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***Platov I.M.***
National Technical University of Ukraine "Ihor Sikorskyi Kyiv Polytechnic Institute"

***Pavlovskyi O.M.***
National Technical University of Ukraine "Ihor Sikorsky Kyiv Polytechnic Institute"

# JUSTIFICATION FOR THE CONTROL SYSTEM FOR VERTICAL MOVEMENT OF A SMALL-SIZED WALKING ROBOT

*The article substantiates and develops a system for controlling the vertical movement of a walking hexapod robot. Typically, the vertical movement of walking robots is achieved through various fixation devices, suction cups, magnets, hydraulic or pneumatic devices, which ensure the contact of the leg and the surface. Recent developments in this field focus on vertical movement through the friction forces between the legs and the surface. Thus, there is no need to use additional equipment and complicate the design. However, such movement requires the development of more complex algorithms.*

*A review of the literature demonstrates the feasibility of such a movement method only in laboratory conditions with a predefined wall configuration. Therefore, an analysis of various scenarios, most closely resembling real conditions, was conducted, and key factors that the control system must consider were identified. Based on this analysis, it was concluded that the most significant situations are when the hexapod platform is in horizontal and vertical positions. In such cases, the movement is divided into two separate tasks, the resolution of which is mandatory for forming vertical movement algorithms. According to the defined requirements, a mathematical model was built, which considers the shift of the robot's center of mass, especially important for lifting useful loads.*

*Additionally, since the real environment is inherently uncertain, the walking robot needs to be equipped with a vision system.*

*To verify the system's performance, a series of test climbs with different scenarios were conducted, namely: vertical climbing when the platform is parallel/perpendicular to the walls, and straight-line movement between two walls.*

*The test results confirmed the performance of the proposed system and identified ways for further development.*

***Key words:*** *control system, robot, inclinometer, vision system, hexapod, vertical movement, mathematical model, center of mass, kinematics.*

**Introduction.** Today, there are many developments and algorithms for small-sized walking robots. The scope of which covers a wide range of needs, in particular, for the movement of the robot over rough terrain, on flat horizontal surfaces, there are also the development of mathematical models that take into account deformations not only of robot structures, but also of the surface, which in turn makes it possible to increase the stability of the robot during movement [1].

It is important to note that the appearance of available and inexpensive components, in particular, miniature servomotors, made it possible to implement many designs, the most common of which are: hexapods – have six limbs and quadropods – have four limbs. The latter, although structurally simpler, have a significant drawback – worse stability on uneven surfaces. They also require the development of more complex algorithms to stabilize the platform, which complicates development and makes it more expensive [2; 3]. Therefore, in this work, the main attention is paid to the hexapod control system.

Recently, there have been attempts to implement vertical movement due to the friction forces of the limbs against the surface on which the robot climbs. The main difference of this method is its increased algorithmic complexity, but unlike existing designs, most of which are implemented on the basis of vacuum suction cups or electromagnets, it does not require changes to the design. The latter should take into account additional loads on the servomotors that occur during lifting, deformation of the limbs and platform, surface deformation, etc.

*Analysis of recent research and publications.* Among the existing works devoted to the implementation and research of the vertical movement of the hexapod due to the frictional forces of the limbs and the surface on which the robot moves, the following can be distinguished:

In the paper [4], the authors propose to consider each limb of the hexapod as a separate manipulator. The sum of the stiffnesses of each limb will be the stiffness of the entire structure and, accordingly, on the basis of this, it is possible to calculate the deformations of the entire structure. Assuming, of course, that the platform is absolutely rigid. Based on this, they obtained the stiffness matrix of the entire system, compensated for the deformation of the walls between which the robot moved and determined what force is necessary to keep it at a height between the walls. Since vertical movement is more complex than horizontal movement and there are many factors that can cause the robot to fall or slip, the authors suggested introducing a safety factor that takes into account insufficient friction and motor torque. The developed techniques were tested on a pre-programmed course. The developers investigated the case with parallel walls, non-parallel walls, investigated the effectiveness of different types of gait from the point of view of safety and reliability of the contact of the robot's limbs with the walls. Correction of inclinations that necessarily occur during ascent was done with the help of an IMU and a PID controller.

The work [5] is aimed at developing the previous methods, in particular, they developed a hexapod motion planner that can solve the problems of climbing between non-parallel walls, bypassing an obstacle between two walls. The authors verified the methods through a series of tests that showed their effectiveness. However, in this case, the geometry of the walls and obstacles was primarily known, so it is impractical to apply the development data outside of laboratory conditions.

In the article [6], the implementation of a motion planner algorithm is presented. The planner is also implemented using nonlinear programming to solve the problem of determining the robot's pose and forces with guaranteed limited risk. The maximum adhesion forces are modeled as a Gaussian distribution. The disadvantages of tripedal gait for vertical movement are investigated according to the mathematical model, as well as movement between heterogeneous walls, i.e., with sections of different surfaces. The design of the leg, which the authors developed to improve surface grip, is presented. As in previous works, the gait was primarily programmed with all geometric parameters of the walls known in advance.

In the work [7], the authors improved the movement algorithm for navigating between walls with protrusions, as well as climbing inside a circular pipe. Additionally, the transition of the hexapod from a flat surface (ground) to a vertical direction (moving between two walls) was investigated.

Taking into account the existing developments, it can be concluded that at the moment vertical movement due to frictional forces needs refinements, namely: implementation of the operation of the hexapod in previously undefined conditions, which was not done in the considered works, in addition, the proposed algorithms require a fairly powerful computing core, which in turn makes it difficult to use hexapods for vertical lifting outside of laboratories and test equipment. Existing developments lack a vision system that can assess the environment and provide information about the geometry of the space and the objects in it. The review of the state of the problem, which was carried out in [8], demonstrates in general the ways of development of hexapod walking robots for vertical movement. Accordingly, for a better disclosure of the research topic, each aspect of the development needs a more detailed consideration.

**Problem statement.** Existing developments take into account many of the listed needs, but real-world application requires a systematic approach that will allow the work to work autonomously, and not only in given laboratory conditions and scenarios. Therefore, this work proposes to improve the existing developments, based on which a control system was created for the vertical movement of the hexapod due to the frictional forces of the limbs and the surface.

**Analysis of typical hexapod movement scenarios.** First of all, let's consider several scenarios that can occur in real conditions. From a review of the existing works, it can be seen that some of the possible options have already been considered, but there are many spatial configurations and types of surfaces that cannot be taken into account in full at the development stage. But, despite this, it is quite enough to consider typical situations that reflect real structures that are widely used in industry (ventilation shafts, channels, etc.), in speleology, etc. For example, in fig. 1 shows the possible configurations of the two walls along which the hexapod can move.

The given configurations can be combined, that is, for example, have an uneven surface, as well as holes or branches, etc. The difficulty of developing movement algorithms is that for error-free operation in this case, it is necessary to take into account a large number of various factors. As mentioned in [8], the structural component is very important for vertical movement, because it determines the conditions under which the robot will be able to lift. If the design is too large, it limits, and in some cases makes it impossible, movement in spaces that are tight enough for maneuvers or bypassing obstacles.

**Control system development.** Taking into account the displacement of the center of mass (CoM) of the entire robot is a very important factor, neglecting which it is difficult and sometimes impossible to control the robot for vertical movement, especially if a payload is installed on it.

The center of mass of the hexapod can be calculated using the following formulas:

$$Xc = \frac{1}{m_r}\sum m_j x_j ; Yc = \frac{1}{m_r}\sum m_j y_j ; Zc = \frac{1}{m_r}\sum m_j z_j . \quad (1)$$

Where *Xc, Yc, Zc* are the coordinates of the CoM of the robot, $m_r$ is the mass of the robot, $m_j$ is the mass of the *j-th* structural element, $x_j$, $y_j$, $z_j$ are the coordinates of *the j-th* structural element.

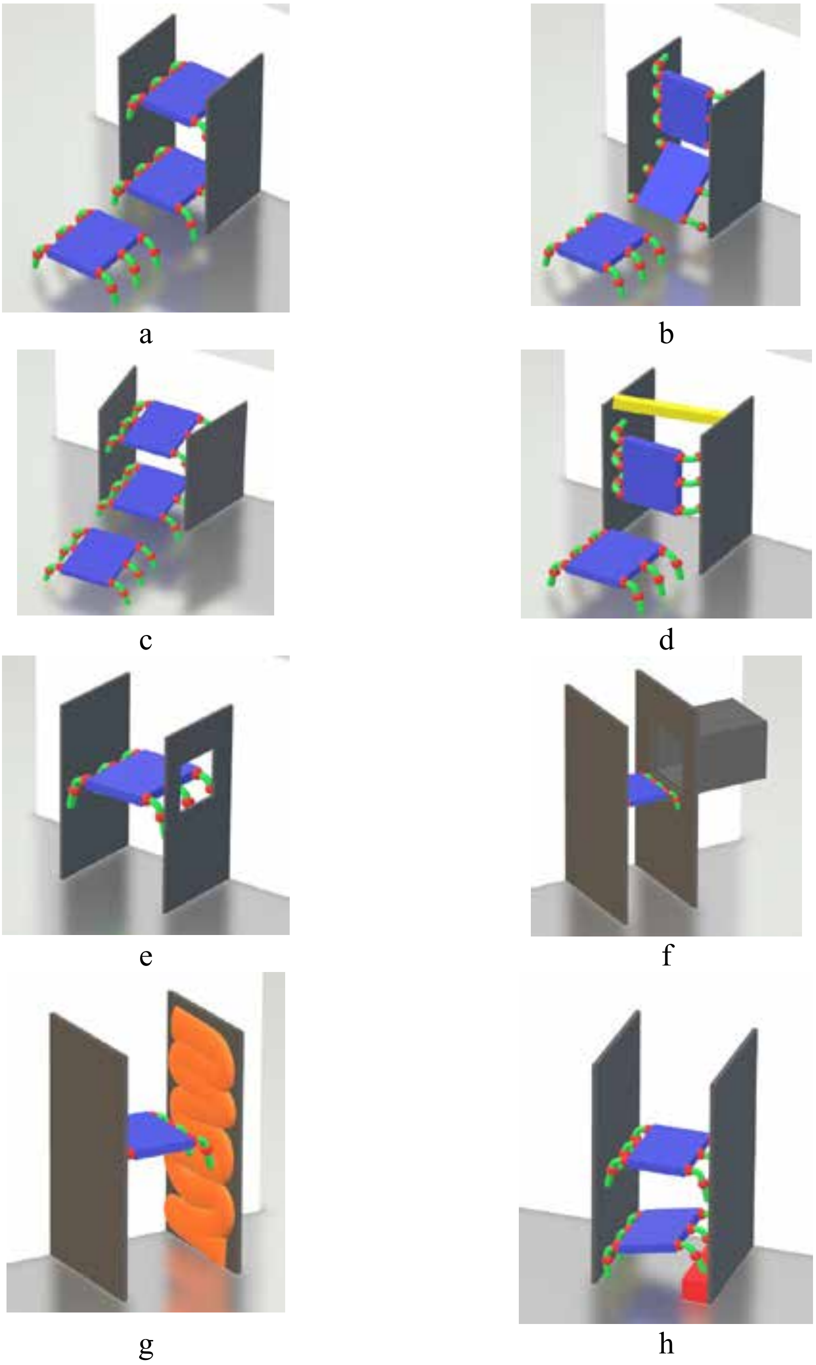



**Fig. 1. Possible spatial configurations of the walls between which the hexapod moves:**
a – robot platform parallel to the ground; b – perpendicularly; c – non-parallel walls; d – the presence of an obstacle between the walls; e – the presence of a hole, a bulge or a depression; f – the presence of branching (one or on several sides); g – uneven wall surface; h – obstacle or a step below the walls

In this case, the movement algorithm must take into account not only the geometry of the surrounding space but also the displacement of the robot's center of mass. This is especially important for vertical lifting, as too much inclination of the platform will lead to displacement of the CoM and redistribution of loads to the actuators, which in turn can lead to a loss of grip of the limbs on the surface and a fall of the hexapod. If you look at fig. 1a, it can be seen that with this arrangement of the robot between the walls, a kind of shoulder is created, on which the force of gravity acts, and if we add to this the possibility of carrying the payload, then the force of pressing the limbs may not be enough. At the same time, in the position shown in fig. 1 b, the hexapod can move freely without falling, having the same components in its design. This suggests that hexapod lifting can be divided into solving two problems: lifting when the platform is parallel to the ground, the platform is perpendicular or at an angle to the ground – two fundamentally different problems, each of which requires a separate approach.

It is convenient to construct the kinematic diagram of the hexapod using 3×3 rotation matrices. At the same time, we will define several construction rules:

1) Z axis is always directed upwards.

2) Y axis is located perpendicular to the limb and coincides with the direction of the Y axis of the platform coordinate system.

3) X- axis is always directed along the limb.

Thus, for one limb, the joint coordinate system will have the following form (Fig. 2).

Such a kinematic scheme realizes the rotation of the limb in the horizontal plane (joint $J_1$) and the lifting of the joints ($J_2$, $J_3$) in the vertical plane. Thus, 3 degrees of freedom are created.

The orientation of the limb and the coordinates of the foot relative to the center of mass of the platform will be determined by a three-dimensional displacement vector relative to the coordinate system of the platform, while we assume that the origin of the coordinates coincides with the center of mass of the latter. The coordinate systems of the platform and the joints of the limb are marked (simplified) in fig. 3.

Displacement $X_0\ Y_0\ Z_0$ relative to $X_p\ Y_p\ Z_p$ are determined at the stage of design development and can be determined from drawings or, directly, measured. To determine the coordinates in space for other joints, we will apply rotation matrices (2)–(4):

$$A_1 = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) & 0 \\ -\sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix}; \tag{2}$$

$$A_2 = \begin{bmatrix} \cos(\beta) & 0 & -\sin(\beta) \\ 0 & 1 & 0 \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix}; \tag{3}$$

$$A_3 = \begin{bmatrix} \cos(\gamma) & 0 & -\sin(\gamma) \\ 0 & 1 & 0 \\ \sin(\gamma) & 0 & \cos(\gamma) \end{bmatrix}; \tag{4}$$

$A_1$ is the rotation matrix of joint $J_1$ around the vertical axis $Z_0$, $A_2$ and $A_3$ are the rotation matrices of joints $J_2$ and $J_3$ around the axis Y. α, β, γ – turning angles, respectively.

When placing the limbs, as shown in fig. 3, it is convenient to conventionally divide the platform into left and right sides, because it is rectangular and all limbs are placed symmetrically. This separation will facilitate further operations with the numbering of limbs and their indices. The designations are shown in fig. 4.

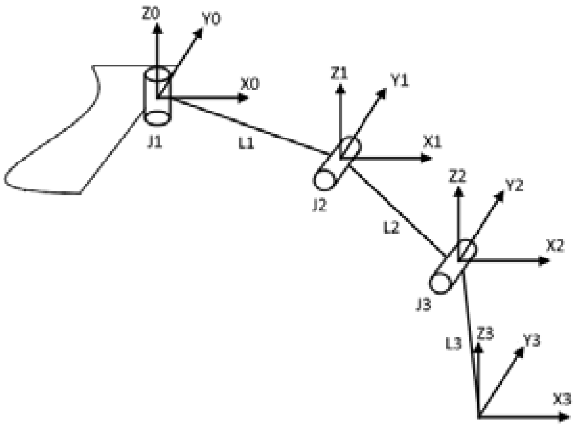



**Fig. 2. Coordinate systems of limb joints**
**$L_{1\text{-}3}$ – link lengths**

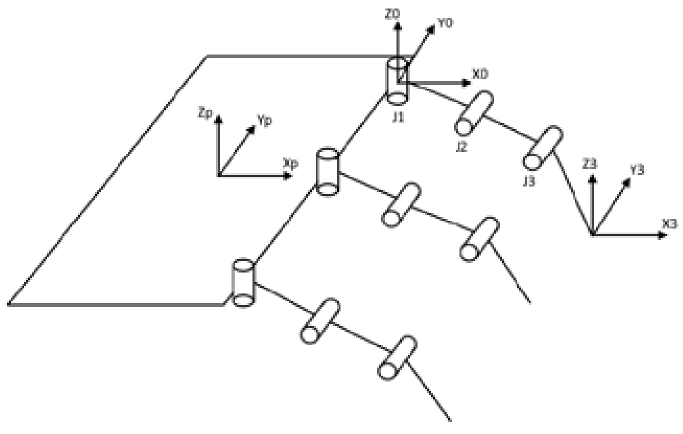



**Fig. 3. Coordinate systems of the platform and joints of the limb**

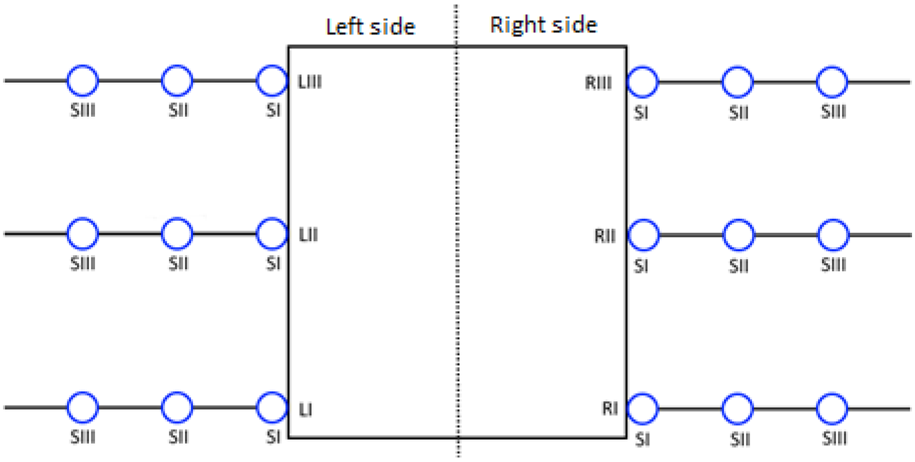



**Fig. 4. Conventional designation of hexapod limbs**
**$L_{I\text{–}III}$ – numbers of limbs on the left side of the platform, $R_{I\text{–}III}$ – limb numbers on the right side of the platform, $S_{I\text{–}III}$ – numbers of servomotors**

The coordinates of the $S_{I axes}$ of the servomotors, which are rigidly connected to the platform, relative to the center of the platform will be determined as (5):

$$L_iS_I = \begin{bmatrix} X_{L_iS_I} \\ Y_{L_iS_I} \\ Z_{L_iS_I} \end{bmatrix}; R_iS_I = \begin{bmatrix} X_{L_iS_I} \\ Y_{L_iS_I} \\ Z_{L_iS_I} \end{bmatrix}; \quad (5)$$

$$i = \text{I} \dots \text{III}$$

As the center of mass of the servo motor, we take its geometric center. Knowing the displacement relative to the axis (joint), which is determined by measurement or from construction drawings, it is possible to determine the CoM coordinates of these servomotors. We denote this displacement as:

$$\begin{bmatrix} X^*_{L_iS_I} \\ Y^*_{L_iS_I} \\ Z^*_{L_iS_I} \end{bmatrix}$$

and add to (5). Thus, the CoM of servomotors rigidly connected to the platform will be determined as follows (6):

$$CoM_{L_iS_I} = L_iS_I + \begin{bmatrix} X^*_{L_iS_I} \\ Y^*_{L_iS_I} \\ Z^*_{L_iS_I} \end{bmatrix}; CoM_{R_iS_I} = R_iS_I + \begin{bmatrix} X^*_{L_iS_I} \\ Y^*_{L_iS_I} \\ Z^*_{L_iS_I} \end{bmatrix}; \quad (6)$$

It is convenient to determine the coordinates of the joints using a direct problem of kinematics, for this we use the rotation matrices (2)–(4) and the coordinates of the joints (5), we get (7):

$$\begin{gathered} L_iS_{II} = A_1 - L_1 + L_iS_I; \\ L_iS_{III} = A_1 \cdot A_2 - L_2 + L_iS_{II}; \\ L_iT = A_1 \cdot A_2 \cdot A_3 - L_3 + L_iS_{III}; \\ R_iS_{II} = A_1^{-1} \cdot L_1 + R_iS_I; \\ R_iS_{III} = A_1^{-1} \cdot A_2^{-1} \cdot L_2 + R_iS_{II}; \\ R_iT = A_1^{-1} \cdot A_2^{-1} \cdot A_3^{-1} \cdot L_3 + R_iS_{III}, \end{gathered} \quad (7)$$

where $L_iT$, $R_iT$ are the coordinates of the foot of the limb.

The CoM of other servomotors is determined by taking into account the displacement from the axis of rotation of the servomotor to its CoM (8):

$$CoM_{L_iS_k} = L_iS_k + \begin{bmatrix} X^*_{L_iS_k} \\ Y^*_{L_iS_k} \\ Z^*_{L_iS_k} \end{bmatrix};$$

$$CoM_{R_iS_k} = R_iS_k + \begin{bmatrix} X^*_{R_iS_k} \\ Y^*_{R_iS_k} \\ Z^*_{R_iS_k} \end{bmatrix}, \quad (8)$$

Where $k = \text{II} \dots \text{III}$.

Taking into account (1) and (6), (8), the formulas for calculating CoM take the final form (9):

$$CoM_r = \begin{bmatrix} Xc \\ Yc \\ Zc \end{bmatrix} = \frac{m_j \cdot \left( CoM_{L_iS_I} + CoM_{R_iS_I} + CoM_{L_iS_k} + CoM_{R_iS_k} \right)}{m_r}. \quad (9)$$

It is worth noting that in this case, the mass of the links and the foot was neglected, since their weight is much less than the weight of the servo motor. Thus, at given angles of rotation of the limbs, $\alpha$, $\beta$, $\gamma$ it is possible to determine the coordinates of each joint and foot of the robot, as well as its CoM.

Knowing the coordinates of all the feet and CoM, as well as the angle of inclination of the platform, for example, according to the readings of the inclinometer, it is possible to build a stabilization and orientation system that will ensure stability during vertical movement. A simplified functional scheme is shown in Fig. 5.

As the primary source of information about the possibility of further movement, the vision system works, which signals whether further movement is possible, if so, then information about the geometry of the surrounding space is supplied to the stabilization system. Data preprocessing implements data filtering and storage. Factory parameters about the initial positions of the limbs and geometric data of the hexapod are read out by the stabilizer. In addition, the angle of inclination of the platform is calculated to determine its orientation relative to the walls between which the hexapod rises. In addition, in the process of lifting, the inclinometer adjusts the position of the limbs and, accordingly, the platform, because during the lifting, distortions of the latter occur due to the errors of the servomotors.

**Experimental research.** For experimental studies, a test stand and a model of a walking hexapod robot were built. MG-995 servomotors with a torque of 0.5 Nm and an ATmega328 microcontroller were used to build the model. The inclinometer is implemented on the basis of the ADXL-335 accelerometer. The vision system is a combination of ultrasonic SR-04 and infrared VL53L0X sensors [9]. For vertical lifting, a tripod gait was used (when with each step, three limbs are in a state of transfer, and the other three are pressed against the walls). The results of the experimental run are shown in fig. 6 a, b.

In this case, the vision system scans the walls and determines their geometric dimensions. In this way, the control system automatically determines the angles of deviation of the limbs necessary for holding the robot and its movement, as well as corrects the tilt of the platform. It can be seen that the developed system works in both cases, but currently it does not take into account the presence of obstacles and other situations that were shown in Fig. 1. Therefore, it needs revisions, which will be presented in further works.

**Conclusions.** This work is devoted to the development of a control system for a hexapod walking robot for vertical movement due to the frictional forces of the limbs and the surface. Unlike existing developments, this type of movement does not require special devices that ensure contact between the limbs and the surface. However, more complex movement algorithms need to be developed, since there are more components that need to be taken into account, unlike moving in the horizon. A review of existing developments showed that currently there are no solutions that would allow the robot to work autonomously in an uncertain environment, all attempts to implement vertical movement are limited to laboratory conditions and pre-programmed actions,

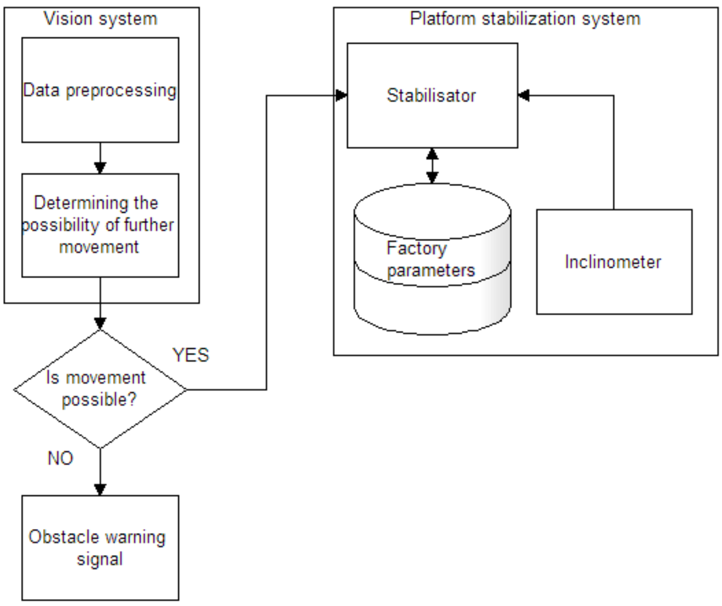
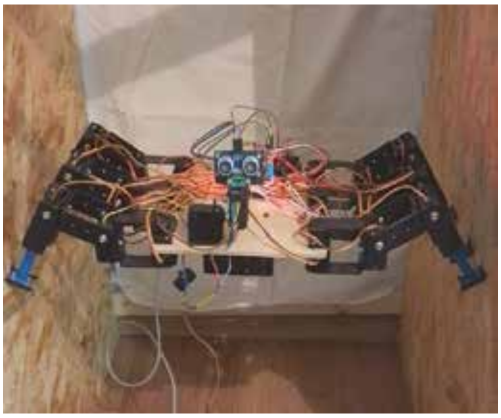
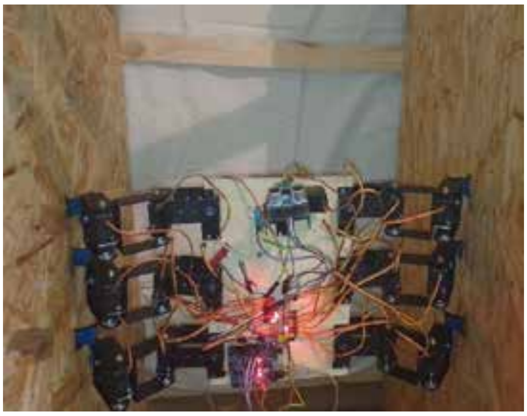



**Fig. 5. Simplified platform stabilization system during vertical movement**



a



b

**Fig. 6. Vertical lifting of the hexapod:**
a – platform parallel to the ground, b – platform perpendicular to the ground

therefore, in this work, a hexapod control system was developed for its lifting due to frictional forces in uncertain conditions.

The vision system determines the geometric parameters of the environment, thanks to which the robot can make decisions precisely in uncertain conditions. Lidar data is pre-processed and based on this, further decisions are made regarding overcoming obstacles or returning to the initial position or informing the operator about an impassable obstacle. The developed stabilizer calculates the displacement of the center of mass of the platform, on the basis of which the balance control is implemented, which protects the work from falls. In addition, the inclinometer determines the orientation of the platform, which makes it possible to climb not only when the platform is parallel to the walls, but also when it is perpendicular. This greatly improves the ability to avoid obstacles.

Experimental studies have confirmed the functionality of the system, but currently it takes into account only some of the possible configurations of the space and needs refinements, which will be covered in future works.

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**Платов І.М., Павловський О.М. ОБҐРУНТУВАННЯ СИСТЕМИ КЕРУВАННЯ ВЕРТИКАЛЬНИМ ПЕРЕМІЩЕННЯМ МАЛОГО КРОДУЮЧОГО РОБОТА**

*У статті обґрунтована і розроблена система керування вертикальним рухом крокуючого робота гексапода. Зазвичай вертикальний рух крокуючих роботів реалізується завдяки застосуванню різноманітних фіксуючих засобів, присосок, магнітів, гідравлічних або пневматичних пристроїв, які забезпечують контакт кінцівки та поверхні. Останні розробки в даному напрямку спрямовані на вертикальний рух за рахунок сил тертя кінцівок і поверхні. Таким чином немає необхідності застосовувати додаткове устаткування та ускладнювати конструкцію. Але, натомість, такий рух потребує розробки більш складних алгоритмів.*

*Огляд літературних джерел демонструє працездатність такого способу руху лише в лабораторних умовах і з попередньо заданою конфігурацією стін. Тому був проведений аналіз різноманітних сценаріїв, які найбільш наближені до реальних умов і виокремлені ключові фактори, які має враховувати система керування. На базі проведеного аналізу був зроблений висновок, що найбільш вагомими є ситуації, коли платформа гексапода знаходиться у горизонтальному та вертикальному положеннях. В такому випадку рух розділяється на дві окремі задачі, вирішення яких є обов'язковим для формування алгоритмів вертикального руху. Відповідно до визначених вимог, була побудована математична модель, яка враховує зміщення центра мас робота, що особливо важливо для підйому корисного навантаження.*

*Також, оскільки реальне середовище є апріорно невизначеним, то крокуючого робота необхідно оснащувати системою зору.*

*Для перевірки працездатності системи була проведена серія тестових підйомів з різними сценаріями, а саме: вертикальний підйом, коли платформа паралельна/перепендикулярна до стін, прямолінійний рух між двома стінами.*

*Результати тестів підтвердили працездатність запропонованої системи і визначили шляхи подальшого розвитку.*

***Ключові слова:*** *система керування, робот, інклінометр, система зору, гексапод, вертикальний рух, математична модель, центр мас, кінематика.*