the robot. Control system and external and internal sensors has the lowest energy consumption while surface attachment system of the robot and functional devices have the highest consumption. With an increase of total mass of the robot and its technological load, it is necessary to increase the power of robot's servos and surface attachment devices of vacuum, mechanical or electromagnetic type. So motion energy accumulation and recycling as well as integration of motion modules are recommended for improving energy efficiency of the climbing robot.

Functional systems of walking climbing robot

Surface attachment and movement system of the robot consists of subsystemforfixation on the surface and servos subsystem. *Fixation subsystem* includes mechanisms for holding the robot on the surface of motion: vacuum, mechanical, electromagnetic or other types of grippers. *Servos subsystem* includes electromechanical, pneumatic or vibrating motors of pedipulators.

Servos subsystem.

Electric servomotors are mostly used due to the flexible programming capabilities as opposed to pneumatic servomotors. In addition, electric servos can use the same power source as the control system, sensors and functional devices. Required power of the servomotors depend on the design parameters of the robot and it's mass. Therefore, it becomes apparent that increasing energy efficiency of servos subsystem is dominant factor.It can be achieved either by reducing the time of their work, as it was described above, or by reusing consumed energy.

Another promising area of reducing energy consumption is integration of the horizontal and vertical movement servomotors with servos for changing robot's orientation. Therefore, in the proposed design of the robot the single servomotor does lifting and rotating movements. Lifting is made due to kinematic connection between supports through the differential screw transmission between front and rear drives, and rotationis a result of the alternate usage of the actuators with grippers not in pairs but diagonally to the robot body.

Fixation on the surface *subsystem* is responsible for attaching body of the robot to the surface of movement. Principal design of the robot depends on selected mechanism of holding on the surface. This selection is determined by the type of terrain and landscape of arbitrary orientated surface where the movement takes place. In addition, selected type of fixation on the surface affects energy costs of this subsystem. For example, dry adhesion and electricity adhesion principles are the most efficient in terms of energy saving, but at the same time are quite new and expensive technologies. Systems with vacuum fixation are most common and widely used. There are two possible options for their implementation.

First option is usage of vacuum suction cups and second – creation of vacuum zone between the robot body and the surface. However, in both cases, creation of vacuum zone requires considerable energy resources. This is particularly important when the robot moves over complex topography and there is a danger of such an emergency as loss of intimate contact with the surface.

It is necessary to minimize the suction area that does not have contact with the surfaceto prevent such phenomenon, when the suction cup is not fixed on the surface and lays at some angle to it.In other words, suction cupshould be positioned properly on the surface of movement.

It is known that during a walk, human person analyzes the surface underfoot due to the sensitivity of the foot. This enables more effective positioning of the foot on complex terrain in terms of movement stabilization. According to this fact, it is recommended to equip pedipulator with articulated link on which suction cups with surface contact sensors are placed. Sensors measure density of the contact with the surface for pedipulator foot. Thus, the control system is able to adjust the position of the robot in the same way as the human corrects the position of his foot on an inclined plane. It allows organization of tight initial contact with the surface for pedipulator.

In addition, modern digital or analog sensors can provide information about the strength of clamping force. It becomes possible to regulate the vacuum generator operationif they are used instead of simple contact sensors. If the holding force is enough, it is possible to move safely. As soon as pedipulator will start to loose contact with the surface, control system will be able to determine the beginning of this process using pedipulator sensors data. It will give an opportunity to increase the power of the vacuum generator or transfer pedipulator to another favorable contact surface or apply extra security measures, such as using extra fixation system.

The monitoring subsystem provides landscape (topology) analysis of the surface of movement. For this purpose, it is proposed to add laser meter or sonar to control subsystem. It will provide an opportunity not only to obtain information about the topography of the surface, but also to carry out its analysis before executing the next movement step. This decision will allow the robot to avoid obstacles and to minimize the time of servomotors usage. At the same time, the energy consumption of these navigation and trajectory calculation units will be much less than required increase of power usage by the motors of the robot to hold it on the problematic surface.

In case of complex surface topography, it can be very effective to use adaptive control based on modern AI (artificial intelligence) methods like neural networks or other machine learning algorithms. This approach allows adapting mobile robot to the surface before performing technological operations. The robot can make its movement on the surface more efficient due to optimization of the step length, trajectory of movement and pedipulators incline angles. In case of surfaces with simple topology, such as the common brick or concrete wall, robot can be trained to avoid contacts with connections of construction elements on the surface of movement. This solution would eliminate reduction of vacuum due to air inflow at the places of bad contact. Adaptation of the robot to the surface with proposed method includes training phase when surface topology changes. Therefore, at this phase automatic control system should use vacuum sensors data to analyze information about reductions of the vacuum due to air inflow in the pedipulator suction cup.

Calculation of dynamic loads for pedipulator

For designing walking mechanisms – pedipulators, it is necessary to synthesize analytical dependences for dynamic loads. According to the scheme on fig. 2 pedipulators propulsive force is:

$$F = F_1 + F_2 , \tag{1}$$

where: F_1 and F_2 – variable propulsive forces of the servos respectively on the first half-cycle of movement – at the stage X_1 and on the second half-cycle of movement – at stage X_2.

At the stage of energy accumulation X_1 propulsive force of two pedipulators equals:

$$F = \frac{2M_1 i}{nz} - 2f , \tag{2}$$

where: M – torque of the servomotor, Nm; i – transmission ratio of pedipulator servomotor; β_1 – the angle of pedipulator axis rotation, degrees, $0 \le \beta_1 \le \beta^{\max}$ (here the values $\beta_1 = 0$ and $\beta_1 = \beta^{\max}$ correspond to the beginning and end of the pedipulator axis rotation); n – module and z – number of cogs of the wheel(gear); f – resistance force (N): $f = J \sin \beta_1$

where: J – variable force of the elastic element, N:

$$J = P_{\min} + jx = P_{\min} + j\left(R_1 - R_1 \cos \beta_1\right) = P_{\min} + jR_1\left(1 - \cos \beta_1\right) \tag{3}$$

where: $P_{\min}$ – preload clamping force (N), j – stiffness (N/m) and x – the value of deformation of the elastic element (potential energy storage), m.

At the stage of accumulated energy usage X_2 when the servomotor is switched off (that is, when $\beta_1 \geq \beta_2 \leq \beta_2^{\max}$ and the beginning and the end of the axis rotation corresponds to the values $\beta_2 = \beta_1$ and $\beta_2 = \beta_2^{\max}$) propulsive force is equal to:

$$F_2 = -J\sin\beta_2 + P_{\min} = jx\sin\beta_2 + P_{\min} = \\ = -\left[jR_1\left(1-\cos\beta_2\right)\right]\sin\beta_2 + P_{\min}, \quad (4)$$

where β_2 – the angle of the pedipulator axis rotation on the stage of energy recycling.

From (4) it is obvious that during the rotation of pedipulators deformation value of elastic elements x decreases from value $x = R_1\left(1-\cos\beta_2\right)$ to value $x = 0$, which means the end of motion using previously accumulated energy above other pair of pedipulators 3 and 4 (see. Fig. 2) which are disengaged from the surface of movement perform free movement. As noted above, the robot body during the full cycle travels distance equal to $X_1 + X_2$. At the same time disabled (free from engagement with the movement surface) grippers 3 and 4 covers double distance: $2(X_1 + X_2)$, due to the simultaneous movement of robot's body and grippers themselves. During this free movement of pedipulators 3 and 4 their elastic elements are not deformed, and therefore disconnected from the surface grippers move along the arc with centers in corresponding points «*c*» and «*d*» and radius $R_2 \geq R_1\cos\beta_1$ under the influence of the torques:

$$M_c = M_d = M_1 i \quad (5)$$

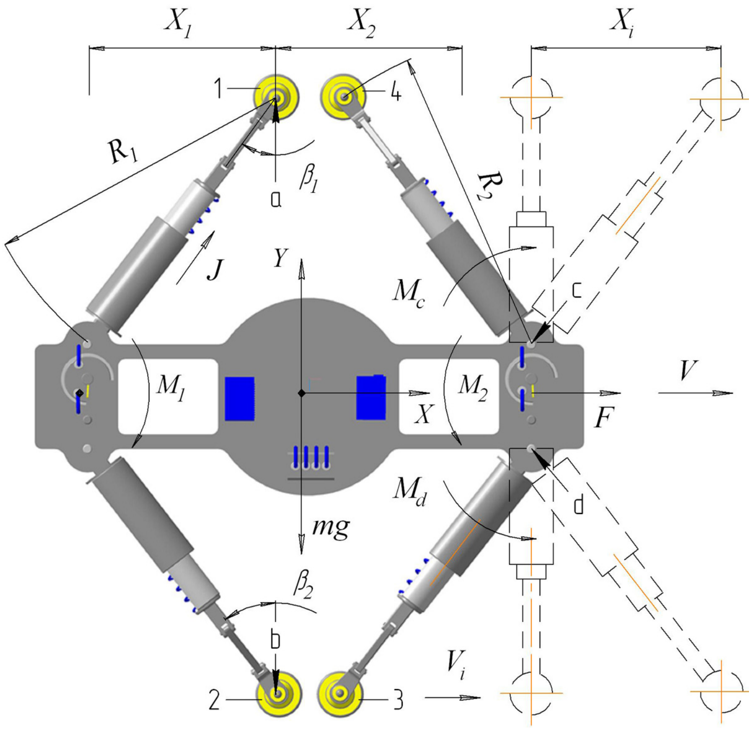

Fig. 2. Loading diagram of pedipulator (plan view):
grippers 1, 2 – attached to the surface and 3, 4 – free from engagement with the surface, respectively

and with linear speed:

$$V_i = V + \omega R_2 = V + \omega_1 i R_2 \quad (6)$$

where: V – linear speed of the robot, m/s; $V = \omega_1 i R_1 \cos\beta_1$; ω and ω_1 – respectively, the angular speed of disconnected pedipulators and the main servomotor of the robot, rad/s.

Clearly, unlike constant speed of free actuators $\omega R_2 = Const$, relative speed of the robot's body and enabled actuators is variable and depends on the rotation angle $\cos\beta_1$ of the working actuators.

The holding force of each pedipulator suction cup is normal to the surface of movement:

$$Q_z = SK_s\left(p_a K_a - p_з\right)K, \text{ (N)} \quad (7)$$

where S is the area bounded by the inner contour of suction cup (m²); $S = \pi d^2/4$; $d = (25...100)10^{-3}$ (m) – the diameter of the vacuum zone; K_s – coefficient of suction area reduction due to the suction cup deformation (K_s = 0.95 ... 0.98);

$p_a = 101\times10^3$ (Pa) – atmospheric pressure; $p_3 = (70...80)\times10^3$ (Pa) – degree of vacuum within suction cup; K_a – coefficient which takes into account changes in atmospheric pressure (K_a = 0.9); K – coefficient which describes air leakage between suction cup and the surface (K = 0.65 ... 0.85).

Tangential holding force of the gripper depends on the roughness of the surface and gripper material:

$$Q_{x,y} = Q_z \mu_n , \quad (8)$$

where μ_n is reduction coefficient of sliding friction.

Condition of robot's fixation on the surface of movement can be represented as

$$\sqrt{Q_x^2 + Q_y^2} \triangleright mg\cos\gamma , \quad (9)$$

where γ is the angle of inclination (rotation) of the longitudinal axis of the robot to the horizon, degrees.

Modelling results

Let us analyze the results of modeling the influence of pedipulator design parameters to the driving forces on the first $\beta = 0...45^0$ and second $\beta = -45^0...0$ phases of movement.

Fig. 3 shows that a 4x increase in stiffness *j* (N/m) of the elastic element (i.e. from *j*=1000 to *j*=4000 N/m) leads to a decrease in driving force by 20.1%.

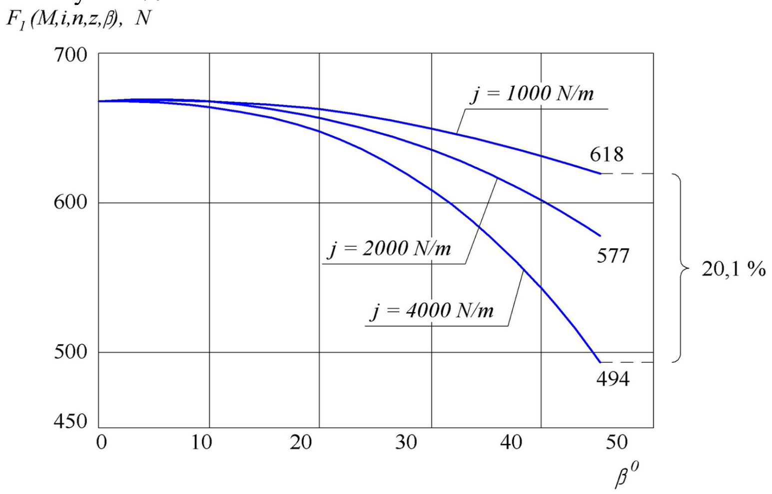

Fig. 3. Change of pedipulator driving force in the first phase of movement $\beta = 0...45^0$ depending on the stiffness of the elastic element for the values of the constants: servomotor torque $M = 10N/m$; transmission ratio *i*=1 ; *n* – module of the gearing unit *n=0,001m* and *z* – number of cogs of the wheel(gear) and the number of its teeth z=30

However, this increase in rigidity of the elastic element allows increasing driving force F_2 for 70.7% in the second stage of movement (Fig. 4) at the same time, when servo drives are turned off and pedipulator moves only by converting accumulated potential energy into kinetic energy.

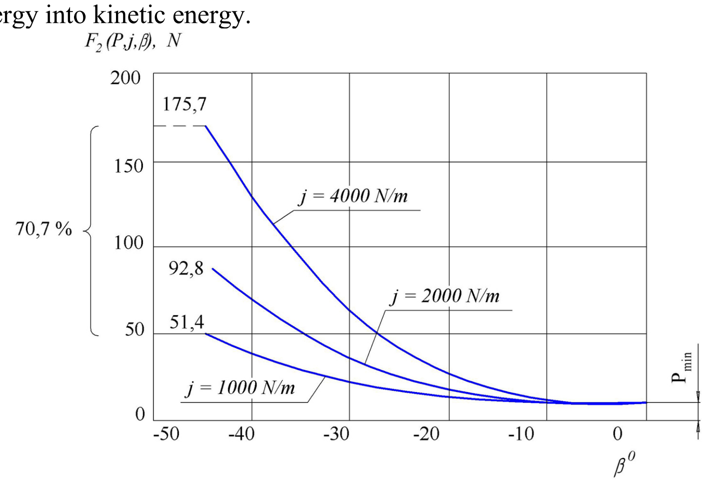

Fig. 4. Change of pedipulator driving force on the second stage of movement $\beta = -45^0...0$ depending on the stiffness of the elastic elements using same values of the constants (see Fig. 3) and initial compression of the elastic element $P = P_{min}$= 10 *N*

The negative impact of increasing the stiffness *j(N/m)* of the elastic element to the driving force can be compensated by an increase in either power, torque or transmission ratio of the servomotor. In the first two cases, there will be also a significant increase in mass of the robot, and thus degradation of its dynamic characteristics. It is therefore recommended to compensate reduction of the driving force caused by increase of the elastic elements stiffness by increasing the transmission ratio. The effectiveness of this solution is shown in Fig. 5, where even a slight increase of the transmission ratio from i=1 to i=1.2 provides full compensation of the driving force reduction, in particular from F = 494 N (Fig. 3) to a value F_1 = 627 N (Fig. 5).

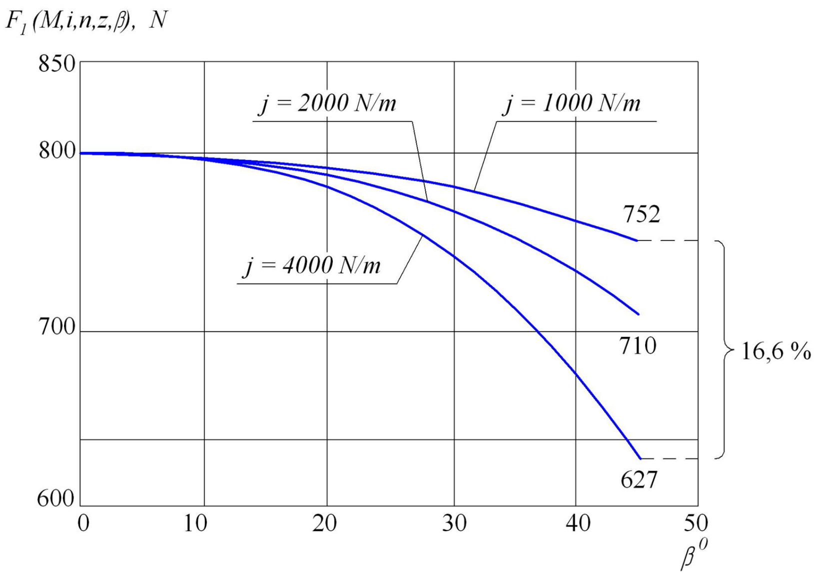

Fig. 5. Compensation of pedipulator driving force drop in the first phase of movement by an increase of the transmission ratio of the servomotor to value i =1,2

This principle will be respected also for any other (arbitrary) numerical values of pedipulator parameters because for constant servomotor power an increase in its transmission ratio does not significantly affect the increase of dynamic loads of the climbing robot. This solution reduces pedipulator speed on the first stage of movement, but also increases accumulation of potential energy (by increasing the stiffness of elastic elements) and, consequently, it will the value of the kinetic energy for pedipulator movement on the second stage when the drive is switched off.

Presented simulation results show benefits of regulation of the kinematic characteristics of the robot instead of changing its dynamic parameters.

Besides, in automatic mode of the servomotor power control it is necessary to take into account the impact of the technological operations done by robot using information about holding force from sensors. It is especially important when overcoming obstacles on the surface of movement. In such cases, it is advisable to adjust the speed or acceleration. It allows finding best values and their ratios for parameters of climbing robot movements in extreme situations. Further research will be devoted to solving this problem.

Conclusions

The use of elastic accumulators for the accumulation of energy as well as integration of the horizontal, vertical and orientation changing movement servomotors provides an opportunity to reduce the total power requirements of the robot significantly. This is crucial for mobile climbing robots.

The proposed approach to pedipulators operation allows from 30% to 40% reduction in energy consumption of the robot, and thus, by reducing motors power requirements allows decreasing robot's weight proportionally. Released energy resources can be spent on improving efficiency of transportation and other technological operations performed by the climbing robot.

Received results of mathematical modeling allow us to move to the next stage of research - physical modeling based on the creation of an experimental sample of the proposed pedipulator. The goal of experimental studies is live testing of design and construction of climbing robot described above.

Мобильный робот вертикального перемещения с упругими аккумуляторами энергии

М.Н. Полищук, В.В. Олейник

Аннотация. *Предложен метод повышения энергетической эффективности роботов вертикального перемещения за счет накопления потенциальной энергии пружинными аккумуляторами. Рассмотрена конструкция патентованного типа педипулятора — нового шагающего механизма, а также способ интеграции модулей движения и удержания робота на поверхности перемещения. Выполнен синтез аналитических зависимостей и приведены результаты моделирования динамических нагрузок.*

Ключевые слова: *мобильные работы, шагающие механизмы, педипуляторы, роботы вертикального перемещения.*

Мобільний робот вертикального переміщення с пружними акумуляторами енергії

М.Н. Поліщук, В.В. Олійник

Анотація. *Запропонований метод підвищення енергетичної ефективності роботів вертикального переміщення за рахунок накопичення потенційної енергії пружними акумуляторами. Розглянута конструкція патентованого типу педипулятора — нового крокуючого механізму, а також спосіб інтеграції модулів руху й утримання робота на поверхні переміщення. Виконаний синтез аналітичних залежностей і наведені результати моделювання динамічних навантажень*

Ключові слова: *мобільні роботи, що крокують механізми, педіпуляторы, роботи вертикального переміщення.*

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