АВТОМАТИЗАЦІЯ ТА ІНТЕЛЕКТУАЛІЗАЦІЯ ПРИЛАДОБУДУВАННЯ

DOI: 10.20535/1970.69(1).2025.331867
UDC 007.52+62-523.8

SOFTWARE ALGORITHMS FOR ENHANCING STABILITY DURING LOCOMOTION OF A WALKING ROBOT

Serhii Spivak, Oleksii Pavlovskyi
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine
E-mail: sergijspivak2002@gmail.com, a_pav@ukr.net

This study develops and tests a method for improving the stability of a quadruped walking robot during straight-line motion by upgrading its control algorithms. Such robots are widely used in military applications, rescue operations, construction, industry, research, and even daily life. Ensuring stability during movement is a critical issue for all types of walking robots, but it is particularly challenging for bipeds and quadrupeds due to their structural features and operational modes.

In the investigation of quadruped robot stability, it was determined that stability can be conditionally divided into dynamic and static stability. Dynamic stability refers to maintaining balance during body movement, while static stability pertains to maintaining balance in a stationary position. A common issue for quadrupeds is falling onto the lifted limb, which is a problem of static stability since it results from losing a support point without body movement.

The paper reviews recent studies and concludes that proposed stability enhancement methods for walking robots can be broadly categorized into structural and algorithmic approaches. Structural methods are commonly used for robot stabilization but are not universal, as they require modifications to the design. Algorithmic methods are more versatile, but their application is often limited by the robot's computational capacity, power constraints, and lack of necessary sensors. After analyzing the limitations of existing methods, a stabilization method was proposed that does not require structural modifications or significant computational resources.

The essence of the method is shifting the center of mass from its initial position within the support triangle formed by the legs in the swing phase. This is achieved by repositioning the support points of the limbs toward the lifted limb. The proposed method was implemented in the robot's motion control algorithm and tested on a quadruped robot model that previously exhibited stability loss when transferring a limb to a new position. A test algorithm was developed, defining a sequence of movements for straight-line locomotion, and an analysis was conducted on the impact of center of mass shifting on the time required to traverse a fixed-length section. The conducted studies demonstrated the feasibility and effectiveness of the proposed method.

Keywords: *ground robotic systems (GRS); software algorithm; walking robot; quadruped; programming; stability; stability improvement; center of mass; algorithmic and structural methods; microprocessor system.*

Introduction

In recent years, the research and use of so-called ground robotic systems have significantly increased, and they are increasingly finding their place in various fields of human activity.

Mobile ground robotic systems (GRS) are specialized functionally oriented systems equipped with a control and navigation system, actuators, power units, and mobility mechanisms that allow them to move across surfaces and perform assigned tasks [1]. GRS can be used in the military sector for reconnaissance, mine clearance, and facility protection; in industry for automated cargo transportation and hazardous tasks; in agriculture for crop monitoring and fertilizer application; in rescue operations for locating victims in disaster zones; and in scientific research for exploring hard-to-reach places or extreme environments [2].

GRS can be classified based on their mode of movement into walking, wheeled, tracked, and hybrid types. Walking NRK use limbs for locomotion similar to animals and humans, allowing them to traverse various terrains and obstacles. Wheeled GRS are the most common robotic systems due to their simplicity in operation and control. They utilize wheels for movement, providing significant advantages in speed. Tracked GRS employ track mechanisms, which offer benefits when navigating difficult terrains such as mud or sand. Hybrid GRS combine multiple locomotion methods, such as wheeled and walking or walking and tracked mechanisms. These combinations allow the robot to take advantage of multiple mobility systems simultaneously.

Among these GRS types, walking robotic systems, also known as walking robots, exhibit the highest mobility. They can overcome complex terrains, climb obstacles, and even perform vertical movements [3, 4]. However, the main drawback of walking robots is the necessity to lift their limbs off the surface for movement, which in turn reduces their stability due to a decrease in the number of contact points with the ground.

Walking robots are generally classified based on the number of limbs into bipeds, quadrupeds, hexapods, and myriapods. Each of these types is examined in more detail below.

Bipeds have two limbs and walk similarly to humans. This type of robot is one of the most complex in terms of stability and balance maintenance. One of the most well-known bipedal robots is the humanoid robot Atlas, developed by Boston Dynamics [5].

Quadrupeds have four limbs and are physiologically similar to four-legged animals. This type of robot is more stable compared to bipeds but can still lose stability and fall under certain conditions. Some examples of quadrupedal robots include ANYmal and Spot, developed by ETH Zurich and Boston Dynamics, respectively [6, 7].

Hexapods have six limbs, which provide high stability, the ability to maintain balance while moving, and good maneuverability. One example of a hexapod is the PhantomX Hexapod, which is often used as an educational or research model [8].

Myriapods have more than six limbs. This type of walking robot has high resistance to falls and is not significantly affected by the loss of several limbs during operation. However, such robots have low maneuverability and may consume a large amount of energy due to their numerous actuators. One example of this type is the OCTOROACH robot [9], which has eight limbs and mimics the movement of insects.

Among the types of walking robots mentioned, the least attention has been given to quadrupeds, hexapods, and myriapods. In this regard, myriapods are primarily demonstrative in nature, as quadrupeds and hexapods can perform nearly all the same tasks as myriapods while offering greater maneuverability and fewer limbs. This, in turn, increases turning and movement speed and reduces energy consumption for operating additional limbs [10]. Quadrupeds, on the other hand, are quite similar to hexapods but have lower stability during movement, which is their main drawback.

Fall resistance, depending on movement speed, is classified into static and dynamic stability [11]. Static stability allows a robot to maintain balance by forming a support area with its limbs during slow movements. Dynamic stability, on the other hand, enables balance retention during fast movement.

Dynamic stability is also referred to as active stability, as it is described as controlled falling onto the lifted limb. In other words, solving the problem of dynamic stability involves calculating the period and phase of each limb's lift. Since addressing this issue allows the robot to perform rapid movements without the risk of falling, it has been well-studied by various researchers, particularly in the context of bipeds and similar systems [4]. However, significantly less attention has been given to static stability during movement, which is primarily achieved through structural symmetry.

Thus, this study will focus on the problem of static stabilization of the robot during slow, straight-line movement.

Problem statement

For a statically stable robot, the projection of the center of mass must always be located within the plane formed by its limbs, as shown in Figure 1.A. Additionally, for the robot to be statically stable, it must have at least three points of contact, meaning that in the case of a quadruped, only one limb can be lifted during a single step iteration.

Let us consider different cases of lifting limbs by the robot. In Figure 1.B, we show a case of a statically stable robot. When lifting limb B, the plane of stable positioning is formed only by limbs A, C, and D. Since the projection of the center of mass, O, is within the boundaries of triangle ABC, the robot will remain statically stable.

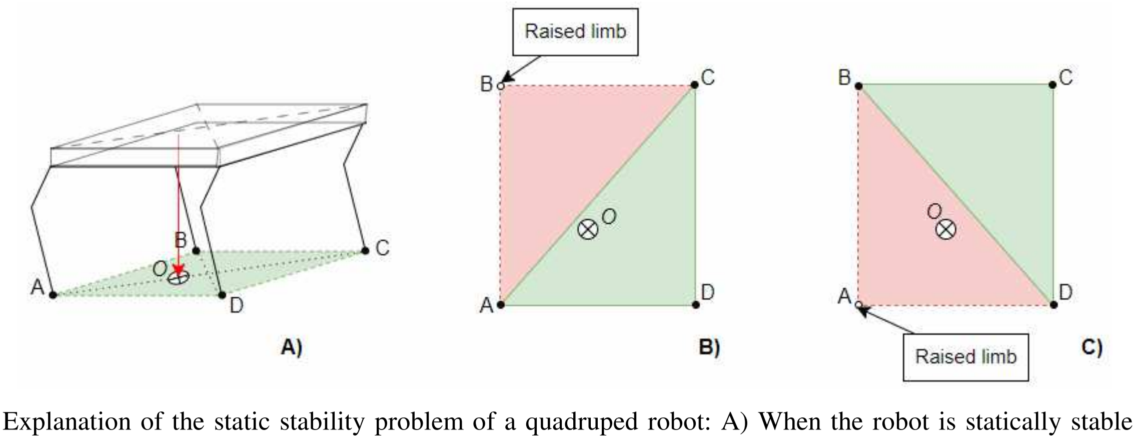

Fig. 1. Explanation of the static stability problem of a quadruped robot: A) When the robot is statically stable and is standing on all four limbs; B) When the robot has one lifted limb and is statically stable; C) When the robot has one lifted limb and is statically unstable

However, with the same center of mass placement, if limb A is lifted, as shown in Figure 1.C, the robot will be statically unstable, since the center of mass is outside the plane of triangle BCD, which could cause it to fall toward the lifted limb.

Thus, for the robot to remain statically stable during movement, its center of mass must always be within the plane formed by at least three limbs. This problem can be addressed in various ways, so a review of existing methods is necessary.

Therefore, the goal of this study is to develop a software algorithm to enhance the static stability during the movement of a walking robot without altering its structural configuration.

Literature review

In recent decades, numerous approaches to the stabilization of quadrupeds have been proposed, which can be divided into structural and algorithmic methods. Structural methods involve modifications to the physical design of the robot, such as adding balancing tails, using segmented torsos, or incorporating elastic elements into the limbs to dampen oscillations [12]. Algorithmic methods, on the other hand, involve creating software solutions that allow the robot's movements to be adapted to ensure its stability.

Among the algorithmic methods of stabilization, significant attention should be paid to the works [13-14], in which the trajectory optimization method is implemented. The general essence of this method lies in calculating the parameters of future movement to find the most optimal trajectory that provides the highest stability against falling for the robot. However, this method is more closely related to dynamic stabilization methods.

In the work [13], the authors focused on optimizing the stability and speed of the robot's movement while implementing a limb trajectory planning method. Two algorithms were implemented for this: optimization of stability margin and optimization of movement speed. The proposed algorithms were tested on a software model in the V-REP environment. According to the simulation results, the algorithms increased the average walking speed by 32.8% and 81.6%, respectively, without losing stability. However, the drawbacks include significant computational power consumption, low efficiency on uneven surfaces, and the absence of active adaptation.

But in the work [14], by using contact sensors, automatic correction of the robot's limb positions was achieved to adapt to possible external influences. The testing of the obtained algorithms was conducted on both software and physical models, showing high adaptability to terrain and stability of movement with a surface tilt angle of up to 15 degrees. However, the drawback is the need for significant computational power for the continuous adaptation of the robot to changes in the external environment, which is not accessible for small-sized walking robots.

An example of natural stabilization implementation is demonstrated in the work [15]. The essence of the method proposed in this work lies in responding to external disturbances acting on the robot in a manner similar to a spring-damper system. This allows for robot stabilization that takes a more natural form, where, in real-time, the robot will attempt to keep its center of mass at the center of the stability polygon formed by its limbs at any given time. The drawbacks of this method include limited system response time, high sensor accuracy requirements, and the need for substantial computational power, which is critically important for ensuring the autonomy of such systems.

Among the structural stabilization methods, notable developments are presented in works [16-17]. These works describe modifications to existing robot designs and the development of a custom, modernized robot design, which, by its working principle, offers greater stability than typical designs. In work [16], a robot design with a tail-like inertial mass attached to the body of the robot via a movable mechanism is shown. This design allows for stabilization of the robot's body during movement by deflecting the tail in the necessary direction. However, the drawbacks include additional power consumption for the operation of the tail mechanism and the need for readjustment of the regulator coefficients for any mass and size characteristics of the robot.

In work [17], a metamorphic quadruped robot design with a movable structure, named MetaRobot I, is demonstrated. This robot can rotate its torso in several sections, which, similar to a spine, allows for a more even distribution of load across the limbs, thereby increasing the robot's stability margin. However, the drawbacks, similar to the tail-like inertial mass, are additional energy consumption for the movement of the elements and the difficulty of easily modifying already completed robot designs.

Despite the high potential application of the discussed methods, they have significant drawbacks that often limit their practical use. Further research should focus on achieving good stability performance with efficiency in energy consumption and computational resources.

Proposed stabilization algorithm

After analyzing the existing advantages and disadvantages of the applied methods for stabilizing walking robots, it was decided to develop a custom stabilization method. The foundation of the algorithm lies in understanding the causes of robot instability. If, when lifting a limb, the robot loses stability due to the loss of one of the support points, it is necessary to shift the center of mass to the center of the newly formed stability polygon. This means shifting away from the lifted limb toward the opposite diagonal, as shown in Figure 2.

Such a shifting method can be performed before lifting any of the limbs, maintaining the robot's stability against falls when lifting any limb. At the same time, the displacement distance for each limb can be individually adjusted to reduce the total time spent on shifting the robot. The proposed method was programmatically implemented in Java and tested for functionality on the prototype of the quadruped robot, as shown in Figure 3.

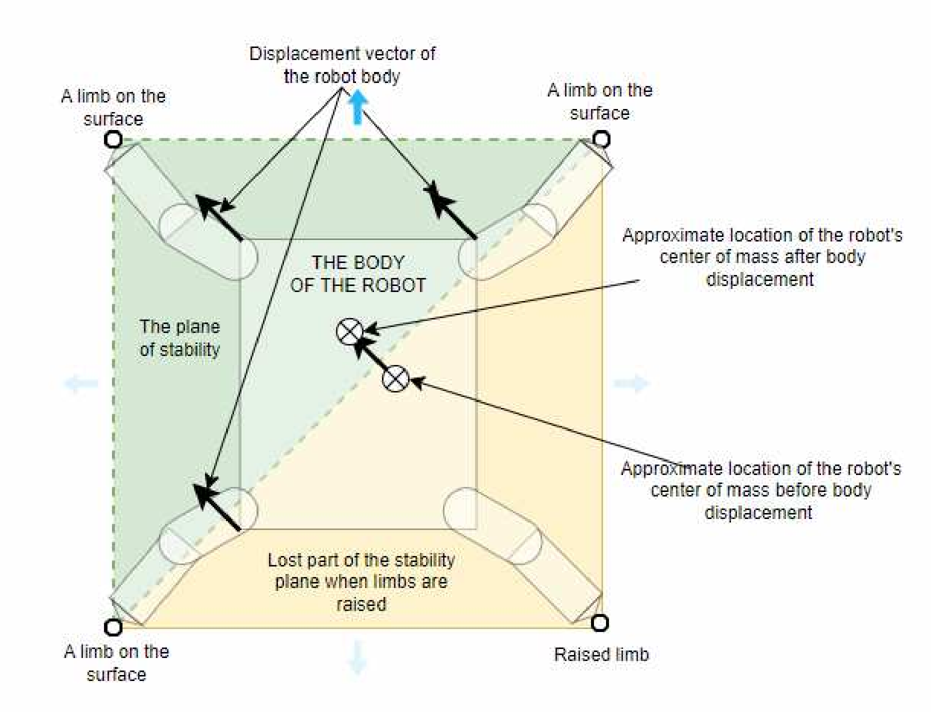

Fig. 2. Explanation of the proposed method for stabilizing the body of a quadruped robot when lifting one of its limbs

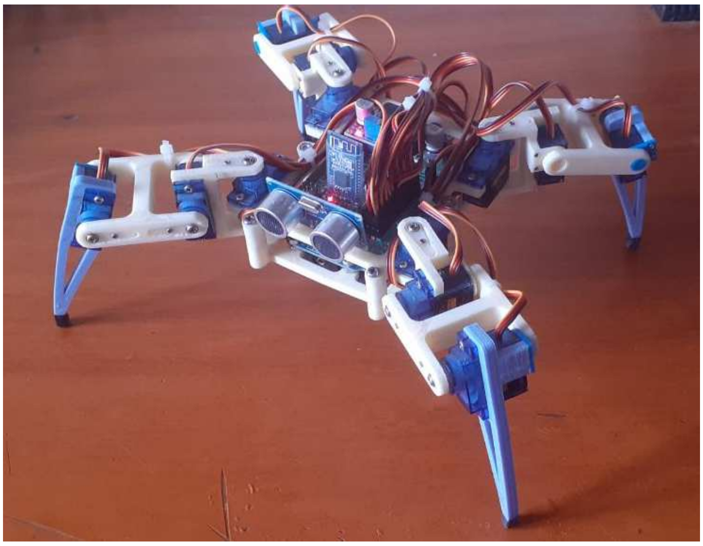

Fig. 3. Prototype of the quadruped robot

As shown in Figure 4A, before the implementation of the proposed method, when lifting a limb, the robot falls onto it because its center of mass is not within the stability triangle. Upon implementing the proposed algorithm, the robot shifts by a specified distance from the lifted limb and lifts it without falling onto it, as shown in Figure 4B.

For effective testing of the stabilization method, a trial algorithm was developed, which includes a sequence of movements for implementing straight-line motion.

Proposed trial algorithm:

1. Programmatically determine the displacement corresponding to the minimum stability margin for the studied construction after lifting one of the limbs.
2. Accept the obtained displacement value as a reference and verify it when lifting other limbs, thus identifying structural deficiencies and asymmetries.
3. If stability is lost when lifting at least one of the limbs, increase the displacement and, accordingly, the stability margin. Repeat step 2.
4. Perform 10 steps with each limb while moving forward.

5. Perform 10 steps with each limb while moving backward.

Additionally, a study was conducted on the effect of shifting the center of mass relative to the uncorrected position (conditional stability margin) on the time required for the robot to cover a distance of 1 meter. The graph of the studied dependency is shown in Figure 5.

As seen from the obtained graph, increasing the displacement of the robot's center of mass results in a greater time expenditure to cover a one-meter distance.

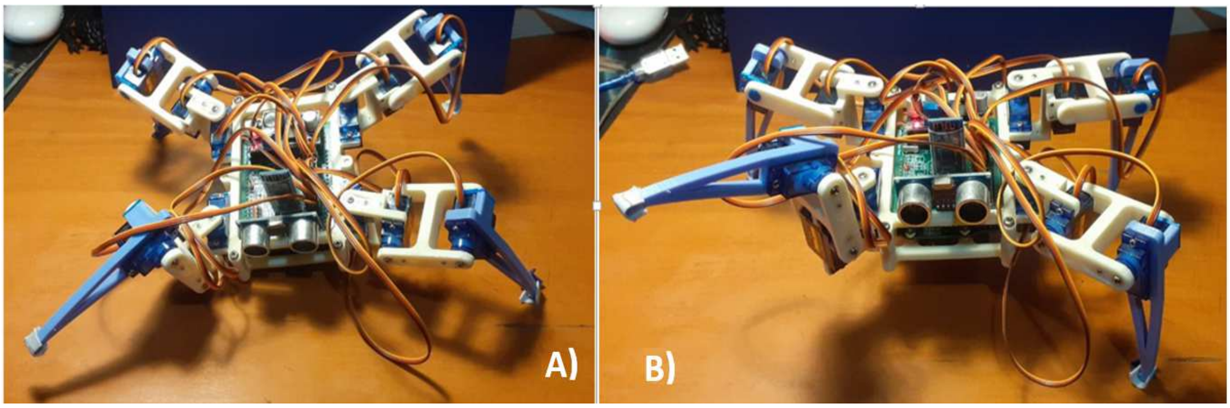

Fig. 4 Testing the stabilization method of the robot: A) model of the quadruped robot before implementing the proposed stabilization method, falling onto the lifted limb; B) model of the quadruped robot after implementing the proposed stabilization method, no longer falling onto the lifted limb

As seen from the obtained graph, increasing the displacement of the robot's center of mass results in a greater time expenditure to cover a one-meter distance. Therefore, it is crucial to select an optimal displacement value that ensures both sufficient stability margin and minimal delay in executing the primary movement. After conducting the study, the algorithm was modified by selecting the minimum stability displacement for each limb individually.

Thus, the obtained results demonstrate the functionality and efficiency of the proposed software algorithm for enhancing static stability with only a slight reduction in the quadruped robot's movement speed. Unlike complex adaptive algorithms, this method does not overload the computational core with additional calculations and, consequently, does not impact energy consumption or the robot's autonomy. The proposed algorithm is universal and can be scaled to similar designs by integrating it into control algorithms with a predefined displacement value that meets the required stability margin.

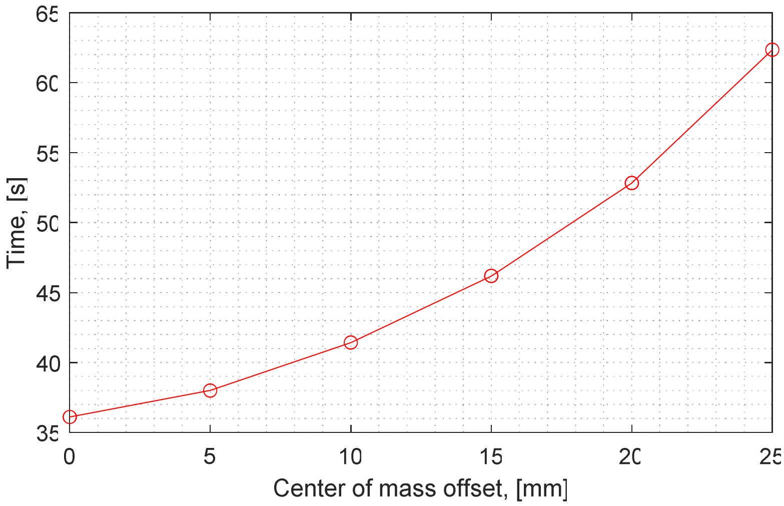

Fig. 5. Graph of the dependence of the time taken to cover a distance of one meter on the robot's center of mass displacement parameter

Future work will focus on studying the impact of different movement speeds on structural stability, performing complex maneuvers, dynamically changing mass and dimensions of various structural parts (such as dirt accumulation or limb wear/damage affecting its length or mass), and modifying the algorithm into a pseudo-adaptive version with minimal computational load. Additionally, it is necessary to model cases of power loss during the swing phase of a limb to assess its effect on overall system stability and explore the possibility of resuming movement after power restoration."

Conclusion

This study reviewed the problem of maintaining a stable position for a quadruped robot during straight-line movement when lifting one of its limbs. An overview of the latest stabilization methods for quadruped robots was conducted, highlighting the relevance of this research topic.

The most commonly used quadruped stabilization methods in recent years were examined, which can be broadly categorized into structural and algorithmic approaches. Structural methods provide a relatively simple solution for ensuring stable robot movement, but they lack universality, requiring either additional mechanisms or a unique robot design. Algorithmic methods are more versatile but are often limited by computational power, power supply constraints, and the absence of necessary sensors. Evaluating the drawbacks of the reviewed methods led to the proposal of a stabilization method that does not require structural modifications while also minimizing the computational load on the robot's control system.

The essence of the method involves shifting the center of mass from its initial position into the support triangle formed by the robot's legs during the swing phase. This is achieved by shifting the support points of the limbs away from the lifted limb.

The proposed method was implemented in the movement control algorithm of a quadruped robot that had stability issues when lifting a limb during movement. To effectively test the method, a trial algorithm was developed, incorporating a sequence of movements for straight-line locomotion. Experimental studies confirmed that after implementing the stabilization method, the quadruped remained stable during straight-line movement. Additionally, an analysis was conducted on the impact of center-of-mass displacement on the time required to traverse a fixed distance. The results highlighted the need for optimizing displacement values for each limb based on the complexity of tasks performed.

Unlike previously reviewed stabilization algorithms, the proposed algorithm does not burden the computational core, does not require additional structural elements, and can be adapted to various quadruped designs. Future research will focus on testing the proposed algorithm in conditions involving challenging terrains, power loss scenarios, and changes in the mass or dimensions of structural elements.

Література

[1] В. Б. Струтинський, А. М. Гурій, *Наземні роботизовані комплекси: монографія*. Житомир, Україна: ПП «Рута», 2023.

[2] О. Купріненко, "Визначення можливостей застосування наземних роботизов'аних комплексів для вирішення завдань інженерної підтримки", *Scientific Collection «InterConf»*, (162), 2023, pp. 290–295. [Електронний ресурс]. Доступно: https://archive.interconf.center/index.php/conference-proceeding/article/view/4072

[3] І. Платов, О. Павловський, «Вертикальний рух малогабаритних крокуючих роботів. огляд стану проблеми», *Bull. Kyiv Polytech. Inst. Ser. Instrum. Mak.*, вип. 65(1), с. 96–103, 2023. DOI: 10.20535/1970.65(1).2023.283444

[4] O. Pavlovskyi, "Walking Small Unmanned Vehicles", in *Advanced System Development Technologies II. Studies in Systems, Decision and Control*, M. Bezuglyi, N. Bouraou, V. Mykytenko, G. Tymchyk, A. Zaporozhets, Eds. vol. 581, 2025. Springer, Cham. DOI: 10.1007/978-3-031-82035-9_11

[5] Atlas® and beyond: the world's most dynamic robots [Online]. Available: https://bostondynamics.com/atlas/

[6] Spot® - The Agile Mobile Robot [Online]. Available: https://bostondynamics.com/products/spot/

[7] Meet ANYmal your new inspector [Online]. Available: https://www.anybotics.com/robotics/anymal/

[8] Beaber, Sameh & Abdelhamid, Ahmed Y. & Elyazed, Maged. (2020). "Road Following for Hexapod Mobile Robot with Adaptive Tripod Gait", in *12th International Conference on Electrical Engineering (ICEENG),* pp. 454-460. DOI: 10.1109/ICEENG45378.2020.9171748.

[9] Andrew Pullin, & N. Kohut, & D. Zarrouk, & R. Fearing, (2012). "Dynamic turning of 13 cm robot comparing tail and differential drive". *Proceedings - IEEE International Conference on Robotics and Automation*, 2012, pp. 5086-5093. DOI: 10.1109/ICRA.2012.6225261.

[10] Yue Gao, Bo Su, Lei Jiang, Feng Gao (2023), Multi-legged robots: progress and challenges, *National Science Review*, vol. 10, is. 5, May 2023, nwac214, DOI: 10.1093/nsr/nwac214

[11] Freyr Hardarson, *Stability analysis and synthesis of statically balanced walking for quadruped robots.* Monograph. Universitetsservice US AB, 2002.

[12] K. Miki and K. Tsujita, "A study of the effect of structural damping on gait stability in quadrupedal locomotion using a musculoskeletal robot," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vilamoura-Algarve, Portugal, 2012, pp. 1976-1981, DOI: 10.1109/IROS.2012.6386256.

[13] Y. Wang, L. Ye, X. Wang, N. Cheng, H. Liu and B. Liang, "A Static Gait Generation for Quadruped

Robots with Optimized Walking Speed," in *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Toronto, ON, Canada, 2020, pp. 1899-1906,
DOI: 10.1109/SMC42975.2020.9282997

[14] Q. Hao, Z. Wang, J. Wang, G. Chen, "Stability-Guaranteed and High Terrain Adaptability Static Gait for Quadruped Robots", *Sensors*, vol. 20, no. 17, 4911, pp. 1-26, 2020.
DOI: 10.3390/s20174911

[15] G. Xin, W. Wolfslag, H.-C. Lin, C. Tiseo and M. Mistry, "An Optimization-Based Locomotion Controller for Quadruped Robots Leveraging Cartesian Impedance Control", *Front. Robot. AI* 7:48, 2020. DOI: 10.3389/frobt.2020.00048

[16] A. Mutka, M. Orsag and Z. Kovacic, "Stabilizing a quadruped robot locomotion using a two degree of freedom tail," in *21st Mediterranean Conference on Control and Automation, Platanias*, Greece, 2013, pp. 1336-1342.
DOI: 10.1109/MED.2013.6608893

[17] C. Zhang, C. Zhang, J. S. Dai, and P. Qi, "Stability Margin of a Metamorphic Quadruped Robot With a Twisting Trunk", *J. Mechanisms and Robotics*. December 2019; vol. 11(6), pp. 1-13, 2019. DOI: 10.1115/1.4044600

УДК 007.52+62-523.8

С. В. Співак, О. М. Павловський
Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна

ПРОГРАМНІ АЛГОРИТМИ ПІДВИЩЕННЯ СТІЙКОСТІ ПРИ ПЕРЕМІЩЕННІ КРОКУЮЧОГО РОБОТА

В роботі розроблено і випробувано метод підвищення стійкості крокуючого робота квадропода під час прямолінійного руху за рахунок модернізації програмних алгоритмів керування. Такі роботи знайшли широке застосування у військовій сфері, рятувальних операціях, будівництві, промисловості, дослідженнях та навіть у повсякденному житті. Проблема забезпечення стійкості під час руху актуальна для всіх типів крокуючих роботів, проте особливо гостро вона постає саме у біподах та квадроподах через конструктивні особливості та режими функціонування таких робототехнічних систем.

Досліджуючи питання стійкості робота квадропода, було визначено, що стійкість можна умовно поділити на динамічну та статичну, де динамічна стійкість – це утримування стійкості при динамічному русі тіла, а статична – при його статичному положенні. Для квадропода частою проблемою є падіння на підняту кінцівку, яка є проблемою статичної стійкості, оскільки це пов'язано з втратою однієї опорної точки при відсутності переміщення тіла.

У статті було проведено огляд досліджень останніх років, зроблено висновок, що запропоновані методи підвищення стійкості крокуючих роботів умовно можна розділити на конструктивні та алгоритмічні. Конструктивні методи є розповсюдженим рішенням для стабілізації робота, але вони не є універсальними і потребують зміни конструкції. Алгоритмічні методи є більш універсальними, але їх використання часто обмежується обчислювальною потужністю робота, параметрами живлення та відсутністю необхідних сенсорів. Оцінивши недоліки розглянутих методів, було запропоновано метод стабілізації, що не потребує конструктивних модифікацій робота та не вимагає від нього великої розрахункової потужності.

Сутність методу полягає у зміщенні центру мас від початкового положення у межах опорного трикутника, який утворено кінцівками в фазі переносу. Це досягається шляхом зміщення точок опори кінцівок у бік піднятої. Запропонований метод було імплементовано в алгоритм керування рухом робота та перевірено на моделі робота квадропода, який мав проблему втрати стійкості в момент переносу кінцівки в нове положення. Було сформовано алгоритм випробувань, що включає послідовність рухів для реалізації прямолінійного переміщення, а також поведено дослідження впливу параметру зміщення центру маси робота на час проходження ділянки фіксованої довжини. Проведені дослідження показали працездатність та ефективність запропонованого методу.

Ключові слова: наземні роботизовані комплекси (НРК); програмний алгоритм; крокуючий робот; квадропод; стійкість; підвищення стійкості; програмування; центр масс; алгоритмічні та конструктивні методи; мікропроцесорна система.

Надійшла до редакції
03 квітня 2025 року

Рецензовано
09 травня 2025 року