UDC 621.8

Overview of suspension systems for mobile wheeled robots

Yaroslav Korobenko[1], *Dmytro Mishchuk*[2], *Maksym Balaka*[3]

[1,2,3]Kyiv National University of Construction and Architecture
31, Air Force Ave., Kyiv, Ukraine, 03037
[1]korobenko_yv@knuba.edu.ua, https://orcid.org/0009-0002-3130-7198,
[2]mischuk.do@knuba.edu.ua, https://orcid.org/0000-0002-8263-9400,
[3]balaka.mm@knuba.edu.ua, https://orcid.org/0000-0003-4142-9703.

Received: 25.09.2024; Accepted: 25.10.2024
https://doi.org/10.32347/gbdmm.2024.104.0301

Abstract. A common type of transport system used in robotics is a wheeled platform with at least one drive axle and some form of suspension for each wheel. Autonomous navigation at high speed over rough terrain is a challenging and relevant task for wheeled robots. To achieve mobility on terrain, a wheeled robot must adapt and respond quickly. The suspension systems of mobile wheeled robots play a key role in ensuring their stability, maneuverability, and overall efficiency. This article presents a comprehensive overview of the different types of suspensions used in modern mobile wheeled robots. The main designs of passive and active, rigid and elastic suspensions are considered, as well as their features, advantages and disadvantages.

As a result of the analysis, it was found that the optimal choice of suspension system depends on the specific operating conditions of the robot and the tasks set. For example, for robots operating in difficult terrain, suspensions with high damping are more suitable, while for robots performing precise maneuvers on a flat surface, suspension stiffness is more important.

The article may be useful for engineers, researchers, and developers of robotic systems who seek to improve the designs of mobile wheeled robots and increase their efficiency and reliability. The conclusions and recommendations presented in the article can contribute to the development of new approaches to suspension design and optimization of existing solutions in the field of mobile robotics.

Keywords: mobile robot, wheel suspension, wheeled robot, analysis, robotic systems.

INTRODUCTION

Mobile robotics has recently undergone rapid development. In particular, mobile wheeled robotic platforms are being actively developed, which can be used for various technological processes in construction. An important part of any wheeled vehicle is its suspension system. The type of suspension system significantly affects the dynamics of a mobile platform that will be moved by a wheeled vehicle. The correct choice of suspension type allows for the effective use of robotic mobile platforms with their high efficiency.

Today, there are a lot number of different types of wheel suspension systems, from simple and cheap to complex and expensive.

This paper presents a review and analysis of existing suspension systems for wheeled robot systems. The results of this article will be useful for robot developers who will be able to choose an effective suspension system for their own development.

PURPOSE OF THE WORK

The main purpose this works is carry out an inspection and analysis of the suspension systems of the mobile robots' wheel drives.

PRESENTATION OF THE MAIN MATERIAL

The choice of the type of suspension system for a wheeled robot depends on many factors, such as the type of surface, the load on the wheel, the maneuverability and stability of the robot. Depending on these different factors, there are several types of passive and active suspensions that are often used in wheeled vehicles.

Passive suspensions do not contain external control systems. At the same time, there are designs that can change their characteristics due to the action of the external environment. Active suspensions contain an external control system with which the suspension parameters are changed during their operation [1].

Rigid passive suspension is the simplest type of suspension of the running wheel. Such suspensions have a simple design and are cheap to manufacture. Their disadvantage is the lack of ensuring constant adhesion of the wheel to the supporting surface when moving the vehicle on an uneven surface. Such suspensions are actively used in robotic warehouse maintenance systems, cleaning robots, advertising works, as well as in military works. For example, the autonomous mobile warehouse robot Proteus (Fig. 1), used in Amazon warehouses has a rigid, unsteering wheel suspension.

Fig. 1. Wheel robot Proteus

Proteus is intended for moving large carts around warehouses. At the same time, the surface on which this robot moves must be solid and flat, usually a concrete floor.

The weight of such a robot can reach up to 365 kg, and the weight of cargo that can be moved by the robot can reach 400 kg [2].

The Proteus robot wheel suspension is typical and contains many variations. On Fig. 2 shows a diagram of a similar suspension based on a patent CN209600680U [3], where shown: *1* – base of the robot platform, *2* – suspension frame, *3* – wheel, *4* – drive module. In such suspension designs, the suspension module can be attached to the robot base via a spring-loaded mounting system (see Fig. 3).

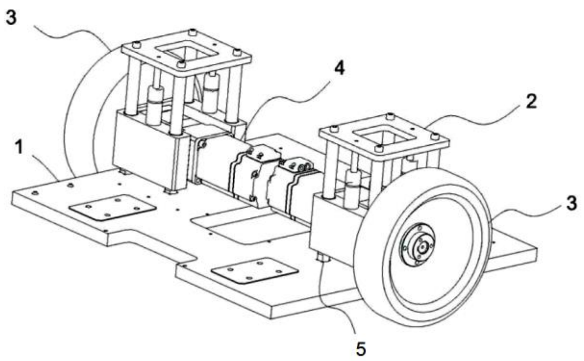


Fig. 2. Patent CN209600680U Transport vehicle: *1* – frame; *2* – trailing link; *3* – wheel; *4* – gear

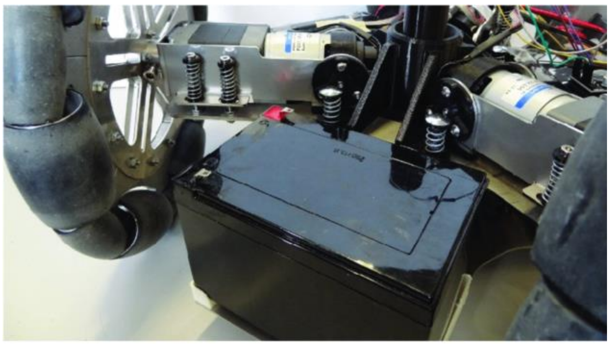


Fig. 3. Spring-loaded attachment of the wheel drive to the robot frame

The Sparrow mobile robotic system (see Fig. 4) for inspections of marine vessel hulls contains wheels with magnets and a rigid suspension [4].

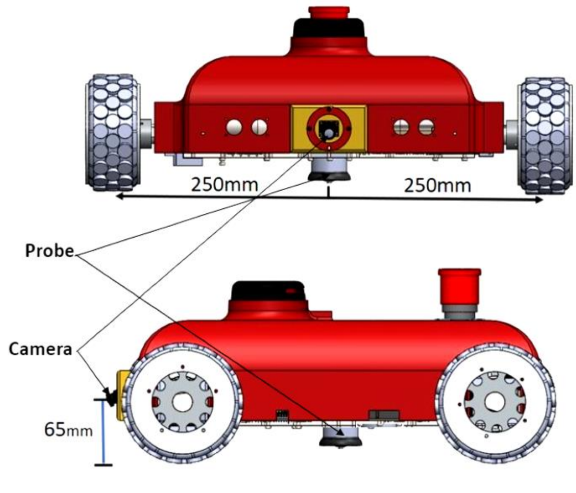


Fig. 4. Sparrow A Magnetic Climbing Robot for Autonomous Thickness Measurement in Ship Hull Maintenance [4]

In the Sparrow robot, each of the four wheels has its own drive mechanism. The Sparrow wheel sub-suspension is rigid and is made in the form of a cantilever mounting of the gearbox with the wheel to the main frame. This is the simplest 4-wheeled mobile platform that does not have a differential mechanism. All wheels have a fixed orientation relative to the chassis and do not rotate. The wheels on one side of the chassis are driven together, and the direction of movement of the robot can be changed by controlling the movement of the wheels on one side. This is realized due to the difference in the driving forces of the wheels from different sides of the chassis.

UGV Sirko-S1 (Fig. 5) is a universal ground robot created by experts from the Brave1 defense cluster. The Sirko-S1 is designed to assist military personnel in transporting cargo, evacuating the wounded, and reconnaissance of enemy positions [5]. This robot also uses a rigid wheel suspension scheme.

Fig. 5. Sirco wheeled drone

Sirko-S1 has four electric motor-wheels from a hoverboard, which are attached to the frame with their cantilever axles. The robot's wheels are pneumatic, which allows you to adjust the height of the ground clearance and driving dynamics.

The botANNIC robot (Fig. 6) also has a rigid suspension scheme and is an alternative to the Sirko-S1 robot design. In contrast to Sirko-S1, in botANNIC the drive motors are mounted on the frame, and the wheels are driven through chain gears located on both sides of the platform [6]. BotANIC has 2 drive electric motors - BM1418ZXF with 500 W and a maximum speed of 2800 min-1.

Fig. 6. Robot botANNIC

In botanic the torque from the electric motors is transmitted to the wheel rotation axis using chain gears. This mobile robotic platform is equipped with 6R 145/70 wheels from an ATV. The botANIC platform is powered by a lithium-ion battery with a nominal voltage of 48 V and a capacity of 40 A·h. The digital equipment of the platform includes an Nvidia Jetson laptop, an Arduino UNO board, four ultrasonic distance sensors and their control boards, an RC receiver for controlling the platform and sending images from the video camera to the remote control, a Wi-Fi router for wirelessly transmitting images from the ZED 2i stereo camera to a personal computer server, as well as for controlling the motors of the mobile robotic platform using a personal computer.

In rigid suspension also designs, drive wheel mechanisms can be used, which are shown in Fig. 7. The wheel in Fig. 7, a has a cantilever shaft that can be rigidly attached to the housing, and the wheel in Fig. 7, b is equipped with a spring balancer [7].

The considered examples of robots show that straight axles are the simplest form of rigid passive suspension, in which the wheels are attached directly to the axle that connects them to the chassis. Straight axles provide minimal complexity and cost, but they make it difficult for the machine to operate accurately on uneven surfaces. For tasks where high accuracy is not required, but low cost equipment is often suitable for use.

The advantages of rigid suspensions are:
• simplicity of construction;
• high strength;
• low cost of production and maintenance.

ISSN(online)2709-6149. Mining, constructional, road and melioration machines, 104, 2024, 28-37

Disadvantages:
- poor adaptation to uneven surfaces;
- poor comfort - vibrations and shocks from the surface are transmitted directly to the chassis, which can affect stability and control.

a

b

Fig. 7. Mecanum Wheel Module: *a* – motor wheel with output shaft; *b* – motor wheel with elastic suspension of the output shaft

To compensate for surface irregularities when using rigid suspensions, robot designs with a hinged and articulated frame are used [8]. For example, the Ironclad robot (Fig. 8) is a four-wheeled robot that has rigid wheel suspension [9]. The articulated frame of the robot partially compensates for uneven road surfaces. Each of the Ironclad robot's wheels is attached to final drives, which in turn are attached to the main frame. The robot's frame is articulated and allows rotation along the vertical and horizontal axes. This increases the grip of the front and rear wheels of the robot with the road surface on uneven surfaces. The wheel drive can be synchronous or independent. The hinge point of the front and rear frames is a weak point in this design, but this structure is much cheaper to work with than a design with active suspension.

Fig. 8. Robot Ironclad

The Lunar Exploration Rover (RATLER) is a four-wheeled vehicle with onboard control and electric drive, which is equipped with a battery (Fig. 9).

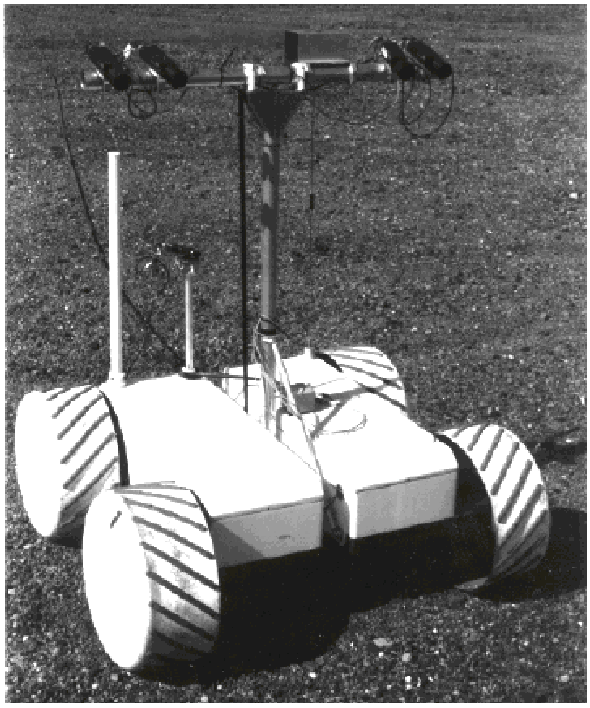


Fig. 9. Robot RATLER

The length and width of the RATLER robot frame are about 1.2 m, and the wheel diameters are 50 cm. The robot chassis is divided transversely into two parts, which are connected by a passive central hinge [10].

Spring-loaded shock absorbers are used to compensate for shocks and vibrations. This improves the handling and stability of the machine, but makes their implementation more difficult. The AMBOT 4400GRP robot (Fig. 10) is standardly equipped with 19-inch tires with a ground clearance of 20.32 cm and independent wheel travel. The robot is driven by an electric motor, independent for each wheel, and the battery capacity is up to 5.4 kWh with an operating time of up to 8 hours. This robot uses a lever-type elastic shock-absorbing wheel suspension. This allows the robot to increase its speed to 20 km/h on uneven terrain, while ensuring smooth and stable movement [11].

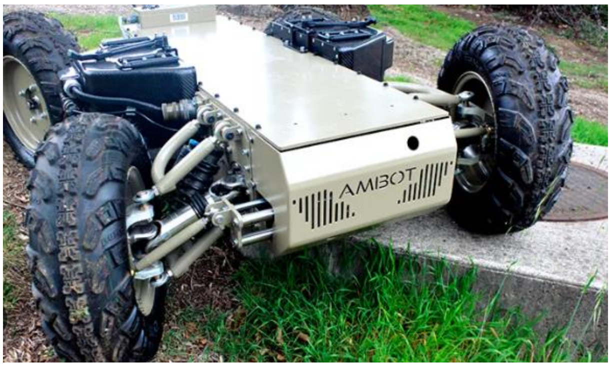


Fig. 10. Robot AMBOT 4400GRP

The suspension design of the AMBOT 4400GRP robot is essentially a double-lever system. Such systems are used to improve stability and maneuverability, especially on uneven surfaces. Double-lever systems can be used for both central and distributed drive (Fig. 11). Such suspensions are complex in design, but they provide a high level of control of wheel adhesion to the road surface.

Parallelogram arms consist of two identical arms (upper and lower) that connect the wheel to the chassis, ensuring independent movement of each wheel and better adaptation to irregularities [12-14].

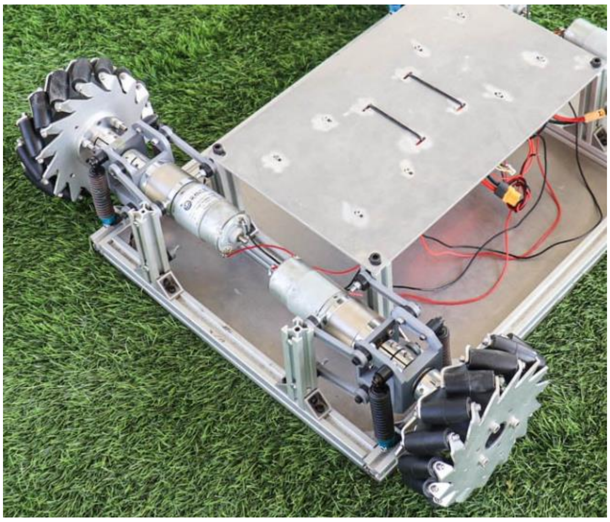


Fig. 11. Suspension with parallelogram levers (a type of double-lever system)

The MacPherson strut suspension has fewer moving parts, while also providing independent movement of each wheel. MacPherson is used on both the front and rear wheels. MacPherson is more compact than the double-lever and has a large distance between the support nodes, which allows it to compensate for large differences in road roughness [15].

Fig. 12. MacPherson suspension

Mars Rovers use complex multi-link suspensions (see Fig. 13), such as Rocker-Bogie, which allow them to overcome significant surface irregularities [16].

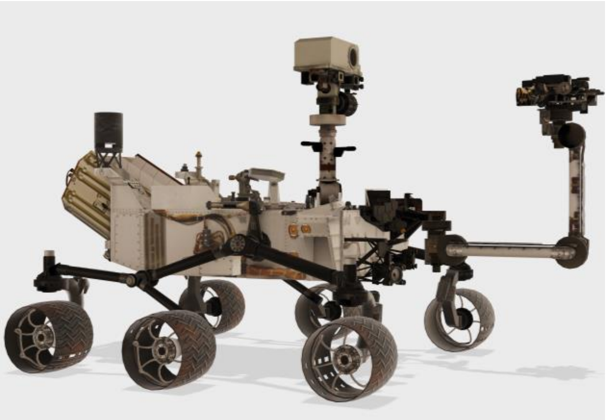


Fig. 13. Curiosity Rover

Rocker-Bogie is a “rocker-bogie” suspension system that was developed in 1988 for use on NASA’s Sojourner Mars rover [5]. The system consists of two symmetrical lever pairs located on opposite sides of the robot body, each of which contains two working parts – a rocker and a bogie. Since the right and left suspension arms are independent of each other, the chassis can overcome various obstacles while ensuring constant contact of all wheels with the surface.

The torsion bars use twisted rods (torsions) that function as springs (Fig. 14). When the wheel is moving, it twists the rod, thereby providing shock absorption. Torsion bars are more compact than traditional springs and can also be adjusted for different conditions by adjusting the torsional force of the rods.

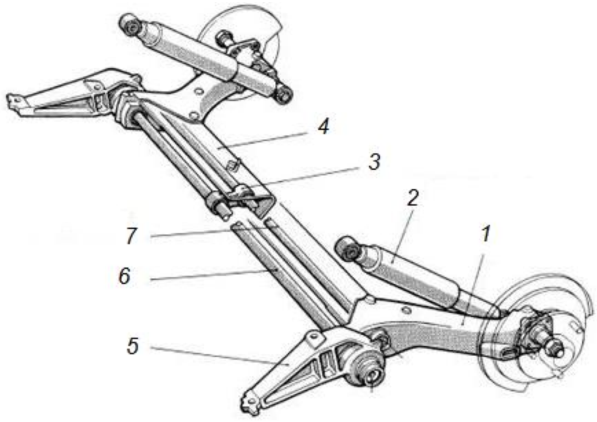
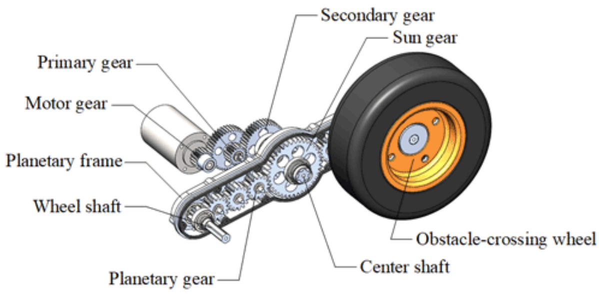


Fig. 14. The torsion bar rear axle:
1 – trailing link; *2* – shockabsorber; *3* – connector; *4* – cross member; *5* – mounting bracket; *6* – front torsion bar; *7* – rear torsion bar

An interesting system is a six-wheeled robot explorer with an adaptive lifting mechanism for exploring planets in difficult terrain (Fig. 5).

a



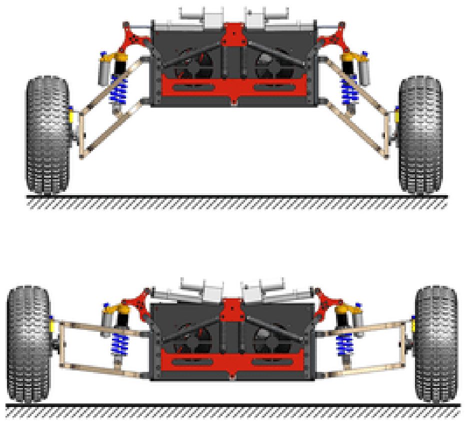
b

Fig. 15. General view of the movable carriage (*a*) and the wheel swing mechanism with drive (*b*)

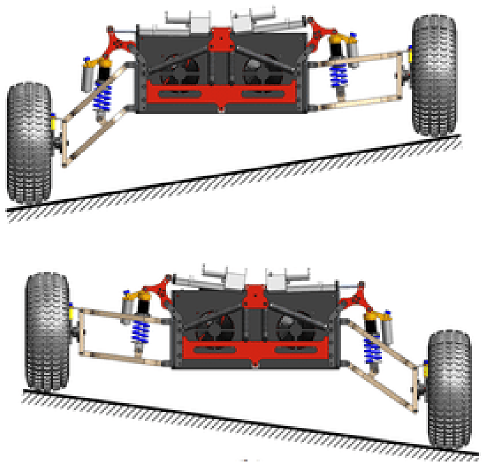
The robot's wheel suspension consists of a rocking mechanism and an articulated frame with a trolley. With the three-rocker structure, the robot can adapt to difficult terrain because the six wheels ensure contact with the supporting surface during movement. This improves the stability of the robot. When the robot moves on a flat surface, it moves by rotating the wheels. When the robot encounters obstacles during movement, the front obstacle-surmounting wheels hold the obstacle, and the rockers on both sides rotate with mechanical adaptability to make the robot rise and cross the obstacle like crab legs.

Active suspensions use external control to change the suspension parameters. For example, electromagnetic, hydraulic, and pneumatic systems are used to actively control the height and stiffness of the suspension. This allows the robot to adapt to different surfaces (see Fig.

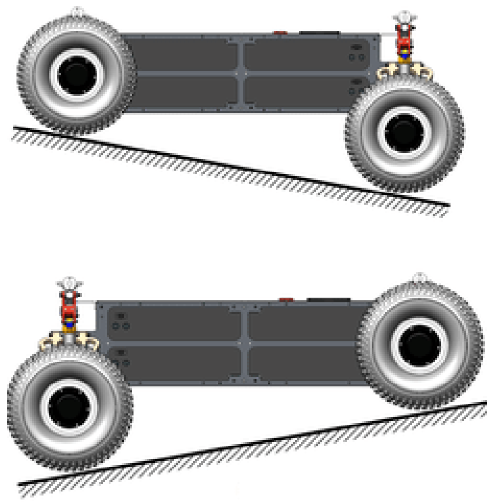
16), but such systems are complex and expensive. Such suspension systems have a fast response and high accuracy, but require significant energy consumption [15].



a



b



c

Fig. 16. Schemes of using a wheel drive with active articulated-lever suspension: *a* – change the COM height, *b* – change the roll angle, *c* – change the pitch angle

NSK has developed a pantograph suspension for wheel-driven service robots. The robot has a low-profile body and a combination of a pendulum structure for the support wheels and a pantograph suspension for the drive wheels (Fig. 17).

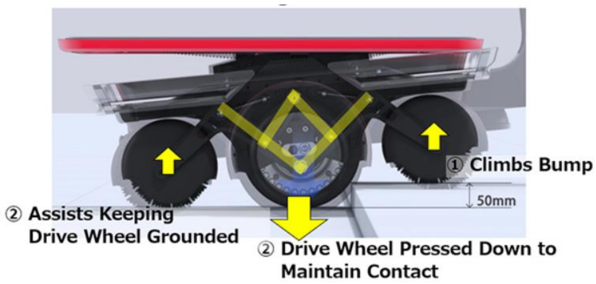


Fig. 17. Pantograph wheel suspension

The NSK pantograph suspension system (see Fig. 17) ensures full wheel contact with the surface. Using this suspension system device, the robot is able to overcome uneven road surfaces, uneven surfaces or height differences of up to 5 cm. The NSK pendulum design maintains the platform orientation (keeps the top surface stable and level) when ascending and descending slopes up to 10° and reduces vibration. The suspension mechanism also reduces the impact of the robot's acceleration and deceleration on the objects being transported, allowing delicate objects to be transported.

Mobile robots with active suspensions can generally change their structure and configuration in various ways to change the center of mass and avoid tipping over when traversing difficult terrain [1, 2]. The Sample Return Rover [16], Scarab [17], ATHLETE [18], Tristar [18], Sherpa [17], Workpartner [15], Azimut [14], TRREx [15, 16] i Hylos [17] are such examples. The Zheng rover design proposes a suspension with a modified active swing suspension that uses the wheel and wheel support cantilever arms to change the robot configuration [18] (see Fig. 18). The mobile robot in Fig. 18 can actively reconfigure itself using the levers of the left and right active suspensions. Using linear actuators, the robot can change the height of each of its sides.

ISSN(online)2709-6149. Mining, constructional, road and melioration machines, 104, 2024, 28-37

Fig. 18. Rover designs Zheng

In this way, the review of wheel suspension systems for robots gives grounds to claim that the design of such mechanisms significantly depends on the purpose and scope of the robot, the cost of its development and production.

Non-adjustable and rigid suspensions are best suited for flat surfaces. However, there are wheel systems in which such suspensions are used for work on rough terrain.

Spring suspensions are used to absorb shocks and vibrations. Such systems are usually combined with shock absorbers to reduce vibrations. Spring suspensions are quite easy to integrate into the robot design, but they are not effective with large irregularities, which can lead to vibrations. Springs and shock absorbers lose their properties over time and require replacement [19].

Torsion bars use twisted rods (torsions) that function like springs, but are more compact. When driving, the wheel causes the rod to twist, providing shock absorption. Like springs, they can lose their properties over time.

Air suspension uses air bags or cylinders to cushion and adjust the height of the chassis.

Hydraulic suspension uses pressurized fluids to adjust the height and cushion. However, hydraulic systems are complex to design and maintain and have a high manufacturing cost.

Electromagnetic suspensions use magnetic fields to provide shock absorption and height control. Such suspensions require a significant amount of energy to operate. However, these suspension systems can instantly adjust height and stiffness.

CONCLUSIONS

Different types of suspension have their own unique advantages and disadvantages. Choosing the optimal suspension system depends on the specific requirements and conditions.

Choosing a suspension depends on:

1. the task that the robot performs and the environment where the robot works;
2. the development and maintenance budget;
3. the weight and size of the robot, as large and heavy robots require stronger and more complex suspension systems;
4. the need for the ability to adapt to rapidly changing conditions.

Suspension springs are important for proper handling of cars traveling at speeds over 8 m/s. At a lower speed than specified, the springs can reduce the robot's mobility because they can change the amount of pressure each wheel has on the ground.

A typical 4-wheel vehicle with independent suspension appears to be touching the ground with equal force on all 4 wheels, but the wheels moving over bumps are actually supporting more weight, and this can lead to reduced traction for light vehicles. A better solution at low speeds would be to raise some of the wheels above the bumps relative to the chassis, thus greatly reducing the changes in weight distribution. This is a characteristic of a wishbone suspension.

The pressure exerted on the ground varies from 20 to 80 kPa for all types of vehicles. This range is so narrow because of the type of soil and materials. There are specialized vehicles designed to travel on loose snow that create an average pressure of only 5 kPa. As a rule of thumb, vehicles with low contact pressure will perform better on loose terrain (e.g. loose snow, sand, dirt), while vehicles with higher contact pressure will perform better on hard surfaces such as asphalt, hard ground, etc.

One way to increase the mobility of a mobile platform is to be able to change the position of the center of mass as needed. This can be achieved by moving a special load around the chassis or by changing the position of various elements on the platform, elements that are heavy enough to perform the task. The diameter of the wheels is another important factor in the mobility of the platform: the larger the wheel, the larger the obstacle that the vehicle can overcome. Considering a very simple platform, a wheel can overcome an obstacle such as a staircase if the height of the obstacle is less than 1/3 of the diameter of the wheel. In four-wheeled all-terrain vehicles, the height of the obstacle can be up to half the diameter of the wheel. There are other ways to overcome a staircase-type obstacle. For example, if a steered wheel is pushed against a vertical wall of an obstacle whose diameter is greater than half the diameter of the wheel, then, given a certain ratio between the pushing force and the load distributed on the wheel, it will rise up the vertical wall. This is one of the principles that ensure the operation of the suspension systems of a seesaw. Good mobility does not necessarily mean that all wheels are in contact with the terrain, best using mechanisms that allow all wheels to be kept on the ground. A good way to solve this problem is to use a chassis that is split transversely, the two parts connected by a passive central hinge.

REFENCES

1. **Ulsoy, A. G., Peng, H., & Çakmakci, M.** (2012). Automotive Control Systems. Cambridge: Cambridge University Press, 396. https:// doi.org/10.1017/CBO9780511844577.
2. Review: I'm Amazon's first autonomous robot. Follow me around on my typical workday (watercooler break included). (2024) https://www.aboutamazon.com/news/operations /amazon-robotics-autonomous-robot-proteus-warehouse-packages.
3. **Zhu Binneng, Ruan Zhaowu, Zhao Laijie**, Kuka robot guangdong co ltd. (2019). Transport vehicle. Patent CN209600680U.
4. **Enjikalayil Abdulkader R, Veerajagadheswar P, Htet Lin N, Kumaran S, Vishaal S. R, Mohan R. E.** (2020). Sparrow: A Magnetic Climbing Robot for Autonomous Thickness Measurement in Ship Hull Maintenan-ce. *Journal of Marine Science and Engineering*, 8(6), 469. https://doi.org/ 10.3390/jmse8060469.
5. **Shpira V.** Review: What can the new Ukrainian wheeled drone Sirco do? (2023). https://mmr.net.ua/ autoworld/war/206065.
6. **Dan Mihai**. (2012). An Overview of Wheeled Mobile Platform Systems. *Build Robots Robotics Theory (SmahingRobotics)*. July 11, 2012. https://www.smashingrobotics.com/an-overview-of-wheeled-mobile-platform-systems/
7. **Azrulhisham E.A. & Abd Wahab Dzuraidah & Mohamed Nik & Haron C.** (2008). Service loads prediction in the reliability characterization of automotive rear axle system. *Engineering Postgraduate Conference* (*EPC*), 1-7.
8. **Bruzzone L., Quaglia G.** (2012). Locomotion systems for ground mobile robots in unstructured environments. *Mech. Sci.*, 3, 49–62.
9. Review: Unmanned Ground Vehicle IRON-CLAD. (2024). https://roboneers.net/en/ iiron-clad-ugv.
10. **Bickler D. B.** (1989). Patent US4840394A. Articulated suspension system. issued 1989-06-20, assigned to NASA.
11. Official site: Wheeled Platforms http://www.ambot.com/ip-wheel.shtml.
12. **Tamer A**. (2019). Design and Development of a Novel Reconfigurable Wheeled Robot for Off-Road Applications. *Dissertation. September* 21.
13. **Song Z., Luo Z., Wei G., and Shang J.** (2021). Design and analysis of a six-wheeled companion robot with mechanical obstacle-overcoming adaptivity, *Mech. Sci*., 12, 1115–1136.https://doi.org/10.5194/ms-12-1115-2021.
14. **Zirong Luo, Jianzhong Shang, Guowu Wei, Lei Ren**. (2018). Module-based structure design of wheeled mobile robot. *Mechanical Sciences Mechanical Sciences* 9(1):103-121. https://doi.org/10.5194/ms-9-103-2018.
15. **Tarokh M., Ho H. D., Bouloubasis A.** (2013). Systematic kinematics analysis and balance control of high mobility rovers over rough terrain. *Robot. Auton. Syst*., 61, 13–24.
16. **Wilcox B. H., Litwin T., Biesiadecki J., Matthews J., Heverly M., Morrison J., Townsend J., Ahmad N., Cooper B.** (2007). ATHLETE: A cargo handling and manipulation robot for the moon. *J. Field. Robot*, 24, 421–434.
17. **Iagnemma K. D., Rzepniewski A., Dubowsky S., Pirjanian P., Huntsberger T. L., Schenker P. S.** (2000). Mobile robot kinematic reconfigurability for rough terrain. *In Sensor Fusion and Decentralized Control in Robotic Systems III. International Society for Optics and Photonics*. Boston, M.A., Ed.; SPIE: Bellingham, WA, USA, Volume 4196, 413–421.

18. Jiang Hui, Guoyan Xu, Wen Zeng, Feng Gao, and Kun Chong. (2019). Lateral Stability of a Mobile Robot Utilizing an Active Adjustable Suspension. *Applied Sciences 9*, no. 20, 4410. https://doi.org/10.3390/app9204410.
19. Mishchuk, D., Mishchuk, Y., & Kalashnikov, O. (2021). Analysis of the control system of the clear logic of the wheel robot with differential drive. *Girnichi, budivelni, Dorozhni Ta meliorativni Mashini*, (97), 12–23. https://doi.org/10.32347/gbdmm2021.97.0201.

Огляд систем підвіски мобільних колісних роботів

Ярослав Коробенко[1], *Дмитро Міщук*[2], *Максим Балака*[3]

[1,2,3] *Київський національний університет будівництва і архітектури*

Анотація. Поширеним типом транспортних систем, які використовуються в робототехніці, є колісні платформи з принаймні однією ведучою віссю та певною формою підвіски для кожного колеса. Автономна навігація з високою швидкістю по пересіченій місцевості є складною і актуальною задачею для колісних роботів. Для досягнення мобільності на місцевості, колісний робот повинен швидко адаптуватися та реагувати. Системи підвісок мобільних колісних роботів відіграють ключову роль у забезпеченні їхньої стабільності, маневреності та загальної ефективності. В цій статті представлено комплексний аналіз різних типів підвісок, які застосовуються в сучасних мобільних колісних роботах. Розглянуто основні конструкції пасивних та активних, жорстких і пружних підвісок, а також їхні особливості, переваги та недоліки.

В результаті проведеного аналізу виявлено, що оптимальний вибір системи підвіски залежить від специфічних умов експлуатації робота та поставлених завдань. Наприклад, для роботів, що працюють в умовах складного рельєфу, більш підходящими є підвіски з високою амортизацією, тоді як для роботів, що виконують точні маневри на рівній поверхні, важливішою є жорсткість підвіски.

Стаття може бути корисною для інженерів, дослідників та розробників робототехнічних систем, які прагнуть покращити конструкції мобільних колісних роботів та підвищити їхню ефективність і надійність. Висновки та рекомендації, наведені у статті, можуть сприяти розвитку нових підходів до проектування підвісок та оптимізації існуючих рішень у сфері мобільної робототехніки.

Ключові слова: мобільний робот, підвіска колеса, колісний робот, аналіз, роботизовані системи.