Forces in Mechanics 16 (2024) 100283

Contents lists available at ScienceDirect

Forces in Mechanics

journal homepage: www.sciencedirect.com/journal/forces-in-mechanics

Mobile rolling robots designed to overcome obstacles: A review

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ARTICLE INFO

Keywords:
Mobile robots with rolling
Obstacle overcoming
Stair climbing
Navigability
Tip-over stability
Motion control

ABSTRACT

Ground mobile robots operating in outdoor environments face multiple challenges, being overcoming obstacles on uneven terrain a prominent one. This challenging task has been addressed by numerous researchers who have developed robots employing various strategies, all aimed at efficiently overcoming increasingly higher obstacles. This article describes 108 robots designed for this purpose, incorporating the principle of rolling for locomotion and obstacle overcoming. These robots have been categorized into six major groups based on their operating principle and strategy for overcoming obstacles. After conducting a meticulous review and comparison, it has been determined that both the definition of the strategy robot will use to overcome an obstacle and the optimized robot design from the early stages of its development through clearly established requirements are the elements that hold the greatest significance in enabling a mobile robot to efficiently overcome an obstacle. In this regard, specific requirements and parameters have been identified that must be considered in the design of the robot to fulfill its purpose. Among these, key considerations include dimensional optimization, robustness, adaptability, energy efficiency, sensory capability, and appropriate navigability.

1. Introduction

Since the emergence of ground mobile robots for outdoor applications, they have gained significant prominence in both the academic and professional contexts. Currently, it is common to find mobile robots participating in a wide range of activities, such as mining, exploration in hazardous and hostile environments [1], military tasks like mine detection and removal [2], surveillance [3], search and rescue operations [4], inspection, fruit harvesting [5], and firefighting [6]. All the accumulated experience in handling ground mobile robots in outdoor environments has found its zenith in the robots used for planetary exploration. In February 2021, the Perseverance rover landed on planet Mars, weighing over 1000 Kg and equipped with state-of-the-art locomotion systems, equipment, and instruments necessary for its monumental task: exploring the hostile surface of this desert-like planet [7].

As can already be seen, the navigation of ground mobile robots in outdoor spaces, where the terrain is characterized by multiple inclinations and irregularities, is a fundamental topic. The efficiency of the robot's movement over the terrain greatly determines the success of any task assigned to it. Therefore, the study of locomotion systems that can enhance the robot's navigability is crucial in the development of these devices. In this regard, there are three common locomotion systems used by ground mobile robots. First, there is wheel traction, which allows the robot to move quickly and efficiently when navigating on hard and rigid surfaces. However, this efficiency decreases when encountering granular materials (e.g., sand) and obstacles, as theoretically, such a robot cannot overcome an obstacle higher than the wheel's radius. These limitations led to the development of other locomotion systems, such as track traction, which improves the robot's grip on the ground, making it more efficient on terrains with loose particles (e.g., sand). However, this system consumes a significant amount of energy, which is a valuable resource, especially when the energy source for these robots is often limited.

Lastly, robots with legs emerged, enabling them to overcome almost any type of obstacle. However, these systems come with the significant drawback that the required mechanical and control systems are more complex, and, in many cases, the forward speed is slower [8]. Each system has its advantages and disadvantages, which has led to the development of hybrid systems that combine, for example, legs with wheels, legs with tracks, or even a combination of legs, wheels, and tracks in a single robot. These systems also share a common goal: improving the robot's ability to overcome obstacles, which are prevalent in uneven terrains. However, despite the existence of these combinations, wheeled robots maintain their prominence, as evident, for example, in the *Perseverance* rover on Mars, which is wheel-driven.

Therefore, this work focuses on wheeled robots and their ability to

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https://doi.org/10.1016/j.finmec.2024.100283
Received 18 December 2023; Received in revised form 6 May 2024; Accepted 9 August 2024

overcome obstacles. 108 designed robots have been reviewed and analyzed, finding that, in general, the problem of obstacle traversal by ground mobile robots has been approached from two perspectives. On one hand, there is the design of robots with suitable physical features for performing this task. On the other hand, there is the programming of appropriate strategies to enable the robot to execute actions that facilitate obstacle traversal. Additionally, this review has highlighted the close interconnection between these two approaches, as the robot's design is directly influenced by the obstacle traversal strategy to be implemented. Conversely, the feasibility of employing a strategy relies on the physical capabilities incorporated into the design. In the end, the description, analysis, and categorization of the design principles necessary for constructing robots capable of performing this task, along with the principles defining obstacle traversal strategies, constitute the primary contribution of this study.

2. Mobile robots capable of overcoming obstacles

In this section, the wheeled robots are classified based on the design developed for obstacle traversal (see Fig. 1); where each design is described, the associated obstacle traversal strategy will be mentioned

2.1. Robots with suspension systems

According to [9], suspension systems enhance comfort and maneuverability characteristics during steering; specifically, they isolate the robot from terrain irregularities, "regulate the vertical movement of the wheel, and ensure tire-to-ground contact to maintain steering maneuverability" (p. 121). Suspension systems used in mobile robotics are primarily classified into two categories based on the type of control implemented:

2.1.1. Passive suspension

This type of suspension has predefined parameters and is not adjustable automatically; therefore, the system's dimensions are fixed, as are its constants that govern stiffness and damping. Within this type of suspension, there are two commonly used configurations:

a. ***Spring - damper:*** According to Hurel et al. [9], these systems "are characterized by not receiving any direct application of external energy. They store energy through springs and dissipate it through dampers" (p. 122). An example of such systems is presented by Zhang et al. [10], which describes a robot with a suspension consisting of a triangular structure, where one leg of the triangle is attached to the chassis, and a spring is incorporated along the hypotenuse (see Fig. 2a). With this mechanism, the robot can adjust the height of its wheels to overcome larger obstacles and, when driven, can surmount these obstacles. Another example of this type is presented in [11], where a four-wheeled robot is composed of three bodies connected by 8 bars and four pairs of spring/damper systems. Additionally, each wheel has independent suspension and is connected to a system consisting of two arms (upper and lower) along with a spring/damper array. These two systems (body articulation and wheel suspension) enable the robot to adapt to uneven terrains and overcome obstacles.

b. ***Rocker Bogie and other Linkage Mechanisms:*** This group includes robots with passive mechanisms consisting of linkages and wheels without the presence of springs or dampers. These mechanisms are designed to adapt to terrain irregularities, allowing the wheels to independently overcome obstacles. Notably, the *Rocker Bogie* mechanism is highlighted in this group, as implemented by NASA in its Planetary Exploration *Rovers*. In [12], it is explained that the mechanism consists of two parts: the *Rocker*, which is connected to the robot's chassis through a rotational joint, along with a differential system that links it to the opposing *Rocker*, causing one to move in the opposite direction to the other. For example, if the front left wheel goes up, the front right wheel is pushed down the same distance. The *Bogie* is a component with two wheels that rotate freely

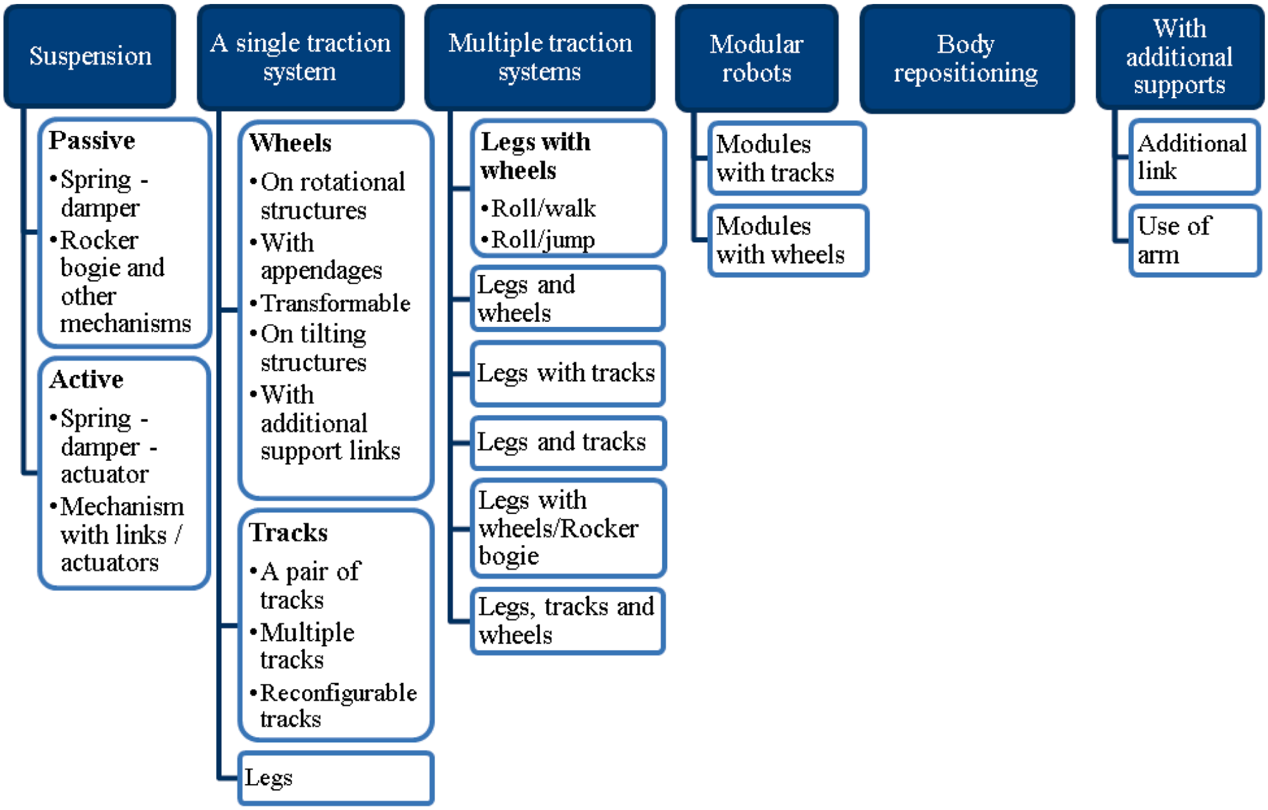

Fig. 1. . Classification of mobile robots for obstacle traversal.

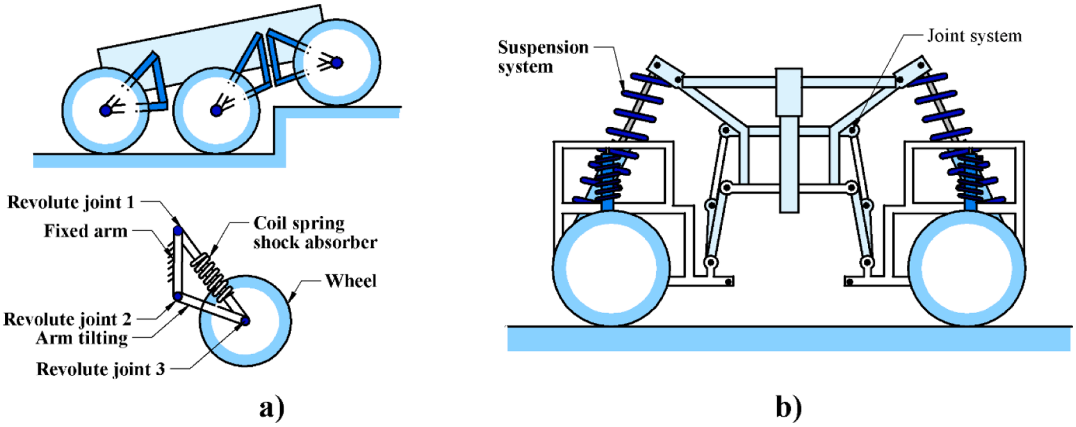

Fig. 2. Mobile robot with passive suspension: (a) Triangular structure suspension [10]; (b) Robot with 8 spring/damper pairs [11].

around a pivot point attached to the *Rocker*, ensuring that both of its wheels always seek contact with the ground (see Fig. 3). This mechanism is exhibited by all NASA-manufactured rovers: *Sojourner* [13], *Opportunity, Spirit* [14], *Curiosity* [15], and *Perseverance* [7]. It is also used in non-space rovers like *Scarecrow* and *SSTB-Lite* [15], as well as in robots such as ATV, designed for generating 3D maps in natural environments [16].

Likewise, there are other robots with analogous mechanisms composed of linkages that enable them to adapt to terrain irregularities and overcome obstacles. For instance, *Workpartner* [17] is a robot equipped with a traction mechanism consisting of four legs and four wheels attached to the tips of the legs (see Fig. 4a). This configuration, known as "*Rolking*", allows for rolling movement. However, when encountering a small obstacle, the leg in contact with it lifts the robot over the obstacle by applying force, facilitating its traverse. Another system designed for a lunar explorer [18] features two lever mechanisms: a positive quadrilateral and a negative quadrilateral (Fig. 4b). Together, they provide the robot with six levers connected to three wheels, allowing the explorer to navigate obstacles while keeping the chassis in a horizontal position.

On the other hand, the *WMR* (Wheeled Mobile Robot) shown by [19] consists of a six-wheeled robot with a four-bar mechanism on each side (see Fig. 4c). This mechanism has a single degree of freedom (DOF) but can adapt to uneven terrain and climb stairs. Finally, the robot described is the *Shrimp*, presented by Siegwart and Nourbakhsh [20], which is composed of six wheels (two on each side, one in the front and one in the back). The lateral wheels are connected to a rocker-type mechanism, and the front wheel is linked to a four-bar mechanism with a spring to ensure continuous contact with the ground, including the surface of an obstacle, which is surmounted by the action of this mechanism along with the push provided by the other wheels (see Fig. 4d).

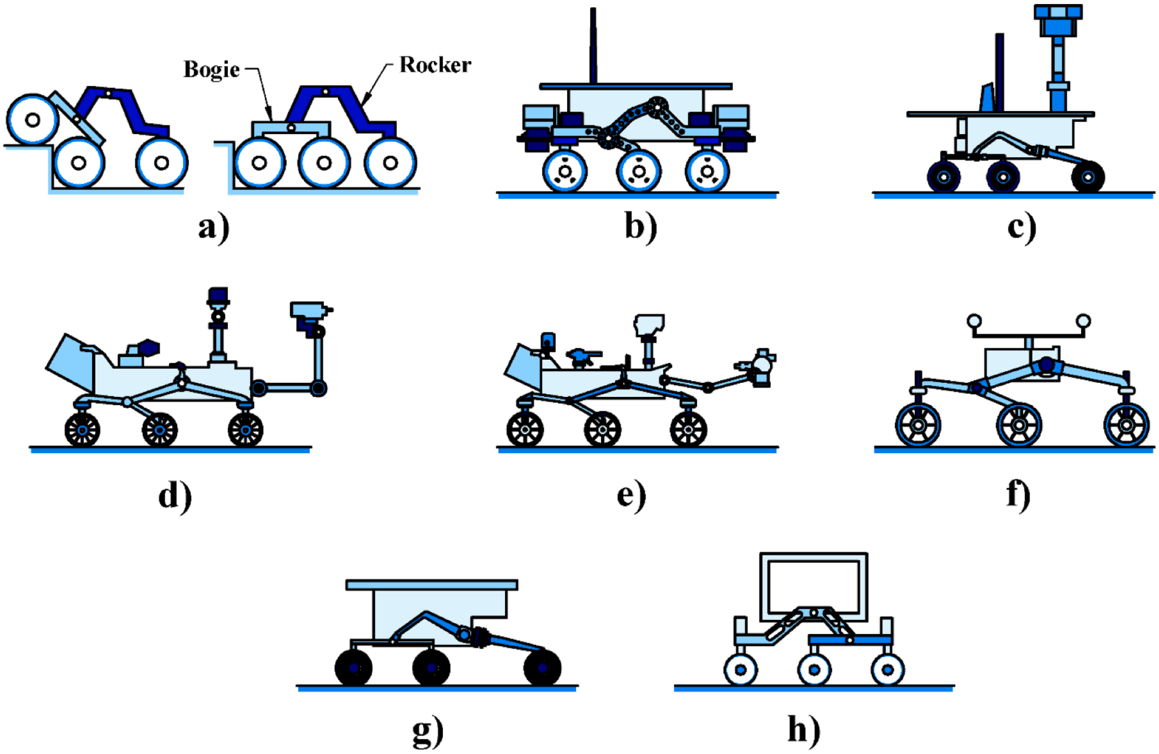

Fig. 3. Robots with *Rocker Bogie mechanism*: (a) mechanism; (b) Sojourner [13]; (c) Spirit y Opportunity [14]; (d) Curiosity [15]; (e) Perseverance [7]; (f) Scarecrow [15]; (g) SSTB-Lite [15]; (h) ATV [16].

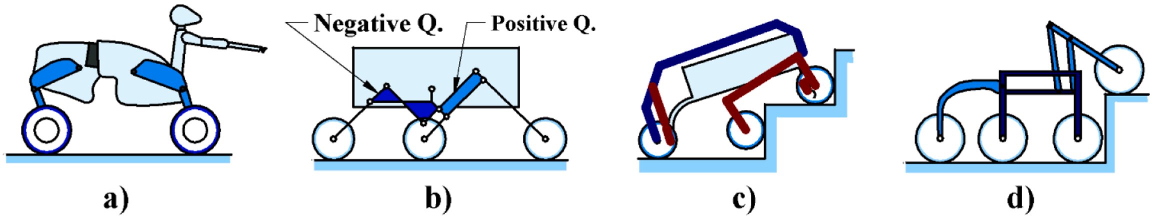

Fig. 4. Robots with linkage mechanisms for passive suspension: (a) *Workpartner* [17]; (b) Lunar Explorer [18]; (c) *WMR* [19] y (d) *Shrimp* [21].

2.1.2. *Active suspension*

According to Hurel et al. [9], "an active suspension stores, dissipates, and introduces energy into the system through actuators, whose operation is regulated by sensors and controllers" (p. 122). In this regard, it is noted that the addition of this new element (actuator) will produce a different effect depending on the mechanism on which it is implemented. This effect is described for the two most commonly used configurations in mobile robotics:

a. ***Spring-Damper-Actuator:*** In this configuration, a typical spring-damper system is supplemented with an actuator coupled in series or in parallel. For instance, in [22], a crewed lunar rover is presented with a suspension system of this type for every two pivot wheels (see Fig. 5a). Its use allows for: adding force to the wheel to ensure ground contact, balancing the height of all 6 wheels to maintain the robot's tilt, lifting a wheel when it's stuck or to overcome obstacles, absorbing vibration, and improving crew comfort.

b. ***Linkage and Actuator Mechanisms:*** In this case, the suspension system is primarily composed of a set of linkages, and the actuator is attached to these to change their position as required. For example, in [23], the *Jet Propulsion Laboratory Sample Return Rover* (SRR) is described, which features a system with two linkages on each side of the robot, with a wheel attached to the tip of each linkage (see Fig. 5b). This system is complemented by an actuator that allows for the adjustment of the opening angle between the two linkages on the same side, which in turn modifies the wheel's contact point with the ground, potentially enhancing the robot's compliance with the terrain. The same principle is described by Shang et al. [24] in a six-wheeled robot (three on each side), with each wheel attached to a linkage. The opening of the two front linkages on the same side is adjustable by means of an installed actuator (orange linkages in Fig. 5c), while the position of the last linkage can be controlled through another actuator or allowed to move freely via a differential system when the actuator is locked.

2.2. *Robots with a single propulsion system*

As mentioned previously, there are three propulsion systems available for terrestrial mobile robots: wheels, tracks, and legs. Below, we describe robots developed to overcome obstacles (and their strategies) that utilize a single propulsion system:

2.2.1. *Robots with wheels*

According to Kang et al. [25], wheels allow robots to be efficient on hard terrain, but traction capability is lost on uneven and obstacle-ridden surfaces since the maximum obstacle height to overcome is equal to the wheel's radius. However, innovative applications have been developed for wheeled robots to increase this maximum height and conquer progressively higher obstacles. These robots and their strategies are described below:

a. ***Wheels on Rotational Structures:*** This group includes robots whose wheels are assembled concentrically on a rotational structure that, when turned, moves the wheels in a circular motion with a radius larger than the wheels' radius, allowing them to reach greater heights to overcome more demanding obstacles. Typically, these systems have 2 DOFs (Degrees of Freedom): one allows the structure to rotate and another provides traction to the wheels, which receive torque from a gear system. For example, [26] describe the *Octal Wheel* robot, which has a total of eight wheels (four on each side), grouped in pairs (two on each side) which are attached to a linkage, when rotated near an obstacle, enables one wheel to be positioned on it to overcome it (see Fig. 6a). Similarly, in [27], the *Epi.q* robot family is presented, where each robot has 12 wheels grouped in trios and assembled on triangular structures, with each wheel being powered through a planetary gear system for rotation (see Fig. 6b). Additionally, the robot's body is divided into two parts with 1 DOF to provide greater mobility to the robot. Finally, in [28], they added an additional DOF to the joint that connects the two parts of the robot's body to improve its maneuverability.

A similar case is presented by Shiroma et al. [29], who describe the *Hanzo* robot; it has two wheels on each side, but only one is mounted at the tip of a linkage, whose opposite end pivots around the center of the other wheel, which is directly attached to the robot's chassis. This allows the wheels moving on the linkage to be in a position higher than the obstacle to overcome (see Fig. 6c). Finally, there's the robot described in [30], which has two bodies connected through a passive joint. The rear body has two driven wheels, and the front body has two linkages (one on each side), attached at their centers to the body using a free rotational joint. Each linkage has two wheels at its end powered through a system of planetary gears, with the sun gear in the center of the linkage, fixed to it. These linkages move freely until the front wheels encounter an obstacle, obstructing their

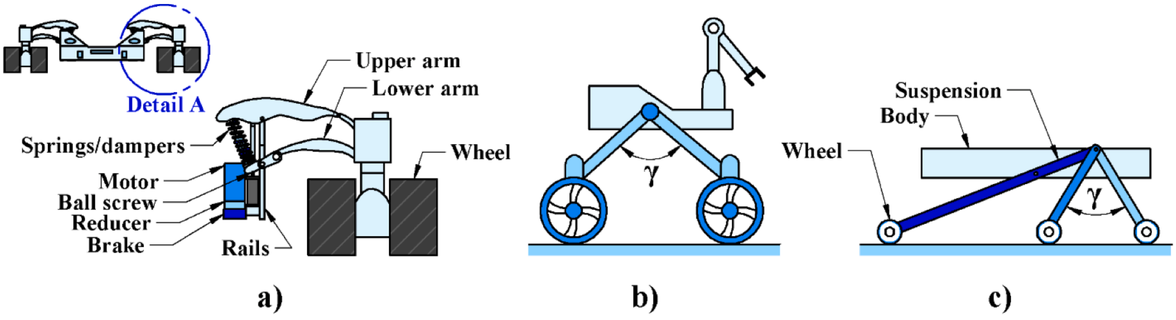

Fig. 5. Robots with active suspension: (a) *Lunar Rover* [22]; (b) *Jet propulsion Laboratory Sample Return Rover* [23]; (c) Robot with six wheels [24].

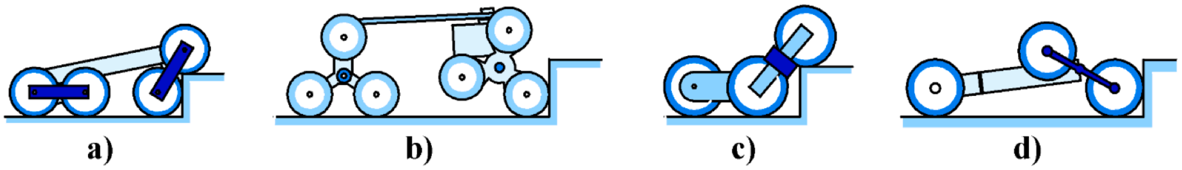

Fig. 6. Robots with wheels on rotational structures: (a) *Octal Wheel* [26]; (b) *Epi.q-1* [27]; (c) *Hanzo* [29]; (d) *Six-wheeled robot* [30].

rotation due to friction. This results in an increase in torque on the sun gear, causing the arm to rotate and position the other wheel of the arm over the obstacle, allowing it to be overcome later (see Fig. 6d). In [31], this design was modified by adding an active joint between the two bodies.

b. ***Wheels with Appendages:*** This category of wheels is bio-inspired, designed by considering the shape of legs in terrestrial insects. Therefore, some researchers refer to them as legs rather than wheels. However, in this research, we align with the criteria of Mertyüz et al. [32], which categorize them as segmented wheels. In this design, the wheel lacks a perimeter edge and, instead, features a circular base that rotates around an axis, with appendages projecting from it that rotate along with the circular base. These protrusions can take various shapes, including those resembling insect legs, like cockroach legs, which assist the robot in overcoming obstacles taller than the wheel's radius. This is achieved as the appendages, when rotating, can hook onto the upper edge of an obstacle and lift the robot's body to overcome it (see Fig. 7a). In designing these robots, [33] has coined them "*Whegs*," a blend of the terms "Wheel" and "Leg." Although these robots enhance their ability to climb obstacles, [32] notes that they are less stable and maneuverable than traditional wheeled robots.

Whegs I is the first robot of this kind, which has 6 wheels, each with three appendages. These appendages are configured to create a tripod-like footprint (similar to cockroaches), meaning three appendages touch the ground simultaneously (2 on one side of the robot and 1 on the other side). Another robot in the same line is *Whegs II*, developed by Lewinger et al. [34]. In this case, the robot's body is divided into two parts and joined through a rotational joint to emulate the body of a cockroach that can flex up or down (see Fig. 7b). With this new joint (connected to an actuator), the robot can flex its body during obstacle climbing, improving its ability to overcome them. Another robot of this type, called *Asguard*, is described in [35], featuring 6 wheels with 5 appendages each. Apart from the number of appendages on each wheel, this robot's distinctive feature is the division of its body into two parts joined by a rotational joint that allows the robot to simulate a twist in the body, significantly enhancing ground traction (see Fig. 7c). Another robot called *Levo* is presented in [36], with two segmented wheels, each with three curved spokes. Additionally, two regular motorized wheels were incorporated for traveling on uneven terrain. To switch between the segmented and regular wheels, the robot has a linear actuation mechanism that raises or lowers the segmented wheels to bring them into contact with the ground (Fig. 7d).

The next design shown corresponds to the IMPASS robot [37], where each wheel has three rods that attach to the central structure of the wheel from an intermediate position to ultimately generate 6 appendages or "spokes." These spokes have variable length because the connection to the central wheel structure is achieved through a system of chains, gears, and pulleys that, through an actuator, can extend one spoke's length (while shortening the other side of the spoke) (see Fig. 7e). With this feature, the robot can overcome larger obstacles and also improve compliance with the ground, as long as the length of each spoke can adapt to the irregularities present in the terrain.

The last two robots presented in this group are hexapods (with six wheels): in the first one, each wheel is formed by three curved spokes shaped like a half-circle [38] (Fig. 7f). In the second one, called Q-Whex, each wheel is made up of a circular sector spanning 240° [39] (see Fig. 7g; although these wheels do not have appendages per se, they are classified within this group as segmented wheels). In both cases, the robots ensure their progress by providing a tripod-like footprint with 3 wheels in contact with the ground. In the case of obstacles, they can overcome them by hooking the upper edge of the obstacle with the end of an appendage or the straight edge of the segmented wheel.

c. ***Transformable Wheels:*** In this type of robots, the ability to overcome obstacles is enhanced by transforming the wheels into a multi-link element that, as a whole, exhibits an effective radius greater than the wheel's own radius. By rotating around the center of the wheel, they can reach and overcome taller obstacles. An example of this is presented by Bai et al. [40]: the Land Devil Ray robot has two wheels that can transform into "legs" (three links for each wheel) through a four-bar mechanism that enables passive transformation when the wheel encounters an obstacle or active transformation through an actuator connected to a clutch that activates the transformation mechanism (Fig. 8a). On the other hand, in [41], the Step robot was developed. It's a robot with two wheels that can transform into three "legs" by deploying circular lobes through a 5-bar mechanism that provides the wheel with 2 DOFs (increased radius and lobe reorientation, see Fig. 8b). Additionally, each wheel has a 4-bar mechanism to ensure independent traction during the transformation.

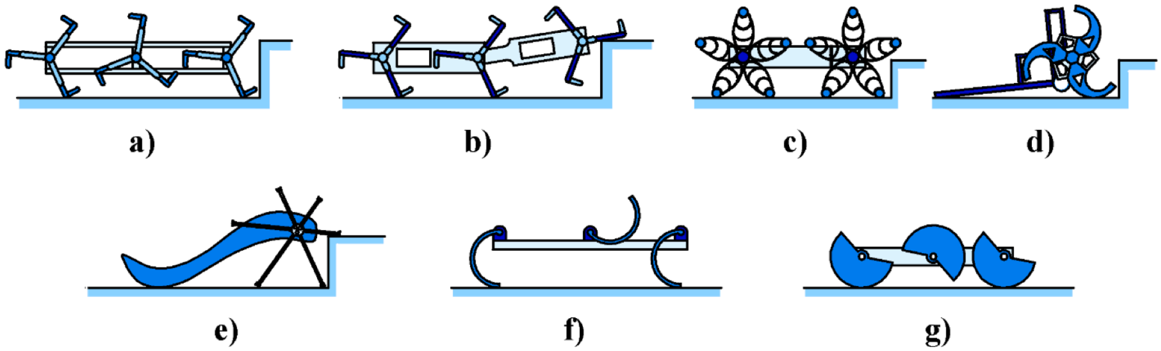

Fig. 7. Wheels with Appendages: (a) *Whegs I* [33]; (b) *Whegs II* [34]; (c) *Asguard* [35]; (d) *Levo* [36]; (e) *IMPASS* [37]; (f) Hexapod robot [38]; (g) *Q-Whex* [39].

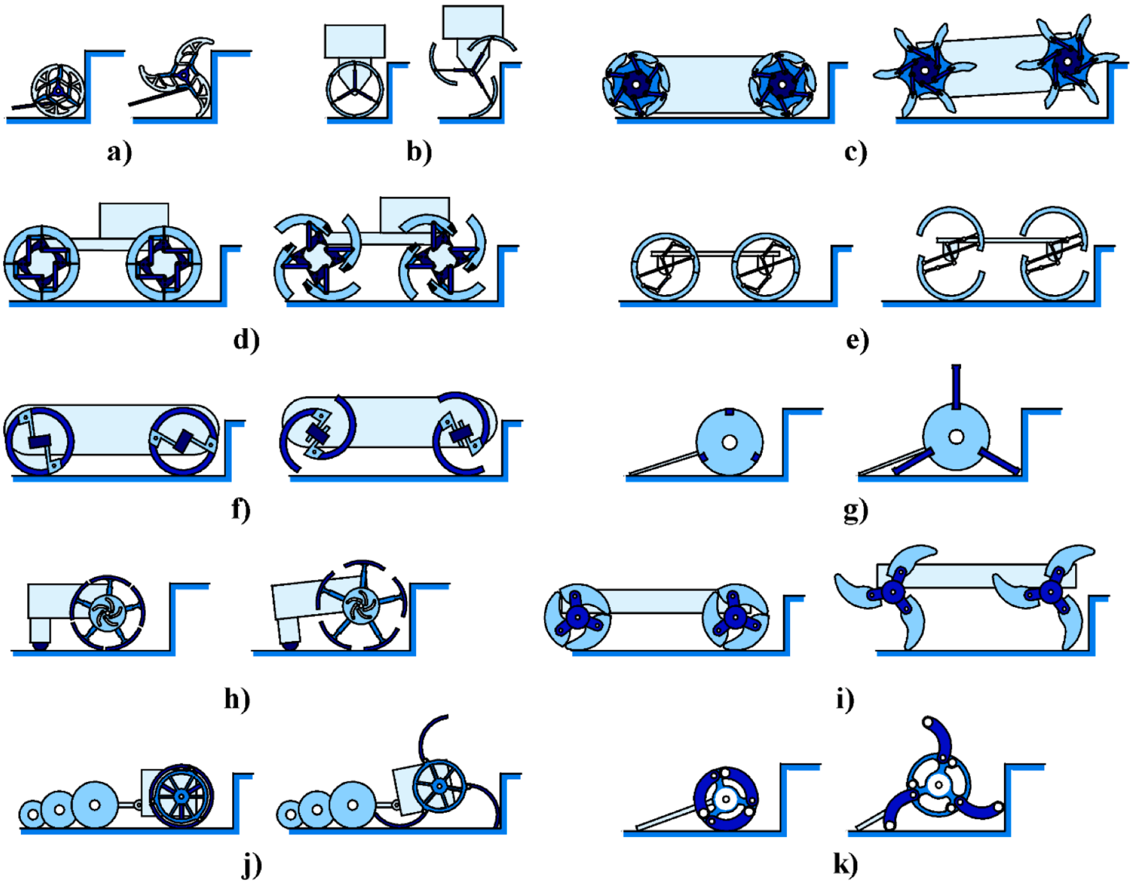

Fig. 8. Robots with transformable wheels: (a) *Land Devil Ray* [40]; (b) *Step* [41]; (c) *Fuhar* [32]; (d) *OmniWheg* [42]; (e) *SWheg* [43]; (f) *TurboQuad* [44]; (g) *Wheel-Legged robot* [45]; (h) Military Surveillance Robot [46]; (i) α-WaLTR [47]; (j) Wheel-legged hybrid robot [48]; (k) Self-morphing robot [49].

Likewise, in [32], *Fuhar* is described, a 4-wheeled robot where each wheel can transform to deploy 6 "fingers." In this case, each wheel has 2 DOFs: one for wheel traction and the other for driving the transformation through a 4-bar mechanism (Fig. 8c). In a similar sense, [42] describes *OmniWheg*, a robot with four wheels, where each wheel can transform into four legs using 4-bar mechanisms (one per leg). The novelty in this case is that 16 rollers have been installed on the legs to make the wheels omnidirectional before deploying the legs (Fig. 8d). On the other hand, [43] describes the SWheg robot, whose wheels can also transform into two segments using 4-bar mechanisms. The important feature in this case is the existence of a "tendon" system that can drive the transformation of all wheels using a single actuator (Fig. 8e).

Additionally, in [44], the *TurboQuad* robot is described, which has four wheels, and each wheel can transform into two "legs" by separating the wheel into two parts (Fig. 8f) through a 2-DOF mechanism (one for traction and another consisting of a pinion and two racks to drive the transformation). Similarly, in [45], there is a robot with two wheels and a mechanism that can deploy three legs around the wheels using a system of linkages, a gear, two racks, and a servomotor for both wheels (Fig. 8g). Likewise, in [46], a robot with two wheels is described, and each wheel can transform into 5 legs using a gear mechanism (pinion - crown) and a cam; in this case, there is one actuator for traction and another connected to the pinion to drive the transformation (Fig. 8h). Continuing with this type of robots, [47] presents *α-WaLTR*, which has two wheels, and each wheel has a central gear plus three leg segments, each containing a partial gear. The central gear is connected to the motor that provides traction, and when it rotates clockwise, it triggers the transformation to deploy the legs; if it rotates counterclockwise, the transformation is reversed (Fig. 8i).

A different mechanism is showcased by Tao et al. [48], where a robot can transform each of its two wheels into three legs through a motor that drives a mechanism consisting of a tri-radial link, two springs, and permanent magnets. When this mechanism rotates around the wheel's hub, it forces the deployment of the three legs onto the wheel (Fig. 8j). Finally, in [49], a robot with two wheels that can deploy 3 rotational legs (each) is described. In this case, each leg is held in the closed position (wheel) due to the action of a magnet. However, when the robot encounters an obstacle, it is programmed to increase the wheel's rotation speed, causing the centrifugal force, along with the torque generated by a torsional spring, to overcome the magnet's attraction, resulting in the transformation (Fig. 8k).

d. ***Wheels on tiltable structures:*** This particular case was presented by Tadakuma et al. [50], who developed the *VmaxCarrier2* robot, which features 4 structures on its main body called Omni-Discs. Each one consists of two discs connected by a rotational hinge joint, and underneath the lower disc, a set of non-steerable wheels is attached (Fig. 9a). The key feature of this design lies in the middle of the two discs, where a pneumatic actuator is housed. When pressurized with air, this actuator tilts the lower disc along with its wheels, preparing it to overcome obstacles with a height greater than the wheel radius. To enable the complete robot to overcome the obstacle, a sequence is executed in which each Omni-Disc is consecutively pressurized with air.
e. ***Wheels with additional supporting linkages:*** This case is presented by a robot called *Transleg*, developed by Wei et al. [51], and it consists of a set of four wheels, where each wheel is attached to a 1-DOF leg that is contained within the circle formed by the wheel. When the robot encounters an obstacle, this leg can be deployed by an

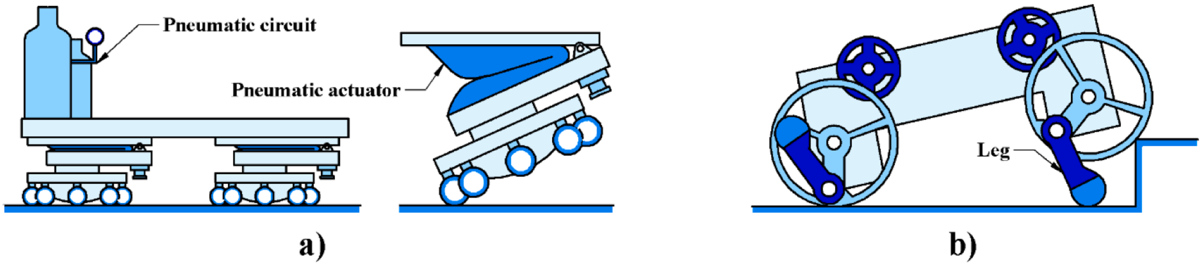

Fig. 9. Robots de ruedas con sistemas especiales: (a) *VmaxCarrier2* [50]; (b) *Transleg* [51].

actuator/pulley/cable system to extend beyond the circular perimeter of the wheel and lift it to a greater height, allowing it to reach the top of the obstacle (Fig. 9b). This leg can be retracted again using the actuator/pulley/cable system along with a torsion spring that generates the necessary force to retract the leg.

2.2.2. Robots with tracks

According to Kang et al. [25], the use of tracks in mobile robots has allowed them to improve traction on uneven terrain or loose particles, but it results in higher energy consumption due to the friction involved. In the case of standard tracked robots, the maximum height of obstacles that can be overcome corresponds to the radius of the wheel to which the track is attached. However, some modifications have been developed to increase this height. These improvements are described below:

a. ***A pair of enhanced tracks:*** A simple yet effective modification is presented by Tao et al. [52], who describe a robot where the front wheel of the track has been replaced by two smaller wheels arranged in a way that the track now has a sloping front with an appropriate "angle of attack" to contact obstacles at their upper edge, which is a fundamental premise necessary to overcome them (Fig. 10a). With this modification, the track can contact the upper edge of taller obstacles, thus increasing the robot's ability to overcome them. On the other hand, [53] describes a mechanism included in the *Dual-crawler-driven* robot, where each track is attached to the robot's body through a single joint (located on the axis of the drive wheel). Additionally, each track has an actuator and a planetary gear system that allows the track to have two movements: traction or the entire track's rotation pivoting on the axis of the driving wheel. The change from traction to rotation is automatic and depends on the friction conditions produced when the robot encounters an obstacle that blocks its progress. At this point, the tracks induce rotation, lifting the robot's body to a position on the top of the obstacle, allowing the obstacle overcoming (Fig. 10b).

b. ***Multiple tracks:*** This group includes robots that have more than one pair of tracks. Firstly, we have the ROBHAZ-DT3 robot developed by [54], which is composed of two bodies joined by a passive rotational joint (Fig. 11a). Each body has two tracks (right and left), but the two tracks on each side are driven by the same motor independently of the body they belong to. The passive joint produces an inclination between the two bodies due to gravitational effects, allowing the robot to better adapt to uneven terrains and obstacles to increase its traction and improve its ability to overcome them. An additional advantage of this robot is the attack angle in the tracks belonging to the front body, which further enhances its obstacle-crossing capabilities.

In the same line, [55] introduces the *RAPOSA* robot, which has similar characteristics to the *ROBHAZ-DT3*. The difference in this case is that the joint connecting the two bodies is actuated by a motor. This allows the robot to lift one of the bodies (the smaller one) to a position over a high obstacle and then, through traction, complete the crossing (Fig. 11b). Another robot belonging to this group is the "Connected Crawler Robot" presented by [56], which consists of three bodies following the same principle implemented by *RAPOSA*. This increases the capability to overcome even taller obstacles since with more bodies, a strategy combining traction and relative inclination between the bodies is used to ensure that one reaches the top of the obstacle, regardless of its height (Fig. 11c). Later on, in [57], more bodies were added to the robot (5 bodies), further enhancing of its already described capabilities.

Another robot with multiple tracks called *TAQT Carrier* was developed by Hirose et al. [58]. This robot has two tracks on each side, which are attached to the chassis by an actuated axle located at the geometric center of the track, allowing them to rotate around this point (Fig. 11d). This feature, along with a mechanism that allows changing the position of the hopper attached to the robot, enables it to overcome obstacles and climb stairs while maintaining stability (since the position of the COG varies when changing the hopper's position). Another robot with different features is described in [59], this Firefighting robot also has two tracks on each side assembled on articulated structures that additionally have a shock-absorbing spring-damper system. These structures allow the relative orientation of the tracks with respect to the robot's main body, providing better terrain adaptability. Additionally, the front tracks have an angle of attack to increase their ability to overcome obstacles (Fig. 11e).

Finally, the robot *Track Walker*, developed by Nagatani et al. [60], is described. It consists of a main body with one track and two lateral

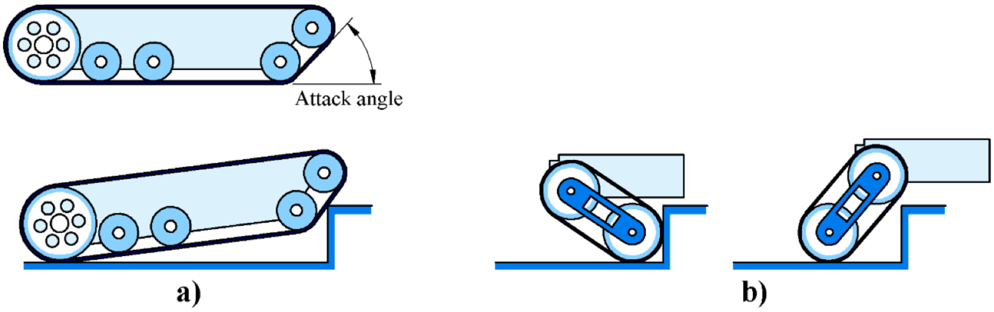

Fig. 10. Robots with tracks: (a) Track with attack angle [52]; (b) *Dual-crawler-driven* [53].

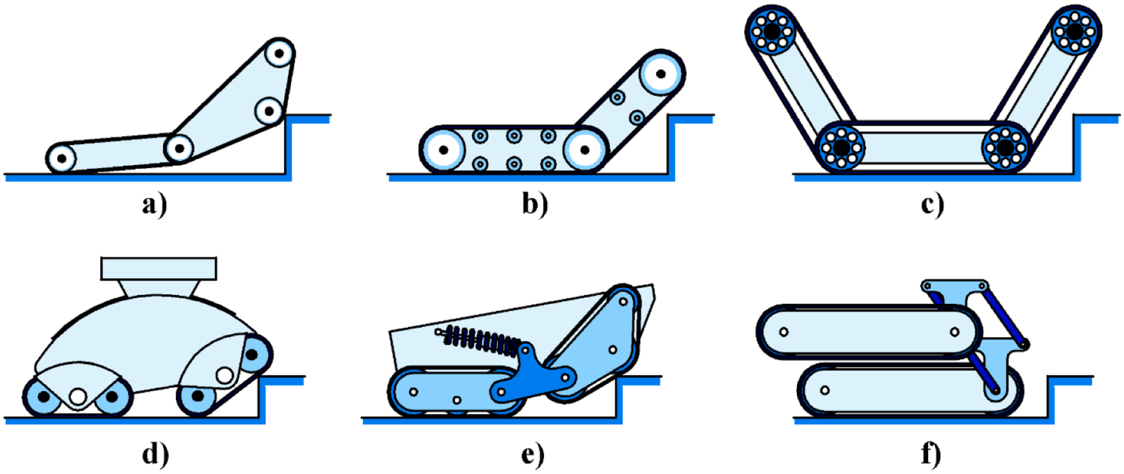

Fig. 11. Robots with Multiple Tracks: (a) *ROBHAZ-DT3* [54]; (b) *RAPOSA* [55]; (c) *Connected crawler* [56]; (d) *TAQT Carrier* [58]; (e) *Firefighting robot* [59]; (f) *Track Walker* [60].

bodies, each with an independent traction track (Fig. 11f). The connection between the main body and the lateral bodies is made through a 3-crank mechanism, allowing the lateral bodies to describe a forward trajectory relative to the main body, generating a "walking" movement between the lateral tracks and the main body. Additionally, each lateral body can rotate around an axis near one of its ends through an additional motor, allowing these tracks to rotate to position themselves over high obstacles and overcome them.

c. ***Reconfigurable Tracks:*** This group includes robots with tracks that can change shape and dimension. Firstly, we have the *LMA* robot developed by Ben-tzvi et al. [61], which features an extendable arm within each track that rotates around the geometric center of the track and has a pulley at its end (Fig. 12a). The arm's length is regulated by a prismatic joint containing a preloaded compression spring, which exerts a force to keep the track taut. When the arm rotates, it allows for a change in the track's shape (both sides' arms rotate synchronously) to achieve different attack angles when overcoming obstacles or to present other shapes for better adaptation to the obstacle as it is being traversed. This same principle was followed by Liu and Liu[62] in developing their *RLMA* robot (Fig. 12b).

Another robot following the same principle is called *VSTR*, presented by Choi et al. [63]. It's a robot that has two 1-DOF links in each track, each with a pulley at one end, and both are attached to the robot's chassis from the geometric centers of the track pulleys (Fig. 12c). When both links are actuated simultaneously in opposite directions, the shape of the track is altered, allowing it to present two suitable attack angles (one in front and one behind the robot) for ascending obstacles or taking a shape appropriate for terrain adaptation. Additionally, in [64], the *RTMBot* was introduced, which also features two arms within each track but interconnected to form a 4-bar linkage mechanism. This means the two arms rotate in the same direction and sense around their rotation axes, creating an attack angle only at the front of the tracks, suitable for overcoming obstacles (Fig. 12d). This robot offers an additional advantage in that its control system allows for different configurations between the left and right sides of the robot, enabling it to adapt to navigate uneven terrains.

A final case is presented by Gao et al. [65], who designed a robot that originally has two large wheels, and each wheel's perimeter is surrounded by a band that is both sturdy and flexible. Inside each wheel, there are two links with 1 DOF each, and they have a pulley at their unarticulated end. These links can extend from inner part of the wheel to press on the band and stretch it, transforming each wheel into a track with variable and appropriate attack angles for overcoming obstacles of different sizes (Fig. 12e).

2.2.3. Robots with legs

They usually base their design on bioinspiration and can have 2 legs (bipedal) [66], 4 legs (quadrupedal) [67], 6 legs (hexapods), or 8 legs (octopods) resembling some living beings. According to Kang et al. [25], these robots can better navigate certain obstacles, but the design, implementation, and control of the robot are more challenging in this case, as the legs typically have multiple joints that must be controlled simultaneously, and coordination is required among all the legs to make

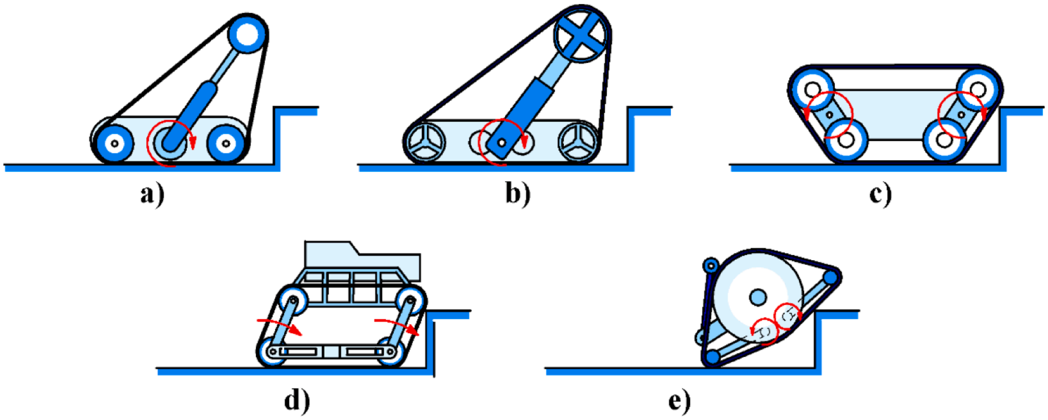

Fig. 12. Robots with reconfigurable tracks: (a) *LMA* [61]; (b) *RLMA* [62]; (c) *VSTR* [63]; (d) *RTMBot* [64]; (e) Flexible track [65].

the robot "walk." The field of legged robotics is extensive; however, this research does not delve into it in depth because its emphasis is on the obstacle-surmounting capabilities of ground robots that rely on rolling, whether with wheels or tracks.

2.3. Robots with multiple locomotion systems

Hybrid robots use two or more locomotion systems simultaneously (wheels, tracks, or legs), enabling them to perform increasingly demanding tasks, including navigating highly uneven terrains and overcoming more complex obstacles. Below, we describe some hybrid robots according to their combination of locomotion systems:

2.3.1. Legs with wheels

This group includes robots that have legs designed to execute modes of movement similar to those of living beings with legs (walking, trotting, jumping), but at their extremities, they have wheels that allow them to switch to wheeled locomotion. According to the mode of movement described by their legs, these robots are classified into two groups:

a. ***Rolling/Walking:*** These robots are characterized by changing their mode of locomotion between rolling and walking when the terrain irregularities demand it. There are multiple robots in this group, and It will be described organized according to the complexity of their legs: In [68], the *PAW* robot was developed, consisting of 4 legs, each with two DOFs: one for rotating the leg forward (or backward) and "scaling" obstacles with rolling (the leg always touches the obstacle and rolls over it), and another for wheel traction at the end of its legs (Fig. 13a). On the other hand, the *Complios* robot, built in [69], also has 4 legs with 3 DOFs each: the first corresponds to wheel traction, the second is a rotational actuator to lift the leg and position it on the obstacle; the third is a passive rotational joint formed by springs at the knee of each leg that allows flexion and absorbs horizontal loads (Fig. 13b). An additional degree of freedom divides the body into 2 parts to provide greater maneuverability to the robot. Likewise, the *MHT* robot was presented in [70], which is a larger and heavier hydraulic robot with 4 legs, each having 3 DOFs: 2 parallel rotational joints at the hip and knee, in addition to wheel traction (Fig. 13c). Overcoming obstacles is achieved by positioning each leg on the obstacle.

On the other hand, in [71], the *Hylos* robot is described (Fig. 13d), while [72] presented the *Hylos II* robot, both robots with differences in size and mass (*Hylos* weighs 10 Kg, whereas *Hylos II* weighs 20 Kg), but with similar constituent features: each of them has 4 legs, with 4 DOFs each: two for moving the leg through actuated rotational joints with linear actuators, while the other two DOFs are used for steering and driving the wheel. To overcome obstacles, the robot bends its legs forward to "scale" using the front wheels for rolling and then bends the legs backward to scale using the rear wheels. Likewise, in [73], the *ANYmal* robot is described, which originally had 4 legs but was modified to add wheels at its ends. Each leg has 4 DOFs: two for moving the hip in two directions (abduction/adduction and flexion/extension), one for moving the knee, and one for driving the wheel Fig. 13e). To overcome obstacles, the robot lifts each leg alternately to position it on the obstacle.

The number of DOFs in the legs can increase in other robots. For instance, in [74], the *Sherpa* robot was developed, which has 4 legs with 6 DOFs each: 2 active DOFs for lifting and laterally displacing the leg, 2 passive DOFs in the leg-wheel junction (for tilting the wheel depending on the terrain irregularity), and finally, 2 more active DOFs for steering and driving the wheel (Fig. 13f).

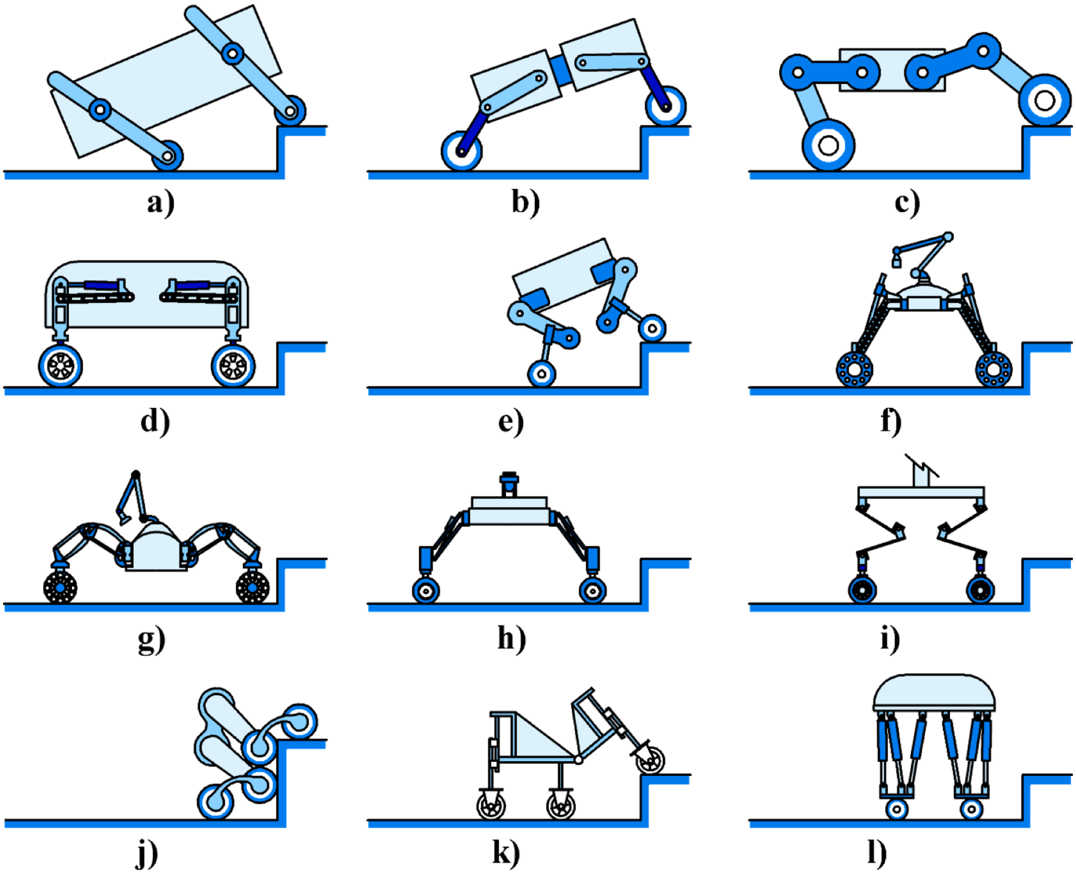

Fig. 13. Robots with legs and wheels that walk and roll: (a) *PAW* [68]; (b) *Complios* [69]; (c) *MHT* [70]; (d) *Hylos* [71] and *Hylos II* [72];(e) *ANYmal* [73]; (f) *Sherpa* [74]; (g) *SherpaTT* [75]; (h) *MAMMOTH* [76]; (i) *Momaro* [77]; (j) *Octopus* [78]; (k) Six-legged/wheeled mechanism [79]; (l) *BIT-NAZA* [80].

Overcoming obstacles in this case involves lifting each wheel to position it over the obstacle. Subsequently, in [75], the *Sherpa* robot was improved to introduce *SherpaTT*, which differs in its design optimization resulting in reduced mass (while *Sherpa* has a mass of 200 Kg, *SherpaTT* has 166 Kg). Additionally, the number of DOFs per leg was reduced: *SherpaTT* has 4 DOFs, as the two passive DOFs in the leg-wheel junction were eliminated (Fig. 13g). Finally, the obstacle traversal process is the same as in the case of *Sherpa*.

Following the same principle for overcoming obstacles, in [76], the *MAMMOTH* robot was introduced, which has 5 DOFs in each leg: 3 rotational joints for leg movement (hip, upper and lower thigh) and 2 for wheel control (drive and steering, see Fig. 13h). Similarly, in [77], the *Momaro* robot was developed, featuring 4 legs with 5 DOFs each: 2 dedicated to wheel control (drive and steering) and 3 distributed along the leg (hip, knee, and ankle), with the particularity that all of them are rotational joints with parallel axes of rotation (Fig. 13i).

It's worth mentioning three additional robots that have the leg/-wheel locomotion system but with completely different action mechanisms: in [78], the *Octopus* robot was developed, which has 4 legs formed by 2 links each (arm and forearm), and it also has 2 driven wheels on each leg: one at the end and another at the elbow (Fig. 13j). In total, the robot has 15 DOFs, of which 8 correspond to the wheels and the rest are distributed among its legs. Its design allows it to touch the ground with all 8 wheels at once and overcome very tall obstacles by using its rear legs to lift the entire body of the robot along with the front legs, as the two rear legs can generate 4 points of contact with the ground.

On the other hand, the robot described by Liu et al. [79], who outlines a mechanism (not yet built) for a 6-legged robot with wheels, has 4 legs (at the ends) with actuated prismatic joints and 2 legs (intermediary) without joints, all assembled into a robot formed by two bodies connected by an actuated rotational joint (Fig. 13k). With this mechanism, the robot could overcome obstacles by using the rotational joint to lift the front half of the body along with the front legs to position them on the obstacle. Subsequently, through this joint, the rear half of the robot's body is raised along with the rear legs to complete the operation.

Finally, in [80], the *BIT-NAZA* robot was developed and further improved and presented as *BIT-NAZA-II* by [81]. It consists of a large robot (385 Kg) with 4 legs, each formed by a parallel robot mechanism with 6 DOFs in each leg (there are 6 linear actuators in each leg, see Fig. 13l). At the end, there is a pair of symmetrical wheels with 2 DOFs (traction and steering). It overcomes obstacles by blocking the wheel traction and walking with its legs, positioning each one on the obstacle.

b. ***Rolling/Jumping:*** In this group, robots are designed to move on flat terrain using their wheels. However, when encountering obstacles, they activate a jumping strategy with their legs to overcome the obstacle. Two robots are included in this group: *Handle* from *Boston Dynamics* [82], which has two-legged wheels at its ends and moves by balancing on its wheels while manipulating loads with an attached arm (Fig. 14a); and *Ascento*, developed by Klemm et al. [83], which has two motorized leg-wheels for rolling (achieved by balancing on its two wheels, see Fig. 14b). In addition, each leg has a hip motor and a torsion spring in the knee that, together, execute a rapid leg contraction and extension movement, allowing the robot to generate jumps to overcome obstacles in its path.

The same jumping principle is followed by the robot presented in [84], which also has two driven wheels attached to the end of two 4-bar mechanisms forming its legs (see Fig. 14c). This robot moves by swinging (although it can also be supported by 4 additional passive wheels), and to overcome obstacles, it activates the two motors installed in its hips to cause a rapid leg extension and subsequent jump.

2.3.2. *Legs and wheels*

This group includes robots that use legs and wheels separately, either by combining both mechanisms or by alternating between them for locomotion. Among the robots that use both mechanisms together is *SCARAB* developed by Mabuchi et al.[85], which has 2 rear legs with 2 DOFs each defined by prismatic joints. It also has two passive front wheels to provide stability to the robot. Additionally, it has a pair of small arms with 1 DOF located between the two wheels, which are used to lift the robot's body when it ascends an obstacle (by pressing the arms against the ground), while the rear legs contribute to propelling the robot (Fig. 15a). Following this same principle, [86] presented the *Wheeleg* robot, which follows the principle of a wheelbarrow: it has 2 front legs with 3 DOFs each, including two prismatic and one rotational joint. It also has two active rear wheels to improve stability and traction (Fig. 15b). To overcome obstacles, the robot alternately positions its legs on the obstacle to lift its body, which is propelled by the wheel traction as well.

Furthermore, in [87], *Crank-wheel* was introduced, a robot with 4 active wheels and 4 legs with hooks attached at their ends. Through two mechanisms, the legs are connected to the wheels in a dependent manner: when the wheels turn, the legs perform oscillatory up-and-down movements, allowing them to hook onto obstacles or move across very uneven terrain (Fig. 15c). Finally, in [88], the *HyTRo-I* robot was developed, which has 4 wheels (two active and two passive) and 4 legs, each with three active rotational joints and one passive linear joint (with a spring to absorb impacts). For its operation, this robot alternates between the two mechanisms: to move on regular terrain, it raises its legs and rolls forward, but in the presence of obstacles, it positions its legs on the ground and walks, alternating between the legs (and even wheels) to overcome the obstacle (Fig. 15d).

2.3.3. *Legs with tracks*

In this group, there are robots that have legs with incorporated tracks within them, allowing the robot to perform complex actions like walking or crawling and also to advance using the traction provided by the tracks. Among the robots in this category are Tehzeeb [89], *Kenaf* [90],

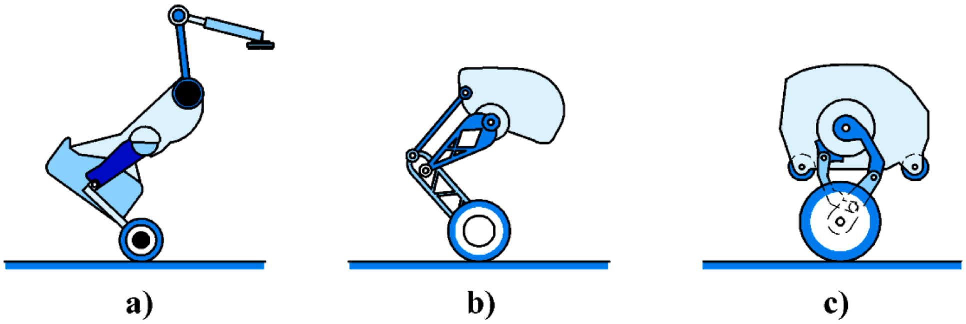

Fig. 14. Robots with legs and wheels that roll and jump: (a) *Handle* from *Boston Dynamics* [82]; (b) *Ascento* [83]; (c) Robot described in [84].

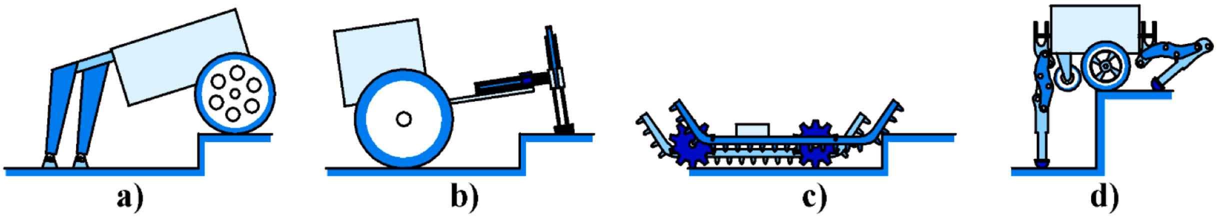

Fig. 15. Robots with legs and wheels: (a) *SCARAB* [85]; (b) *Wheeleg* [86]; (c) *Crank-wheel* [87]; (d) *HyTRo-I* [88].

MINBOT-I [91], MINBOT-II [92], and the robot shown by [93]. In these five robots, the operating principle is the same: they have two tracks attached to their main body, and additionally, they have 4 arms with 1 DOF each attached to the body. Each arm also has a track that, along with the tracks on the robot's body, enhances traction by allowing them to better adapt to the terrain's irregularities (Fig. 16a–e). Moreover, when obstacle traversal is required, the arms function as legs, enabling the robot to walk and position these "legs" on the obstacle.

Another similar robot called *Telerob Telemax* is presented by Brunner et al. [94]. It also features four arms with tracks, but in this case, the tracks on the robot's main body are eliminated. Nevertheless, this robot can walk with its arms to overcome obstacles and does not lose its traction capabilities. The design of the tracks is conceived to maintain a good ground contact area while using this mode of locomotion (Fig. 16f). On the other hand, in [95], the robot *ResQuake* is introduced, which has two tracks on its main body and four arms attached to the robot. The difference in this case lies in the arms, as each one has two links actuated by a single actuator that moves them at different speeds (using gears with different transmission ratios). Additionally, each link has its own track (Fig. 16g). Although this robot can walk, it is more effective to implement a strategy for overcoming obstacles, which involves using an angle of attack on the arms' tracks to make contact with the obstacle and climb it.

Another robot in this group with some special characteristics is called *Elf* and was presented by Yamauchi et al. [96]. This robot also has 4 arms, each with two links, two independent active rotational joints, and a track only on the end link of the arm. This feature provides greater maneuverability with its arms for walking and overcoming obstacles. Additionally, its body (which also has two tracks) has an active joint that separates it into two parts and allows one of the tracks to be raised higher than the other to better adapt to the terrain (Fig. 16h).

In the same group, the robot *iRobot PackBot*, described in [97], appears. This robot, which has two tracks on the main body, has two arms with 1 DOF each that rotate on rotational joints. Each arm has a track attached, allowing the robot to move with combined locomotion modes: using all the tracks, including those on the arms, to adapt to uneven terrain, or using the arms as independent legs to climb obstacles (hook onto them, see Fig. 16i). The same principle is employed by the robot developed in [98] (Fig. 16j). However, in this case, a future improvement is proposed by adding a hydraulic mechanism for arm extension, which increases obstacle-crossing capability by 16.7 %.

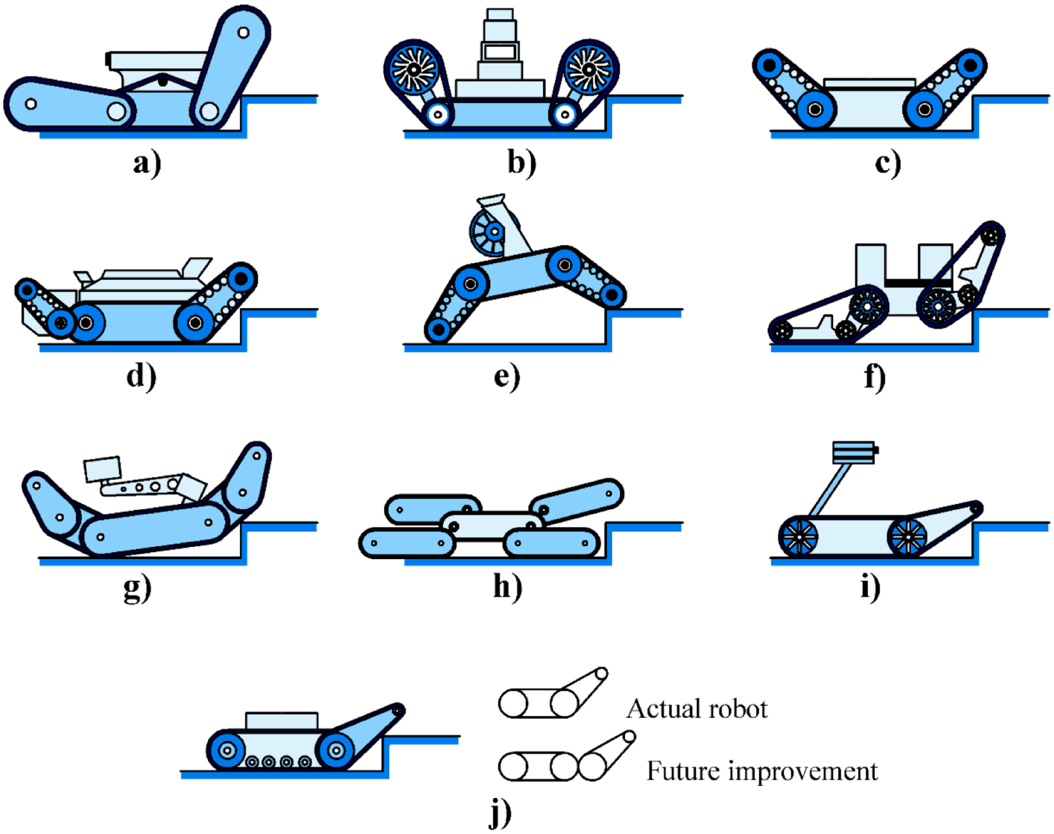

Fig. 16. Legged robots with tracks: (a) *Tehzeeb* [89]; (b) *Kenaf* [90]; (c) Robots with 4 legs [93]; (d) MINBOT-I [91]; (e) MINBOT-II [92]; (f) *Telerob Telemax* [94]; (g) *ResQuake* [95]; (h) *Elf* [96]; (i) *iRobot Packbot* [97]; (j) Tracked rescue mobile robot [98].

2.3.4. *Legs and tracks*

This group includes robots that have both of these locomotion systems but separated from each other. An example is the *Quadruped tracked* robot presented by Fujita et al. [99], which has two tracks attached to its main body and four independent legs with 4 DOFs each (Fig. 17a). When the robot is on flat or sandy terrain, it raises its legs and moves using the tracks. However, when it encounters an obstacle, it positions its legs on the ground, lifts its body, and walks over the obstacle.

2.3.5. *Legs with wheels/Rocker Bogie*

This unusual combination of different traction systems was found in the *Spider-leg* robot presented by [100], which has 8 wheels and combines passive and active suspension: 2 wheels per side (4 in total) are attached to the *bogie* of the *Rocker Bogie* mechanism, which allows them to move freely and adapt to the terrain's irregularities. The remaining 4 wheels are connected to 4 legs (one per leg), each with 1 DOF, formed by a 4-bar mechanism, a linear actuator, and a shock-absorbing mechanism (spring/damper, see Fig. 17b). With these legs, the robot can overcome small obstacles using only the spring/damper and large obstacles by lifting the legs to position them over the obstacle.

2.3.6. *Legs, tracks, and wheels*

This group includes those robots that combine the three common modes of locomotion, such as the robots *Azimut* (Fig. 17c) and *Mobit* (Fig. 17d) presented by Michaud et al. [101,102], respectively. Both of them have 4 legs, 4 wheels, and 4 tracks combined in sets of three. This means that on each leg, a track and a wheel are attached, with the wheel positioned closer to the robot's chassis. This configuration enables the robot to move using four modes of locomotion: rolling, walking, using the tracks, or combining all three to overcome obstacles. It can use some wheels for propulsion while lifting its body off the ground with some of its legs to overcome obstacles. An improvement to these robots is presented in [103], where two additional tracks are added to the robot's main body, enhancing traction when the robot navigates highly irregular terrains (Fig. 17e).

On the other hand, in [104], the robot *WheTLHLoc* is described, which has two tracks, two legs with 1 DOF each (independent), and two actuated wheels, with each wheel installed at the end of a leg. Additionally, the robot features two caster wheels installed at the rear of the main body, enabling the robot to operate using all three modes of locomotion: with the wheels, lowering the legs so that the robot is supported by only three wheels (two active and one passive), with the tracks, or with the legs, primarily in operations to climb obstacles with their assistance (Fig. 17f).

Finally, another robot belonging to this group was developed by Zhu et al. [105], named the *Wheel-track-leg Hybrid Robot*. It has 4 tracks (two on each side) that are attached to the robot through an active joint that allows them to rotate and act as legs if necessary or reposition themselves to move the robot using the traction provided by the tracks. Additionally, it has two support legs (front and rear) with 1 DOF each, which can be positioned on tall obstacles and assist the robot in overcoming them (Fig. 17g). It also has an additional mechanism with wheels attached to the main body of the robot (independent of the tracks and legs) that allows the robot to move on flat terrain. However, to do so, the robot must lift the tracks and legs to prevent them from touching the ground.

2.4. *Modular robots*

In this group, robots with segmented bodies composed of multiple modules with similar physical characteristics are included. These modules are interconnected through actuated joints. Through this system, these robots can take on various shapes and configurations that allow them to better adapt to the irregularities of the terrain. In the case of obstacles, they can assume positions or shapes that help overcome them. Furthermore, the different modules can mutually propel each other to advance over obstacles. Two subgroups have been identified based on their locomotion system:

2.4.1. *Modules with tracks*

These robots consist of multiple modules with track-based propulsion systems. Two representative cases in this group are the *AMOEBA-I* developed by Li et al. [106] and *A-II* (Amoeba II) developed by Li et al. [107]. In the case of *AMOEBA-I,* it consists of three modules (one central and two side modules), each equipped with a track. The side modules are connected to the central module through a linkage and two rotational joints (Yaw and Pitch), allowing them to change positions, enabling the robot to assume various configurations, including serial, parallel, and triangular positions (Fig. 18a). To overcome obstacles, the serial or triangular configuration can be used, where one module is lifted to position itself on the obstacle (using the active joint that connects the

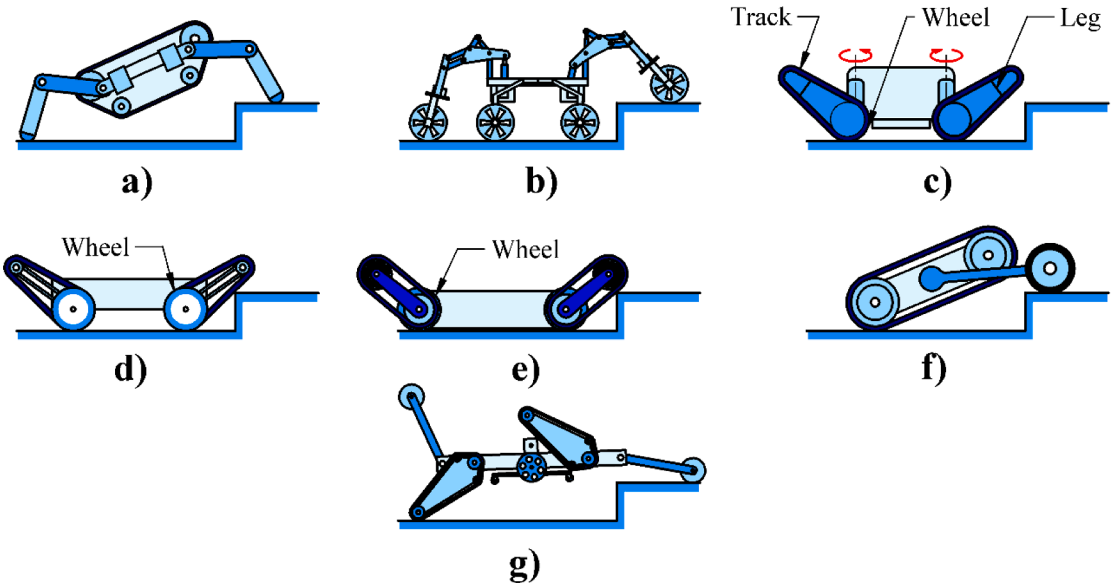

Fig. 17. Robots with multiple locomotion systems (less common configurations): (a) *Quadruped tracked* [99]; (b) *Spider-leg* [100]; (c) *Azimut* [101]; (d) *Mobit* [102]; (e) Wheel-tracked mobile robot [103]; (f) *WheTLHLoc* [104]; (g) *Wheel-track-leg Hybrid Robot* [105].

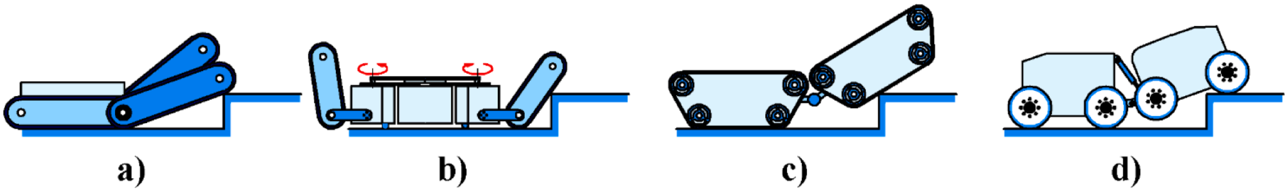

Fig. 18. 2.4.Modular Robots: (a) *AMOEBA-I* [106]; (b) *A-II* [107]; (c) JL-2 [109]; (d) Modular Robot with wheels [110].

modules), while the remaining modules act as counterweights to prevent tip-over. Once one module has positioned itself on the obstacle, it can pull the other modules, which contribute using their own traction.

In the case of robot A-II, the central module has been removed and replaced with an articulation unit without a track, featuring two rotational joints designed to facilitate the coupling with the side modules. These joints are actuated by a single actuator that allows the simultaneous movement of the two side modules in the Yaw direction, changing the shape of the robot from a serial configuration to a parallel one (Fig. 18b). Each side module also has an actuated joint in the Pitch direction, enabling one module to elevate relative to the central unit and the other module. To overcome obstacles, the serial configuration is used (similar to AMOEBA-I), but the operation is carried out using only the side modules.

Finally, it's worth mentioning the JL-I robots developed by Guanghua et al. [108] and their improved version, JL-2, developed by Wang et al. [109]. These robots are comprised of independent modules, each with two tracks, and they can self-connect through a spherical joint with 3 controlled degrees of freedom (rotation in all three joint axes), forming a serial robot (a succession of modules placed one after the other). To overcome obstacles, one module is lifted using the rotational joint to position it above the obstacle to be overcome, while the risk of the robot toppling over is avoided due to the counterbalance exerted by the other connected modules on the ground. Once one module has been positioned over the obstacle, it can pull the other modules, which contribute using their own traction (Fig. 18c).

2.4.2. *Modules with wheels*

These robots differ from the previous group due to the locomotion system used, which, in this case, consists of wheels. An example of this is the robot presented by Zhou et al. [110], which is composed of two large modules, each equipped with 4 wheels. These modules are connected through a passive spherical joint that allows for relative yaw between the two robots, and hydraulic cylinders that enable the robot to execute a strategy for overcoming obstacles: By retracting the cylinders, the front module can be lifted, assisted by the friction generated as it climbs over the obstacle (Fig. 18d). Subsequently, the rear module is pulled by the module that has already overcome the obstacle. However, for this to occur, there must be sufficient tractive force in both the pulling and pulled modules (with the latter climbing over the obstacle with the aid of friction).

2.5. *Robots with body repositioning*

The principle used by these robots to overcome obstacles is based on repositioning the center of gravity (COG) to facilitate the execution of the strategy. For example, the robot presented by Sim et al. [111] consists of a platform with 4 wheels (each with traction and steering) that can move the main body of the robot in two directions (pitch and roll) because the body is articulated to the platform through a joint with 2 DOFs (Fig. 19a). When the robot is about to climb an obstacle, it tilts the body backward, increasing the normal force of the rear wheels, while reducing the friction/traction required to make the front wheels climb the obstacle by scaling it.

Another analogous case is presented by the robot *RSTAR* [112], which has two wheels and three wheels with appendages on each side (to improve grip on very rough terrain). All these wheels are connected to two mechanisms: a 4-bar mechanism (FBEM) that allows the body to move backward or forward, and an additional one that rotates the entire structure of the FBEM (along with the wheels) to increase the contact area of the wheels with the ground. When the robot is in front of an obstacle, it uses the FBEM to move the body backward, shifting the COG, causing the robot to tip backward, lifting the front of the robot to an appropriate height. In this situation, the robot advances with the rear wheels until the front wheels are on top of the obstacle to overcome it (Fig. 19b).

2.6. *Robots with additional supports*

These robots use an additional element to create an extra point of contact with the ground, enabling them to exert pressure against the ground to lift the robot's main body to reach and overcome obstacles. This additional support can be provided by an element provided for this purpose or another element with different functions (e.g., manipulators) that can also be utilized for this purpose. The following robots in this group are described, classified according to the type of support they use:

2.6.1. *Additional link*

In this group, we have robots that have a dedicated link for the sole purpose of generating support to lift the robot's body and overcome an obstacle. Typically, a fixed location for support is established according to the designed strategy, making its use limited to certain obstacles with predefined shapes and positions. An example of this group is the robot developed by Chiu et al. [113] called *FUMA*, which has 4 wheels and an articulated link with 1 DOF located at the rear of the robot, equipped with a rigid element as the end effector (Fig. 20a). To overcome obstacles, the robot must approach the object from its rear to allow the additional link of *FUMA* to make contact with the obstacle and facilitate lifting a part of the robot. The robot then advances so that part of its body rests on the obstacle. Total overcoming is achieved through the

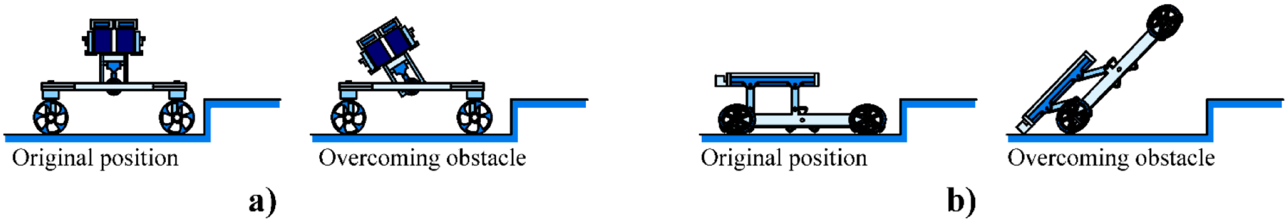

Fig. 19. Robot with Body Repositioning: (a) 4-Wheeled Robot [111]; (b) *RSTAR* [112].

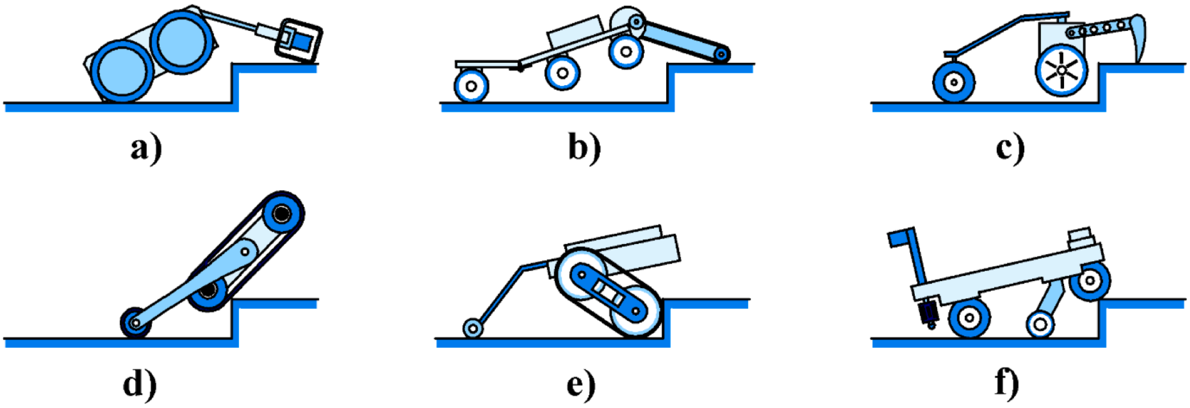

Fig. 20. Robots with additional link: (a) *Fuma* [113]; (b) Robot with track on the additional link [114]; (c) *Mantis 2* [115]; (d) *FlipBot* [116]; (e) *Dual-crawler-driven* with leg [117]; (f) Robot with oscillating arms [118].

traction of the wheels already positioned on the obstacle. Another robot with the same principle was presented by Kececi [114], which has 6 wheels and a link located at the front of the robot for the same purpose. In this case, the strategy used is the same as with the *FUMA* robot, but now the additional link has a small caterpillar track that allows it to generate rolling contact with the ground as the robot advances supported on this link (Fig. 20b).

In the previous cases, the additional link generates a point of contact on the surface of the obstacle to be overcome. This principle is also followed by the robot *Mantis 2* described by Bruzzone et al. [115], which has two wheels with traction and a small axle with two passive wheels at its end to provide stability to the robot. Additionally, it has 2 leg-like hooks that are attached to the robot through an active rotational joint (Fig. 20c). When the robot encounters an obstacle, these two legs rotate downward to make contact with the pinnacle of the obstacle, lifting the robot's body and pushing it forward (by latching onto the obstacle). When the wheels complete a full 360° rotation, the robot will have completely overcome the obstacle.

But not all robots in this group position the additional link on the obstacle. The *FlipBot* robot presented by Seo et al. [116] is composed of two tracks and a supporting leg formed by two links attached to the sides of the robot and connected by a roller-shaped link to form a single leg that rotates around the robot's body through an active rotational joint (Fig. 20d). When the robot encounters an obstacle, the tracks touch it and begin to climb it due to friction. As this happens, the robot tilts but does not overturn since the additional leg is positioned on the underside of the obstacle, generating a reaction force that prevents tipping and allows the tracks to continue climbing the obstacle until it is overcome.

Additionally, the case presented by Lan and Ma [117] is described, where they developed a robot with tracks that are attached to the main body through an actuated joint and can rotate relative to the body (as previously shown in Fig. 10b). Now, a fixed leg has been attached to the rear section of the robot, which has a small wheel as an end effector (Fig. 20e). When the robot encounters an obstacle, the activation of the joint that connects the body to the tracks induces a rotation of the robot's body, lifting it to position it on the obstacle. This elevation is assisted by the leg, which, in an uncontrolled manner, comes into contact with the ground, generating a force that propels the body upward to reach the top of the obstacle. Finally, another robot is presented, which has four driven Swedish wheels and two swinging arms with passive Swedish wheels at their ends [118]. When the robot encounters an obstacle, two linear actuators are activated, extending the arms so that the passive wheels touch the ground while the front of the robot is lifted, leaving the front wheels on the obstacle (Fig. 20f). Then, to lift the rear part of the robot and complete the obstacle crossing, the robot has two linear actuators at the back, which extend two passive wheels that, upon touching the ground, allow the rest of the robot to be lifted.

2.6.2. *Use of the arm*

In this latter group, robots have an arm with DOFs>1, primarily used for other functions (manipulation, etc.), but it is also utilized to create an additional contact point with the ground, enabling the robot to assist in overcoming obstacles. In comparison to the previous group (additional link), these robots can create contact points in different positions using their arms, providing them with greater maneuverability to overcome obstacles of various shapes or positions. One example is the *Helios VII* robot [119], which is a tracked robot with a 4-DOF arm that has two passive wheels at the elbow and at its end (interchangeable with a gripper). These wheels allow the arm to make rolling contact with the ground to lift part of the robot's body. If the obstacle is of low height, the strategy positions the arm in front to raise the front part of the robot's body sufficiently to overcome the obstacle (see Fig. 21a). However, if the obstacle is of significant height, the arm contacts the ground behind the robot, inducing a rotation of the platform that will lift and rotate around a point located at the front of the tracks to align parallel to the obstacle (vertical). Subsequently, in a second movement, the arm presses down on the ground again to produce a second rotation of the platform, which afterwards rotate around the point on the tracks that contacts the pinnacle of the obstacle, positioning it adequately to overcome the obstacle through traction on the tracks.

The same principle is followed by the tracked robot *HMR*, developed by Ben-Tzvi [120], which consists of a mobile platform from which a 2-link arm with 3 DOF and two passive wheels (elbow and end, see Fig. 21b) can be deployed (and folded). This design allows it to execute the same obstacle-overcoming strategy as described for *the Helios VII* robot. Furthermore, the subsequent robots, *Helios VIII* [121] and *Helios IX* [122], have also been developed based on the same principle of action. In these cases, the wheels at the end have been removed, and only the passive wheels at the elbow remain, which are still useful for assisting the robot in overcoming obstacles according to the described strategy.

On the other hand, the *Alacrane* robot (modified) designed for rescue operations consists of a robust tracked platform and a 6-DOF hydraulic manipulator with a rigid and sturdy metal claw as its end effector. This claw can make contact with the ground to lift the front part of the robot's body and assist it in overcoming obstacles (Fig. 21c). Due to the robot's large size and the articulation limitations of the arm, a strategy was designed in [123], which is executed sequentially and cyclically: the arm in contact with the ground raises the robot's body slightly, which then advances to touch the obstacle. At this point, the arm loses contact with the ground and is retracted/extended to reposition the COG and to prevent tipping. Subsequently, it makes contact with the ground again to lift the robot's body a bit more, allowing it to advance over the obstacle.

Additionally, in [124], a strategy is described that is used by *HEAP*, an excavator robot equipped with 4 wheels mounted on legs and

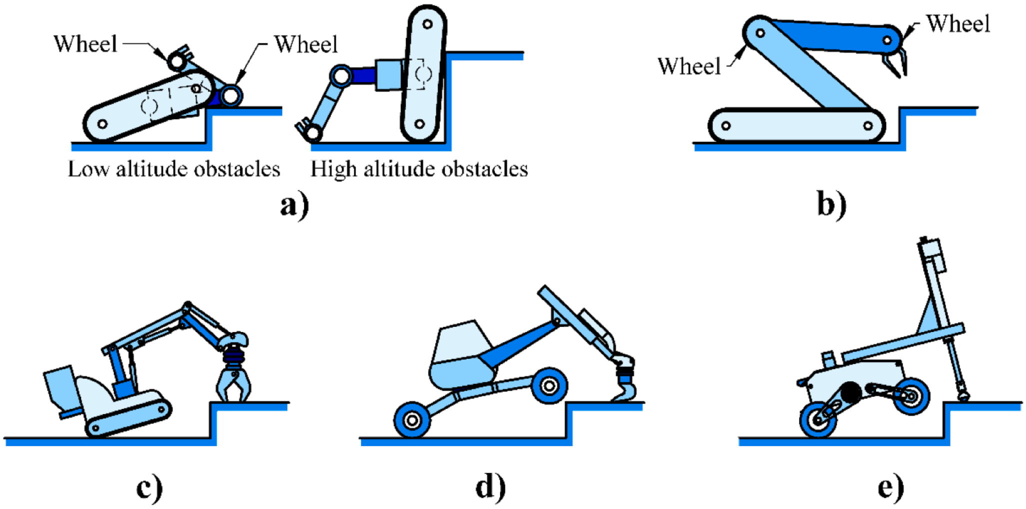

Fig. 21. Robots with ground-contacting arm: (a) Helios series [119,121,122]; (b) *HMR* [120]; (c) *Alacrane* [123]; (d) *HEAP* [124]; (e) Lázaro [125].

provided with an arm with a rigid and sturdy shovel as its end effector, which can also be utilized as a tool to assist the robot in overcoming obstacles (Fig. 21d). In this case, the arm does not have the articulation limitations of *Alacrane*. Therefore, the strategy for overcoming obstacles includes the following steps: first, the arm makes contact with the ground to lift the front part of the robot's body, which, after advancing, can be positioned on the obstacle. Subsequently, by relocating the end effector of the arm, a new point of contact with the ground can be generated to lift the rear part of the robot, allowing it to complete the obstacle traversal. This same strategy is employed by the *Lázaro* robot [125], which features an arm equipped with two joints and a wheel as its end effector, designed especially to provide an additional point of contact with the ground that can be used to enhance its stability against tipping and for overcoming obstacles (Fig. 21e).

After examining the operation of 108 robots capable of overcoming obstacles, Table 1 provides a summary of relevant parameters for a group of these robots (those for which information was provided by the researchers). In addition to basic information such as dimensions, mass, maximum speed, and operational type, three key parameters stand out: wheel radius (r; or pulley radius in tracked systems or nominal radius for transformable or segmented wheels), maximum obstacle height the robot can overcome (Ho), and the Ho/r ratio, which quantifies the robot's ability to overcome obstacles independently of wheel size. In this sense, it is verified under which procedure (source) the Ho/r ratio was obtained, highlighting three alternatives: a theoretical definition derived from equations and based on dimensional limitations of the robot; definition through simulations, mostly conducted via multi-body dynamic simulation, and finally, experimental definition through tests where robots overcome obstacles of varying heights.

On the other hand, the number of degrees of freedom (DOFs) used by the robot for obstacle traversal (including traction and articulations) is also quantified. When analyzing these parameters, it is generally found that a higher number of DOFs increases the robot's ability to overcome obstacles. This factor, while influential, is not determinative, as robots with fewer DOFs were also found to have a good capacity for overcoming obstacles, which is associated with appropriate design characterized by the use of parts (e.g., links) with suitable lengths. This allows the robot to enhance its ability to overcome obstacles despite having fewer DOFs. Based on these findings, it can be concluded that the ability to overcome obstacles, although associated with the implemented obstacle traversal strategy, is also strongly dependent on appropriate and optimized design.

Therefore, Table 2 is presented, listing some additional parameters that designers have possibly considered for the design of the studied robots. These parameters include: optimization in the sizing of the robot to achieve efficient overcoming of the obstacles considered as minimum requirements; structural robustness to achieve high resistance to demanding tasks; adaptability or the robot's ability to adjust to the obstacle to overcome it comfortably; energy efficiency, considered in the selection of low-consumption actuators and in the optimal sizing of the parts.

On the other hand, other parameters were also observed that some authors took into consideration and are related to the operation of the robot during the execution of the overcoming strategy. These include: real-time performance, which involves evaluating processes at each instant to ensure efficient task execution; optimization of the overcoming process, adjusting movements and actions to achieve obstacle overcoming with minimal energy consumption and/or processing; handling of unknown obstacles, through sensory systems that allow the characterization of any obstacle and its overcoming (as long as they do not exceed the dimensional capabilities of the robot); applicability in 2D/3D, or the capacity of the strategy to allow the overcoming of fully irregular obstacles (3D) or structured ones that can be modeled in 2D (e.g., steps); scalability, or the ability to adapt to an increase in requirements; and finally, the nature of the strategy, which can be deliberative or reactive; in this regard, it was observed that almost all studied robots use reactive strategies based on the activation of behaviors and/or movements when obstacles are detected. Only in some cases was a deliberative strategy observed where a sequence of movements is planned and executed to overcome the obstacle.

Finally, Table 2 includes a column indicating those robots that have already been implemented in real-world applications where there are irregular terrains with obstacles. These robots have mainly performed tasks such as planetary exploration, search and rescue, agriculture, security, surveillance, counter-terrorism, firefighting, and cargo transportation

3. Discussion

After reviewing all types of robots capable of overcoming obstacles and describing all the strategies they employ, five principles have been determined to define the strategies for overcoming obstacles. The design of a strategy will be based on the use of one of these principles or their combination. These are described below:

a. ***Adaptation to the obstacle's shape:*** In this case, the robot has an active or passive mechanism that allows the traction-generating element (wheels or tracks) to adapt to the irregular terrain or obstacle's shape without losing contact with the ground, thereby optimizing traction while avoiding instability due to discontinuous

Table 1
Dimensions and characteristics of robots that overcome obstacles.

Name of robot	Dimensions $L \times W \times H$ (m)	Mass (Kg)	functioning	V (m/s)	r (m)	H_o (m)	H_o/r	Source	Dof
SLATS [10]	1.65 × 1.40 × 0.80	420.0	Passive suspension	0.196	0.225	0.27	1.20	S	6
Sojourner [12,13]	0.65 × 0.48 × 0.30	11.5	Rocker bogie	0.007	0.065	0.20	3.08	E	6
Spirit and opportunity [14]	1.50 × 2.30 × 1.50	176.5	Rocker bogie	0.046	0.125	0.20	1.60	E	6
Curiosity [15,126]	2.80 × 2.80 × 2.20	899.0	Rocker bogie	0.042	0.250	0.75	3.00	E	6
Lunar explorer [18]	–	–	Links for passive suspension	0.090	0.150	0.28	1.87	S/E	6
WMR [19]	0.43 (L)	–	Links for passive suspension	–	0.060	0.17	2.75	E	6
Shrimp [21]	0.60 × 0.20 ($L \times H$)	3.1	Links for passive suspension	–	0.055	0.22	4.00	S/E	6
Octal Wheel [26]	–	15.0	Wheels on structures	–	0.103	0.20	2.00	E	8
Epi.q-1 [27,127]	0.36 × 0.28 × 0.16	2.6	Wheels on structures	0.500	0.025	0.09	3.60	E	4
Hanzo [29]	–	–	Wheels on structures	2.700	0.200	0.33	1.65	E	4
Six-wheeled robot [30]	0.40 × 0.36 ($L \times W$)	10.7	Wheels on structures	0.010	0.078	0.09	1.16	S/E	4
Asguard [35]	0.95 × 0.50 × 0.44	9.5	Segmented Wheels	2.000	0.220	0.34	1.54	T	4
Impass [37]	–	–	Wheels with appendages	–	0.550	0.91	1.65	T	6
Hexapod robot [38]	0.50 × 0.40 × 0.14	4.3	Wheels with appendages	0.216	0.135	0.22	1.63	E	6
Q-Whex [39]	0.28 × 0.20 × 0.04	2.4	Segmented Wheels		0.067	0.12	1.86	E	6
Land Devil Ray [40]	0.3 (W)	1.5	Transformable wheels	–	0.100	–	2.80	E	4
Step [41]	–	30.0	Transformable wheels	0.333	0.125	0.12	0.96	E	2*
Fuhar [32]	0.44 × 0.25 × 0.27	9.8	Transformable wheels	2.200	0.044	0.17	3.96	S/E	8
OmniWheg [42]	0.51 × 0.47 × 0.25	5.5	Transformable wheels	–	0.190	0.26	1.37	E	8
TurboQuad [44]	0.71 × 0.37 × 0.16	18.5	Transformable wheels	–	0.105	0.14	1.38	E	8
Wheel-Legged [45]	–	–	Transformable wheels	0.099	0.045	0.12	2.67	E	3
α-WaLTR [47]	0.72 × 0.59 × 0.30	11.0	Transformable wheels	0.500	0.110	0.22	2	E	4
Wheel-legged hybrid robot [48]	0.60 × 0.40 × 0.15	5.0	Transformable wheels		0.075	0.16	2.13	S	4
Self-morphing robot [49]	0.21 × 0.19 × 0.70	0.3	Transformable wheels	1.820	0.035	0.05	1.33	E	2
Transleg [51]	0.34 (L)	–	Links on wheels	0.055	0.055	0.09	1.71	S	8
Tracked Robot [52]	–	62.0	Tracks	0.600	0.250	0.36	1.44	T	2
Raposa [55]	0.75 × 0.37 × 0.18	27.0	Multiple tracks	0.500	0.09	0.17	1.89	E	3
Connected crawler [56]	0.35 × 0.13 ($L \times W$)	0.6	Multiple tracks	–	0.02	0.15	7.50	E	4
LMA [61]	0.4 (L)	34.0	Reconfigurable tracks	–	0.074	0.18	2.43	S/E	3
VSTR [63]	0.80 × 0.56 × 0.15	34.0	Reconfigurable tracks	–	0.075	0.32	4.27	E	3
RTMBot [64]	0.70 × 0.50 × 0.30	–	Reconfigurable tracks	–	0.045	0.20	4.44	T/E	4
Paw [68]	0.49 × 0.17 ($L \times H$)	20.9	Legs with wheels	–	0.032	0.14	4.50	T/E	8
Hylos II [72]	0.70 × 0.45 ($L \times W$)	20.0	Legs with wheels	0.600	0.075	0.19	2.53	E	12
Crank-wheel [87]	1.20 × 0.59 × 0.31	28.0	Legs and wheels	0.066	0.100	0.30	3.00	T	2
Tracked robot [91]	1.20 × 0.50 × 0.37	58.0	Legs with tracks	1.000	0.105	0.50	4.76	T/E	10
ResQuake [95]	0.80 × 0.40 × 0.26	25.0	Legs with tracks	0.320	0.130	0.40	3.07	E	6
Tracked rescue robot [98]	0.81 (L)	38.0	Legs with tracks	–	0.100	0.19	1.9	E	3
Body Rotational Robot [111]	0.60 × 0.46 × 0.45	15.3	Body reposition	0.005	0.080	0.19	2.36	E	5
Rstar [112]	0.21 – 0.24 (L)	–	Body reposition		0.029	0.06	1.89	S/E	4
Fuma [113]	0.63 × 0.59 × 0.89	30.0	Additional link	1.000	0.150	0.33	2.20	E	3
Mantis 2 [115]	0.35 × 0.30 × 0.20	–	Additional link	0.638	0.055	0.16	2.91	T/E	4
Swing arms robot	0.77 × 0.58 × 0.56	18.8	Additional links	5.200	0.073	0.23	3.2	T	8
Helios VII [119]	0.71 × 0.63 ($L \times W$)	84.0	Arm touching the ground	0.200	0.115	0.59	5.13	S	6
Helios VIII [121]	0.54 × 0.49 ($L \times W$)	43.0	Arm touching the ground	0.833	0.101	0.46	4.55	E	6
Helios IX [122]	0.57 × 0.49 ($L \times W$)	38.0	Arm touching the ground	1.667	0.101	0.47	4.65	E	6
HMR [120]	0.81 × 0.63 × 0.18	65.0	Arm touching the ground	1.000	0.090	0.70	7.78	E	4
Lázaro [125]	0.47 × 0.43 × 0.25	26.0	Arm touching the ground	0.280	0.075	0.14	1.87	T/S/E	4

$\boldsymbol{L \times W \times H}$: length, width and Height of the robot; **r:** track o wheel radius (nominal radius in case of robots with transformable or segmented wheels). **V:** max. velocity of the robot; $\mathbf{H_o}$: Max. height of the obstacle that the robot can overcome; $\mathbf{H_o/r}$: Height-to-wheel-radius ratio; **T**: theorical; **E**: experimentation; **S**: Simulation; **DOF:** actuated degrees of freedom involved in the process of overcoming obstacles (including traction and articulations).
(*) Steering is not possible for this robot.

ground contact. Some robots that use this principle are equipped with passive and active suspension.

b. ***Use of traction:*** These robots maximize the traction generated by their wheels or tracks to overcome obstacles, mainly by creating tractive forces resulting from friction large enough to provide the thrust needed for some parts of the robot to scale obstacles upon contact, even in cases where the obstacle's shape does not facilitate overcoming it (e.g., vertical obstacles). Additionally, traction allows parts of the robot that have passed the obstacle to pull the rest of the robot to complete the task. Examples in this group include robots with angled attack tracks, reconfigurable tracks, some modular robots, and robots with body repositioning.
c. ***Positioning parts on the obstacle:*** This is the most commonly used mechanism and involves placing parts of the robot onto the obstacle, even if those parts lose contact with the ground. In this case, stability is ensured by the remaining parts of the robot that still touch the ground, creating a viable support polygon to prevent tipping. Complete obstacle traversal is achieved either by the successive positioning of parts on the obstacle (walking) or by using traction to pull the rest of the robot and complete the task. These robots include those equipped with wheels and legs, wheels with legs, legs and tracks, transformable wheels, wheels on rotational structures, among others.
d. ***Redistribution of reaction forces:*** This mechanism allows the robot to modify the magnitude of reaction forces between the traction elements of the robot and the ground, increasing some to enhance ground friction and, consequently, traction, or decreasing them to lift a part of the robot that contributes to overcoming obstacles. This mechanism has been observed in some robots with active suspension that increase or decrease reactive forces using an actuator that adds energy to the suspension system and in robots with body repositioning that change the COG's location, achieving the redistribution of reaction forces between the robot and the ground.

Table 2
Parameters considered in the design of robots for obstacle overcoming.

Name of robot	Dimensional optimization	Robustness	Scalability	Adaptability	Energy efficiency	Real-time performance	optimization of the overcoming process	Handling of unknown obstacles	Applicability in 2D/3D	Implementation in real-world applications
Sojourner [13]	√	√		√			√	√	3D	Planetary exploration
SLATS [10]		√		√			√		2D	–
Spirit and opportunity [14]	√	√	√	√		√	√	√	3D	Planetary exploration
ATV [16]				√		√	√		3D	Forest exploration
WMR [19]	√		√	√	√	√	√	√	2D	–
Shrimp [21]		√					√		3D	Mining, construction, agriculture and search
Six-wheeled robot [24]				√			√		3D	–
Epi.q-1 [27,127]	√		√	√			√	√	3D	–
Six-wheeled robot [30]	√			√			√		3D	–
Whegs II [34]		√		√		√	√		2D	–
Asguard [35]	√	√		√	√	√	√	√	2D	Security, surveillance
Levo [36]	√	√		√			√		2D	–
Impass [37]				√			√		2D	Search and rescue, reconnaissance and anti-terrorist response.
Hexapod robot [38]	√	√		√			√		2D	–
Q-Whex [39]	√	√	√	√		√	√		3D	Search and rescue, reconnaissance surveillance
Land Devil Ray [40]	√	√	√	√		√	√		2D	Search and rescue
Step [41]	√	√		√			√		2D	–
OmniWheg [42]	√	√	√	√		√	√		2D	–
TurboQuad [44]		√		√		√			2D	–
Wheel-Legged [45]	√			√			√		2D	–
Military Surveillance Robot [46]	√	√		√			√		2D	military surveillance
Wheel-legged hybrid robot [48]	√	√		√			√		3D	Counterterrorism, detection and reconnaissance
Dual-crawler-driven [53]				√			√		2D	–
ROBHAZ-DT3 [54]	√	√		√		√	√	√	3D	Search and rescue
RAPOSA [55]		√		√		√		√	3D	Search and rescue
Connected crawler [56]				√			√		2D	–
TAQT Carrier		√		√			√	√	2D	Freight transport
Firefighting robot [59]	√	√		√			√		2D	Firefighting
Track Walker [60]	√	√		√			√		3D	Exploration
LMA [61]		√		√			√		2D	–
VSTR [63]	√	√		√	√	√	√	√	3D	Real rescue operations
RTMBot [64]	√	√		√			√		2D	–
PAW [68]				√			√		2D	–
Complios [69]	√	√		√		√	√	√	3D	–
MHT [70]		√		√			√		3D	–
Hylos II [72]		√		√		√	√		2D	–
ANYmal [73]		√	√	√	√	√	√	√	3D	Exploration
MAMMOTH [76]				√			√		3D	–
Octopus [78]		√		√		√	√	√	2D	–
6-leg/wheel mechanism [79]		√				√	√		2D	–

(*continued on next page*)

Table 2 (*continued*)

Name of robot	Dimensional optimization	Robustness	Scalability	Adaptability	Energy efficiency	Real-time performance	optimization of the overcoming process	Handling of unknown obstacles	Applicability in 2D/3D	Implementation in real-world applications
BIT-NAZA [80]		√		√			√		2D	–
Ascento [83]	√	√							2D	–
Jumping robot [84]		√		√			√		3D	–
Wheeleg [86]				√			√		2D	–
HyTRo-I [88]	√	√		√	√		√		2D	–
MINBOT-I [91]		√					√		2D	Mine search and rescue
MINBOT-II [92]	√	√		√	√		√		3D	Mine search and rescue
Tracked rescue mobile robot [98]	√	√		√			√		2D	Search and rescue
Spider-leg [100]	√	√		√			√	√	2D	–
Azimut [101]	√	√	√	√		√	√		3D	–
Mobit [102]		√		√		√	√			–
Wheel-tracked mobile robot [103]	√	√		√			√		2D	–
WheTLHLoc [104]	√	√		√			√		2D	–
AMOEBA-I [106]		√		√					3D	–
JL-2 [109]		√		√			√		2D	–
Modular robot with wheels [110]		√		√			√		3D	–
Four-wheeled robot [111]				√			√		2D	–
RSTAR [112]	√	√	√	√	√	√	√	√	2D	–
FUMA [113]				√			√		2D	Search and rescue
Mantis 2 [115]	√			√	√		√		3D	Surveillance and inspection
Robot with swinging arms [118]	√			√			√		2D	–
Helios VII [119]		√		√			√		2D	Search and rescue
Helios VIII [121]	√	√		√		√	√		2D	Search and rescue
Helios IX [122]	√	√		√	√		√		2D	Search and rescue
HMR [120]		√		√			√		3D	Search and rescue, military operations and inspections

e. ***Jumps:*** This novel mechanism uses the principles of dynamics to facilitate the complete elevation of the robot, meaning that all contact points of the robot with the ground are simultaneously lost for a brief moment. In this case, the robot is propelled to jump over the obstacle and overcome it, landing in a position that allows it to maintain stability and continue its journey. This mechanism was observed in robots equipped with wheeled legs designed for this purpose.

These principles greatly influence the morphology of the robot, which must meet a set of requirements defined during the early stages of robot development, and they have a significant impact on its efficiency in performing the task of overcoming obstacles. Finally, the following requirements are listed:

(a) ***Definition of the operation principle and strategy for obstacle overcoming:*** It is necessary to preselect the principle to be used for overcoming the obstacle (according to the principles listed previously). In this regard, new robots can be defined that combine these principles in a way that allows for greater efficiency and versatility. Based on this, a specific strategy must be designed for the robot to follow in overcoming obstacles, according to a chosen paradigm for its implementation: deliberative, if all the robot's actions are planned before starting the obstacle overcoming; reactive, if the robot adopts unplanned actions as it encounters obstacles; or hybrid, if there is a combination of both approaches.

(b) ***Definition of mechanical systems and mechanisms:*** This includes defining a morphology and DOFs according to the type of obstacle to be overcome and the desired strategy to be implemented. It is important to develop new mechanisms that consider multiple motion systems, as they are effective for facing different situations. Additionally, the design of deployable mechanisms can be considered to place a component of the robot on the obstacle to be overcome, as this facilitates the subsequent overcoming process, according to the strategy to be implemented.

(c) **Robot sizing:** The robot must have dimensions in its movable and fixed parts, as well as sufficient joint limits to overcome the obstacle. It is important to note that the dimensions and shape of the obstacle should be obtained before starting the overcoming strategy, so that it can be evaluated whether the robot has the dimensional and joint capabilities to overcome it, knowing that these capabilities are typically established in the robot's design phase.

(d) ***Traction and suspension systems:*** The robot must have sufficient mechanical capabilities to overcome the obstacle; these capabilities are typically related to the mechanical limitations of the actuators. For example, the maximum torques generated by the traction motors must be sufficient to pull the robot over the obstacle and facilitate its progress, or the maximum torques/ forces generated by other actuators must be sufficient to lift the robot and overcome the obstacle. This requirement is usually considered during the robot's design phase and is defined considering the maximum dimensions of the obstacle that is intended to be overcome.

    Additionally, the robot must have appropriate grip to enable it to advance and overcome the obstacle. This requirement must be addressed from two perspectives: firstly, defining appropriate suspension systems that allow continuous contact of the traction-generating elements (e.g., wheels) with the ground; secondly, studying the terrain mechanics or contact characteristics between the robot and the ground that must be evaluated before or during the execution of the overcoming strategy based on aspects such as: the type of terrain (hard, with particles) and its characteristics, such as friction.

(e) ***Use of advanced materials:*** The use of lightweight yet durable materials such as carbon composites and advanced alloys ensures durability without compromising maneuverability. For elements in contact with the ground, materials with appropriate characteristics such as friction coefficients should be selected to ensure grip and traction. This is crucial for operations in hostile or unknown environments.

(f) ***Perception systems and sensors:*** The robot must have a set of appropriate sensors that allow it, first of all, to perceive the environment to obtain data aimed at detecting an obstacle, characterizing it, and estimating its dimensions. This includes the integration of a set of state-of-the-art sensors, including LiDAR, sonars, and stereoscopic cameras, which allow detailed perception of the environment to identify and classify obstacles. Additionally, the robot must have other sensors that allow it to evaluate its state during the obstacle overcoming process, to ensure that it operates within normal functioning parameters and that the strategy is being executed as planned.

(g) ***Energy Autonomy:*** During the design phase, it is essential to consider integrating an autonomous energy system, which will undoubtedly require physical space for energy storage and/or generation, affecting the sizing and weight of the robot. In this regard, technologies such as solar power or new high-capacity batteries can be considered to extend operations without the need for frequent recharges.

(h) ***Robust Control:*** Robust control strategies must be developed to enable the robot to respond to unexpected changes in the environment and maintain navigability. These strategies should take into account factors such as the slope of the obstacle, terrain friction, and external disturbances.

(i) ***Standardized Evaluation Methods:*** Developing standardized methods to compare the performance of mobile robots in overcoming obstacles under various conditions is crucial. These methods should include evaluation of design optimization, efficient environment detection and characterization, operational optimization, energy savings, and effectiveness in overcoming obstacles.

(j) ***Experimental Validation:*** Prioritizing experimental tests in realistic conditions over simulations is crucial. Simulations often cannot replicate all the real variables that the robot will face in environments such as planetary exploration, agriculture, and outdoor surveillance. Conducting tests in these scenarios helps evaluate the practical applicability of the developed robot.

(k) ***Adequate Navigability:*** the robot must meet criteria to ensure its navigability or the ability to move on the terrain. This includes aspects such as the robot's ability to overcome the obstacle without causing a rollover that would render the robot unusable (rollover stability) [125,128]; the ability to move without losing its position due to total slippage [129], and the ability to steer [130], in cases where the robot needs to change its trajectory during obstacle overcoming. These aspects should be evaluated before or during the strategy execution (depending on the degree of reactivity) to guarantee success in fulfilling this task.

(l) ***Integration of Artificial Intelligence:*** Finally, the use of AI is enabling the development of innovative robots that can implement variable strategies for overcoming obstacles and adaptive control, achieving adaptability, learning, and real-time decision-making. This is essential for improving the navigability of robots in dynamic environments with irregular and changing topography.

4. Conclusions

This article provides a comprehensive review of 108 ground mobile robots with wheels designed to overcome obstacles. The study classifies these robots into six main categories based on their operating principle and obstacle avoidance strategy. From the analysis conducted, it was found that both defining the obstacle avoidance strategy and optimizing the robot's design are crucial for achieving efficient obstacle overcoming. This suggests that robot designers must carefully consider both the physical aspects of the robot and the control algorithms that guide it. In this regard, an analysis of the various requirements to design efficient robots for the obstacle overcoming task was conducted.

Among these requirements, the importance of robot sizing, along with the design of traction and suspension systems, stands out, allowing for improved adaptability, maneuverability, and ground contact, especially on uneven terrains. Specifically, these systems enable the robot to adapt to the irregularities of the terrain and maintain traction by ensuring a normal contact force with the ground, which is essential for overcoming obstacles. On the other hand, the study emphasizes the need for robust control strategies that enable the robot to respond to unexpected changes in the environment and maintain navigability. These strategies must consider factors such as obstacle slope, terrain friction, and external disturbances.

Additionally, from this study, some relevant factors for the design of future robots can be considered, including exploring new designs that combine different operating principles and obstacle overcoming strategies for greater efficiency and versatility. Furthermore, prioritizing the need for experimental validation over simulation is crucial to evaluate the practical applicability of designed algorithms since it considers multiple factors that cannot be accounted for during simulations. It would be worthwhile for this validation process to include realistic tests in scenarios where these robots normally operate: planetary exploration, agriculture, outdoor surveillance, search and rescue in disaster areas, among others.

Moreover, it would be valuable to investigate more advanced obstacle overcoming strategies that leverage artificial intelligence to enhance adaptation, learning, and real-time decision-making. This would improve the efficiency in the navigability of wheeled ground robots in dynamic environments with irregular and even changing topography, such as terrains with loose obstacles (rocks, logs, etc.) that the robot needs to overcome. This should be associated with studies that improve the integration of sensors and perception systems to increase the situational awareness of the robot and its ability to navigate complex terrains.

Finally, standardized evaluation methods should be developed to compare the performance of different wheeled mobile robots for obstacle overcoming under various conditions. These methods should include the evaluation of design optimization, efficient environment detection and characterization, operational optimization, energy savings, effectiveness in the obstacle overcoming process, among other aspects.

CRediT authorship contribution statement

Jesús M. García: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Franklyn G. Duarte:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

No data was used for the research described in the article.

Acknowledgments

This work was partially supported by the 01-025-2016 project of Decanato de Investigación of Universidad Nacional Experimental del Táchira, Venezuela.

References

[1] F. Matsuno, S. Tadokoro, «Rescue robots and systems in Japan,», in: IEEE International Conference on Robotics and Biomimetics, Shenyang, 2004, https://doi.org/10.1109/ROBIO.2004.1521744.

[2] M. Guarnieri, R. Kurazume, H. Masuda, T. Inoh, K. Takita, P. Debenest, R. Hodoshima, E. Fukushima, S. Hirose, «Helios system: a team of tracked robots for special urban search and rescue operations,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, 2009, https://doi.org/10.1109/IROS.2009.5354452.

[3] S. Moosavian, H. Semsarilar, A. Kalantari, «Design and manufacturing of a mobile rescue robot,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, 2006, https://doi.org/10.1109/IROS.2006.281835.

[4] J. Casper, R.R. Murphy, «Human-Robot Interactions during the robot-assisted urban search and rescue responde at the World Trade Center,», in: IEEE Transactions on Systems, man, and cybernetics-Parte B 33, June 2003, pp. 367–385, https://doi.org/10.1109/TSMCB.2003.811794, n°.

[5] Q. Feng, X. Wang, W. Zheng, Q. Qiu, K. Jiang, «New strawberry harvesting robot for elevated-trough culture,», International Journal of Agricultural and Biological Engineering 5 (2) (2012) 1–8, n°.

[6] M. Zhenming, L. Deliang, «Suspension system design of all-terrain fire-fighting robot,», in: International Conference on Virtual Reality and Intelligent Systems, Hunan, 2018, https://doi.org/10.1109/ICVRIS.2018.00120.

[7] P. Boeder, C. Soares, «Mars 2020: mission, science objectives and build,», in: Proc. SPIE11489, Systems Contamination: Prediction, Control, and Performance 11489, 2020, pp. 1–17, https://doi.org/10.1117/12.2569650.

[8] Y. Changlong, M. Shugen, L. Bin, «Development of a shape-shifting mobile robot for urban search and rescue,», Chinese Journal of Mechanical Engineering 21 (2) (2008) 31–35, https://doi.org/10.3901/CJME.2008.02.031, n°.

[9] J. Hurel, A. Mandow, A. García-Cerezo, «Los sistemas de suspensión activa y semiactiva: una revisión,», Revista iberoamericana de automática e informática 10 (2) (2013) 121–132, https://doi.org/10.1016/j.riai.2013.03.002, n°.

[10] S. Zhang, X. Zhao, W. Su, H. Wu, Z. Dai, Z. Chen, «The design of suspension mechanism and analysis of obstacle ability to rescue robots,» *Recent Developments in Mechatronics and Intelligent Robotics*, in: K. Deng, Z. Yu, S. Patnaik, J. Wang (Eds.), ICMIR 2018. Advances in Intelligent Systems and Computing, Springer, 2018, https://doi.org/10.1007/978-3-030-00214-5_85 vol. 856.

[11] Z. Wang, J. Zhao, G. Zeng, «Modeling, simulation and implementation of all terrain adaptive five DOF robot,», Sensors 22 (6991) (2022) 1–29, https://doi.org/10.3390/s22186991, n°.

[12] J. Ma, J. Cheng, D. Zuang, «Analysis of Sojourner's six-wheeled rocker suspension appended with driving moment,», International Conference on Information Engineering and Computer Science (2009) https://doi.org/10.1109/ICIECS.2009.5363163.

[13] D. Bickler, «Roving over Mars,», Mechanical Engineering (1998) 74–77, https://doi.org/10.1115/1.1998-APR-6.

[14] R. Lindemann, D. Bickler, B. Harrington, G. Ortiz, C. Voorhees, «Mars exploration rover mobility development,», IEEE Robotics & Automation Magazine 13 (2) (2006) 19–26, https://doi.org/10.1109/MRA.2006.1638012, n°.

[15] M. Heverly, J. Matthews, J. Lin, D. Fuller, M. Maimone, J. Biesiadecki, J. Leichty, «Traverse performance characterization for the mars science laboratory rover,», Journal of Field Robotics 30 (6) (2013) 835–846, https://doi.org/10.1002/rob.21481, n°.

[16] M. Morita, T. Nishida, Y. Arita, M. Shige-eda, E. di Maria, R. Gallone, N. I. Giannoccaro, «Development of robot for 3D measurement of forest environment,», Journal of Robotics and Mechatronics 30 (1) (2018) 145–154, https://doi.org/10.20965/jrm.2018.p0145, n°.

[17] S. Ylönen, A. Halme, «WorkPartner - Centaur like service robot,», in: IEEE/ASME International Conference on Intelligent Robots and Systems, Lausanne, 2002, https://doi.org/10.1109/IRDS.2002.1041477.

[18] B. Chen, R. Wang, L. Yang, L. Jin, L. Guo, «Design and simulation research on a new type of suspension for lunar rover,», in: IEEE International Symposium on Computational Intelligence in Robotics and Automation, Jacksonville, 2007, https://doi.org/10.1109/CIRA.2007.382864.

[19] C. Woo, H. Choi, S. Yoon, S. Kim, Y. Kwak, «Optimal design of a new wheeled mobile robot based on a kinetic analysis of the stair climbing states,», Journal of Intelligent Robot Systems 49 (2007) 325–354, https://doi.org/10.1007/s10846-007-9139-8.

[20] R. Siegwart, I. Nourbakhsh, Introduction to autonomous mobile robots, 1 ed., The MIT Press, Cambridge, 2004.

[21] R. Siegwart, P. Lamon, T. Estier, M. Lauria, R. Piguet, «Innovative design for wheeled locomotion in rough terrain,», Robotics and Autonomous Systems 20 (2-3) (2002) 151–162, https://doi.org/10.1016/S0921-8890(02)00240-3, n°.

[22] B. Bluethmann, E. Herrera, A. Hulse, J. Figuered, L. Junkin, M. Markee, R. Ambrose, «An active suspension system for lunar crew mobility,», in: IEEE Aerospace Conference, Big Sky, 2010, https://doi.org/10.1109/AERO.2010.5446895.

[23] K. Iagnemma, A. Rzepniewski, S. Dubowsky, P. Schenker, «Control of robotic vehicles with actively articulated suspensions in rough terrain,», Autonomous Robots 14 (1) (January 2003) 5–16, https://doi.org/10.1023/A:1020962718637, n°.

[24] J. Shang, Z. Luo, D. Fan, F. Zhao, «A six wheeled robot with active self-adaptive suspension for lunar exploration,», in: International Technology and Innovation Conference, Hangzhou, 2006.

[25] S. Kang, W. Lee, M. Kim, K. Shin, «Robhaz-rescue: Rough-terrain negotiable teleoperated mobile robot for rescue mission,», in: IEEE International Workshop on Safety, Security and Rescue Robotics, Kobe, 2005, https://doi.org/10.1109/SSRR.2005.1501248.

[26] Y. Takita, N. Shimoi, H. Date, «Development of a wheeled mobile robot " Octal Wheel " realized climbing up and down stairs,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Sendai, 2004, https://doi.org/10.1109/IROS.2004.1389774.

[27] G. Quaglia, R. Oderio, L. Bruzzone, R. Razzoli, «A modular approach for a family of ground mobile robots,», International Journal of Advanced Robotic Systems 10 (296) (2013) 1–11, https://doi.org/10.5772/56086, n°.

[28] A. Botta, P. Cavallone, L. Tagliavi, L. Carbonari, C. Visconte, G. Quaglia, «An estimator for the kinematic behaviour of a mobile robot subject to large lateral slip,», Applied Sciences 11 (1594) (2021) 1–10, https://doi.org/10.3390/app11041594, n°.

[29] N. Shiroma, Y. Chiu, Z. Min, I. Kawabuchi, F. Matsuno, «Development and control of a high maneuverability wheeled robot with variable-structure functionality,», in: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, 2006, https://doi.org/10.1109/IROS.2006.281839.

[30] Z. Song, Z. Luo, G. Wei, J. Shang, «Design and analysis of a six-wheeled companion robot with mechanical obstacle-overcoming adaptivity,», Mechanical Sciences 12 (2) (2021) 1115–1136, https://doi.org/10.5194/ms-12-1115-2021, n°.

[31] Z. Song, Z. Luo, G. Wei, J. Shang, «A portable six-wheeled mobile robot with reconfigurable body and self-adaptable obstacle climbing mechanisms«, Journal of Mechanisms and Robotics 14 (5) (2022) 1–21, https://doi.org/10.1115/1.4053529, n°.

[32] I. Mertyüz, A. Tanyıldızi, B. Taşar, A. Tatar, O. Yakut, «FUHAR: A transformable wheel-legged hybrid mobile robot,», Robotics and Autonomous Systems (133) (2020) 1–15, https://doi.org/10.1016/j.robot.2020.103627, n°.

[33] R. Schroer, M. Boggess, R. Bachmann, R. Quinn, R. Ritzmann, «Comparing cockroach and whegs robot body motions,», in: IEEE International Conference on Rocbotics & Automation, New Orleans, 2004, https://doi.org/10.1109/ROBOT.2004.1308761.

[34] W. Lewinger, C. Harley, R. Ritzmann, M. Branicky, R. Quinn, «Insect-like antennal sensing for climbing and tunneling behavior in a biologically-inspired mobile robot,», IEEE International Conference on Robotics and Automation (2005) https://doi.org/10.1109/ROBOT.2005.1570761.

[35] M. Eich, F. Grimminger, F. Kirchner, «A versatile stair-climbing robot for search and rescue aplications,», in: IEEE International Workshop on Safety, Security and Rescue Robotics, Sendai, 2008, https://doi.org/10.1109/SSRR.2008.4745874.

[36] D. Son, J. Shin, Y. Kim, T. Seo, «LEVO: Mobile robotic platform using wheelmode switching primitives,», International Journal of Precision Engineering and Manufacturing 23 (2022) 1291–1300, https://doi.org/10.1007/s12541-022-00696-1.

[37] J.B. Jeans, D. Hong, «IMPASS: Intelligent mobility platform with active spoke system,», in: IEEE International Conference on Robotics and Automation, Kobe, 2009, https://doi.org/10.1109/ROBOT.2009.5152735.

[38] Y. Ni, L. Li, J. Qiu, Y. Sun, G. Qin, Q. Han, A. Ji, «A novel wheel-legged hexapod robot,», Biomimetics 7 (146) (2022) 1–12, https://doi.org/10.3390/biomimetics7040146, n°.

[39] G. Zhang, S. Ma, J. Liu, X. Zeng, L. Kong, Y L, «Q-Whex: A simple and highly mobile quasi-wheeled hexapod robot,», Journal of field robotics 40 (6) (2023) 1444–1459, https://doi.org/10.1002/rob.22186, n°.

[40] L. Bai, J. Guan, X. Chen, J. Hou, W. Duban, «An optional passive/active transformable wheel-legged mobility concept for search and rescue robots,», Robotics and Autonomous Systems 107 (2018) 145–155, https://doi.org/10.1016/j.robot.2018.06.005.

[41] Y. Kim, Y. Lee, S. Lee, J. Kim, H. Kim, T. Seo, «STEP: A new mobile platform with 2-DOF transformable wheels for service robots,», IEEE/ASME Traasactions on Mechatronics 5 (4) (2020) 1859–1868, https://doi.org/10.1109/TMECH.2020.2992280, n°.

[42] R. Cao, J. Gu, C. Yu, A. Rosendo, «OmniWheg: an omnidirectional wheel-leg transformable robot,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Kyoto, 2022, https://doi.org/10.1109/IROS47612.2022.9982030.

[43] Z. Liu, C. Dai, X. Liu, J. Zhou, Z. Jia, «Hybrid wheel-leg transformable robot with minimal actuator realization,», in: 2022 International Conference on Advanced Robotics and Mechatronics, Guilin, 2022, https://doi.org/10.1109/ICARM54641.2022.9959370.

[44] W. Chen, H. Lin, Y. Lin, P. Lin, «TurboQuad: a novel leg–wheel transformable robot with smooth and fast behavioral transitions,», IEEE Transactions on Robotics 33 (5) (2017) 1025–1040, https://doi.org/10.1109/TRO.2017.2696022, n°.

[45] H. Suwoyo, T. Hidayat, F. Jia-nan, «A transformable wheel-legged mobile robot,», International Journal of Engineering Continuity 2 (1) (2023) 27–39, n°.

[46] I. Sayeed, S. Anjum, M. Akhtaruzzaman, «Design and develop of a transformable wheel mechanism for a military surveillance robot,», The MIST Journal of Computer Science and Engineering 01 (01) (2022) 11–16, n°.

[47] C. Zheng, S. Sane, K. Lee, V. Kalyanram, K. Lee, «α-WaLTR: adaptive wheel-and-Leg transformable robot for versatile multiterrain locomotion,», IEEE Transactions on Robotics 39 (2) (2023) 941–958, https://doi.org/10.1109/TRO.2022.3226114, n°.

[48] Y. Tao, C. Gao, Y. Shi, M. Li, M. Zhang, D. Liu, «Analysis of motion characteristics and stability of mobile robot based on a transformable wheel mechanism,», Applied sciences 12 (23) (2022) 1–19, https://doi.org/10.3390/app122312348, n°.

[49] S. Ryu, Y. Lee, T. Seo, «Shape-morphing wheel design and analysis for step climbing in high speed locomotion,», IEEE Robotics and automation letters 5 (2) (2020) 1977–1982, https://doi.org/10.1109/LRA.2020.2970977, n°.

[50] K. Tadakuma, R. Tadakuma, S. Hirose, «Motions on steps and slopes of omni-directional mobile robot,"VmaxCarrier2",», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, 2005, https://doi.org/10.1109/IROS.2005.1545384.

[51] Z. Wei, G. Song, H. Sun, Q. Qi, S. Liu, G. Qiao, «Step-climbing maneuver for transleg in the wheeled mode,», in: 18th International Conference on Advanced Robotics (ICAR), Hong Kong, 2017, https://doi.org/10.1109/ICAR.2017.8023647.

[52] W. Tao, Y. Ou, H. Feng, «Research on dynamics and stability in the stairs-climbing of a tracked mobile robot,», International Journal of Advanced Robotic Systems 9 (146) (2012) 1–9, https://doi.org/10.5772/52850, n°.

[53] Q. Quan, S. Ma, «Controllable postures of a dual-crawler-driven robot,», Mechatronics 20 (2010) 281–292, https://doi.org/10.1016/j.mechatronics.2010.01.001.

[54] W. Lee, S. Kang, M. Kim, K. Shin, «Rough terrain negotiable mobile platform with passively adaptive double-tracks and its application to rescue missions,», in: IEEE International Conference on Robotics and Automation, Barcelona, 2005, https://doi.org/10.1109/ROBOT.2005.1570341.

[55] C. Marques, C. Joao, P. Lima, J. Frazao, I. Ribeiro, R. Ventura, «Raposa: semi-autonomous robot for rescue operations,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, 2006, https://doi.org/10.1109/IROS.2006.281836.

[56] S. Yokota, Y. Ohyama, H. Hashimoto, J. She, K. Kawabata, P. Blazevic, H. Kobayashi, «Development of the Connected Crawler Robot for rough terrain,», in: 4th International Conference on Informatics in Control, Automation and Robotics, Robotics and Automation, Angers, 2007. http://doi.org/10.5220/0001624203960401.

[57] S. Yokota, Y. Ohyama, H. Hashimoto, J. She, H. Kobayashi, P. Blazevic, «Development of rough terrain mobile robot using connected crawler -Derivation of sub-optimal number of crawler stages,», in: A. Zemliak (Ed.), Frontiers in Robotics, Automation and Control, InTech, 2008, pp. 376–390.

[58] S. Hirose, T. Sensu, S. Aoki, «The Taqt Carrier: A Practical terrain- adaptive quadru-track carrier robot,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Raleigh, 1992, https://doi.org/10.1109/IROS.1992.601941.

[59] J. Zhao, Z. Zhang, S. Liu, Y. Tao, Y. Liu, «Design and research of an articulated tracked firefighting robot,», Sensors 22 (5086) (2022) 1–24, https://doi.org/10.3390/s22145086, n°.

[60] K. Nagatani, H. Kinoshita, K. Yoshida, K. Tadakuma, E. Koyanagi, «Development of leg-track hybrid locomotion to traverse loose slopes and irregular terrain,», Journal of Field Robotics 28 (6) (2011) 950–960, https://doi.org/10.1002/rob.20415, n°.

[61] P. Ben-tzvi, S. Ito, A. Goldenberg, «A mobile robot with autonomous climbing and descending of stairs,», Robotica 27 (2009) 171–188, https://doi.org/10.1017/S0263574708004426.

[62] Y. Liu, G. Liu, «Interaction analysis and posture optimization for a reconfigurable tracked mobile modular manipulator negotiating slopes,», in: IEEE International conference on Robotics and Automation, Anchorage, 2010, https://doi.org/10.1109/ROBOT.2010.5509986.

[63] K. Choi, H. Jeong, K. Hyun, H. Choi, Y. Kwak, «Obstacle negotiation for the rescue robot with variable single-tracked mechanism,», in: IEEE/ASME international conference on Advanced intelligent mechatronics, Zurich, 2007, https://doi.org/10.1109/AIM.2007.4412417.

[64] Z. Luo, J. Shang, Z. Zhang, «A reconfigurable tracked mobile robot based on four-linkage mechanism,», Journal of Central South University 20 (2013) 62–70, https://doi.org/10.1007/s11771-013-1460-8.

[65] X. Gao, D. Cui, W. Guo, Y. Mu, B. Li, «Dynamics and stability analysis on stairs climbing of wheel–track mobile robot,», in: International Journal of Advanced Robotic Systems 14, 2017, pp. 1–13, https://doi.org/10.1177/1729881417720783, n°.

[66] A. Kumar, P.B. Kumar, D.R. Parhi, «Intelligent navigation of humanoids in cluttered environments using regression analysis and genetic algorithm,», Arabian Journal for Science and Engineering 43 (2018) 7655–7678, https://doi.org/10.1007/s13369-018-3157-7.

[67] P. Biswal, P.K. Mohanty, «Modeling and effective foot force distribution for the legs of a quadruped robot,», Robotica 39 (8) (2021) 1504–1517, https://doi.org/10.1017/S0263574720001307, n°.

[68] K. Turker, I. Sharf, M. Trentini, «Step negotiation with wheel traction: a strategy for a wheel-legged robot,», in: 2012 IEEE International Conference on Robotics and Automation, Saint Paul, Minnesota, 2012, https://doi.org/10.1109/ICRA.2012.6224645.

[69] A. Bouton, C. Grand, F. Benamar, «Obstacle negotiation learning for a compliant wheel-on-leg robot,», in: 2017 IEEE International Conference on Robotics and Automation, Sigapure, 2017, https://doi.org/10.1109/ICRA.2017.7989281.

[70] C. Wong, K. Turker, I. Sharf, B. Beckman, «Posture Reconfiguration and Navigation Maneuvers on a Wheel-Legged Hydraulic Robot,», in: L. Mejias,

P. Corke, J. Roberts (Eds.), Field and Service Robotics. Springer Tracts in Advanced Robotics, Springer, 2015, pp. 215–228, https://doi.org/10.1007/978-3-319-07488-7_15.

[71] P. Jarrault, C. Grand, P. Bidaud, of a Poly-articulated Mobile Robot During Obstacle Clearance,», in: V. Padois, P. Bidaud, O. Khatib (Eds.), Romansy 19 – Robot Design, Dynamics and Control. CISM International Centre for Mechanical Sciences, Springer, 2013 https://doi.org/10.1007/978-3-7091-1379-0_36 vol. 544.

[72] C. Grand, P. Jarrault, F. Amar, P. Bidaud, «Experimental evaluation of obstacle clearance by a hybrid wheel-legged robot,», Experimental Robotics. Springer Tracts in Advanced Robotics 109 (2016) 47–58, https://doi.org/10.1007/978-3-319-23778-7_4. M. Hsieh, O. Khatib y V. Kumar, Edits., Springer.

[73] V. Medeiros, E. Jelavic, M. Bjelonic, R. Siegwart, M. Meggiolaro, m. Hutter, «Trajectory optimization for wheeled-legged quadrupedal robots driving in challenging terrain,», IEEE Robotics and Automation Letters 5 (3) (2020) 4172–4179, https://doi.org/10.1109/LRA.2020.2990720, n°.

[74] F. Cordes, A. Dettmann, F. Kirchner, «Locomotion modes for a hybrid wheeled-leg planetary rover,», IEEE international conference on robotics and biomimetics (2011) https://doi.org/10.1109/ROBIO.2011.6181694.

[75] F. Cordes, F. Kirchner, A. Babu, «Design and field testing of a rover with an actively articulated suspension system in a mars analogue terrain,», Journal of Field Robotics 35 (7) (2018) 1149–1181, https://doi.org/10.1002/rob.21808, n°.

[76] W. Reid, F. Pérez-Grau, A. Göktogan, S. Sukkarieh, «Actively articulated suspension for a wheel-on-leg rover operating on a martian analog surface,», in: 2016 IEEE International Conference on Robotics and Automation, Stockholm, 2016, https://doi.org/10.1109/ICRA.2016.7487777.

[77] M. Schwarz, T. Rodehutskors, M. Schreiber, S. Behnke, «Hybrid driving-stepping locomotion with the wheeled-legged robot Momaro,», in: 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, 2016, https://doi.org/10.1109/ICRA.2016.7487776.

[78] M. Lauria, Y. Piguet, R. Siegwart, «Octopus: an autonomous wheeled climbing robot,» http://www.asl.ethz.ch/robots/octopus, 2008 (accessed: 01 April 2015).

[79] X. Liu, L. Chang, S. Zhao, H. Dong, Z. Li, «Study on the obstacle crossing dynamics of a leg-wheeled mine rescue robot,», International Journal of Science 6 (1) (2019) 118–122, n°.

[80] F. Guo, S. Wang, J. Wang, «A search-based control architecture for wheel-quadruped robot obstacle negotiation,», in: 2018 Annual American Control Conference (ACC), Milwaukee, 2018, https://doi.org/10.23919/ACC.2018.8430848.

[81] K. Xu, S. Wang, J. Wang, X. Wang, Z. Chen, J. Si, «High-adaption locomotion with stable robot body for planetary exploration robot carrying potential instruments on unstructured terrain,», Chinese Journal of Aeronautics 34 (5) (2021) 652–665, https://doi.org/10.1016/j.cja.2020.11.012, n°.

[82] IEEE, «Handle,» https://robots.ieee.org/robots/handle/, 2021 (accessed: 30 April 2021).

[83] V. Klemm, A. Morra, C. Salzmann, F. Tschopp, K. Bodie, L. Gulich, N. Küng, D. Mannhart, C. Pfister, M. Vierneisel, F. Weber, R. Deuber, R. Siegwart, «Ascento: A two-wheeled jumping robot,», in: 2019 International Conference on Robotics and Automation, Montreal, 2019, https://doi.org/10.48550/arXiv.2005.11435.

[84] T. Guo, J. Liu, H. Liang, Y. Zhang, W. Chen, X. Xia, M. Wang, Z. Wang, «Design and dynamic analysis of jumping wheel-legged robot in complex terrain environment,», Frontiers in neurorobotics 16 (1066714) (2022) 1–17, https://doi.org/10.3389/fnbot.2022.1066714, n°.

[85] T. Mabuchi, T. Nagasawa, K. Awa, J. Shiraki, T. Yamada, «Development of a stair-climbing mobile robot with legs and wheels,», Artificial Life and Robotics 2 (4) (1998) 184–188, https://doi.org/10.1007/BF02471179, n°.

[86] S. Guccione, G. Muscato, «The Wheeleg robot,», IEEE Robotic & automation magazine 14 (4) (2003) 33–43, https://doi.org/10.1109/MRA.2003.1256296, n°.

[87] H. Nakano, S. Hirose, «Crank-wheel: A brand new mobile base for field robots,», in: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vilamoura, 2012, https://doi.org/10.1109/IROS.2012.6385826.

[88] D. Lu, E. Dong, C. Liu, M. Xu, J. Yang, «Design and development of a Leg-Wheel Hybrid Robot “HyTRo-I”,», in: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Tokyo, 2013, https://doi.org/10.1109/IROS.2013.6697232.

[89] J. Suthakorn, S. Shah, S. Jantarajit, W. Onprasert, W. Saensupo, S. Saeung, S. Nakdhamabhorn, S. Reaungamornrat, «On the design and development of a rough terrain robot for rescue missions,», in: IEEE International Conference on Robotics and Biomimetics, Bangkok, 2009, https://doi.org/10.1109/ROBIO.2009.4913280.

[90] K. Sakurada, S. Suzuki, K. Ohno, E. Takeuchi, S. Tadokoro, N. Hata, N. Miyahara, K. Higashi, «Real-time prediction of fall and collision of tracked vehicle for remote-control support,», in: Proc. IEEE/SICE International Symposium on System Integration, Sendai, Japan, 2010, https://doi.org/10.1109/SII.2010.5708298.

[91] W. Wang, Z. Du, L. Sun, «Kinematics analysis for obstacle-climbing performance of a rescue robot,», in: IEEE International Conference on Robotics and biomimetics, Sanya, 2008, https://doi.org/10.1109/ROBIO.2007.4522406.

[92] W. Wang, W. Dong, Y. Su, D. Wu, Z. Du, «Development of search-and-rescue robots for underground coal mine applications,», Journal of Field Robotics 31 (3) (2014) 386–407, https://doi.org/10.1002/rob.21501, n°.

[93] W. Wang, D. Wu, Q. Wang, Z. Deng, Z. Du, «Stability analysis of a tracked mobile robot in climbing stairs process,», in: IEEE International Conference on Mechatronics and Automation, Chengdu, 2012, https://doi.org/10.1109/ICMA.2012.6284387.

[94] M. Brunner, T. Fiolka, D. Schulz, C. Schlick, «Design and comparative evaluation of an iterative contact point estimation method for static stability estimation of mobile actively reconfigurable robots,», Robotics and Autonomous Systems 63 (1) (2015) 89–107, https://doi.org/10.1016/j.robot.2014.09.003, n°Septiembre.

[95] A. Kalantari, E. Mihankhah, S. Moosavian, «Safe autonomous stair climbing for a tracked mobile robot using a kinematics based controller,», in: 2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Singapure, 2009, https://doi.org/10.1109/AIM.2009.5229765.

[96] G. Yamauchi, T. Noyori, K. Nagatani, K. Yoshida, «Improvement of slope traversability for a multi-DOF tracked vehicle with active reconfiguration of its joint forms,», in: Proc. IEEE International Symposium on Safety, Security and Rescue Robotics, Toyako-cho, Japan, 2014, https://doi.org/10.1109/SSRR.2014.7017678.

[97] J. Valls, G. Dissanayake, «Automatic fine motor control behaviours for autonomous mobile agents operating on uneven terrains,», in: 3rd International Symposium on Practical Cognitive Agents and Robots, Toronto, 2010, https://doi.org/10.1145/1967112.1967117.

[98] L. Shang, H. Wang, H. Si, Y. Li, T. Pan, «Investigating the obstacle climbing ability of a coal mine search-and-rescue robot with a hydraulic mechanism,», Applied Sciences 12 (20) (2022) 1–14, https://doi.org/10.3390/app122010485, n°.

[99] T. Fujita, T. Sasaki, Y. Tsuchiya, «Hybrid motions by a Quadruped Tracked mobile robot,», in: 2015 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), West Lafayette, 2015, https://doi.org/10.1109/SSRR.2015.7443010.

[100] A. Suresh, N. Ajithkumar, S. Kalathil, A. Simon, V. Unnikrishnan, D. Mathew, P. Basil, K. Dutt, G. Udupa, C. Hariprasad, M. Menon, A. Balakrishnan, R. Ramachandran, A. Murali, B. Shankar, «An advanced spider-like rocker-bogie suspension system for mars exploration rovers,», in: J. Kim (Ed.), Robot Intelligence Technology and Applications 4, Advances in Intelligent Systems and Computing, Springer, 2017, pp. 423–447, https://doi.org/10.1007/978-3-319-31293-4_34.

[101] F. Michaud, D. Letoumeau, M. Arsenault, Y. Bergeron, R. Cadrin, «Azimut, a leg-track-wheel robot, », IEEE/RSJ Conference on intelligent Robots and Systems (2003) https://doi.org/10.1109/IROS.2003.1249254.

[102] X. Duan, Q. Huang, N. Rahman, J. Li, Q. Du, «Kinematic modeling of a small mobile robot with multi-locomotion modes,», in: IEEE/ASME International Conference on Intelligent Robots and Systems, Beijing, 2006, https://doi.org/10.1109/IROS.2006.282276.

[103] X. Gao, X. Guan, Y. Yang, J. Zhang, «Design and ground performance evaluation of a multi-joint wheel-track composite mobile robot for enhanced terrain adaptability,», Applied sciences 13 (12) (2023) 1–19, https://doi.org/10.3390/app13127270, n°.

[104] L. Bruzzone, M. Baggetta, S. Nodehi, P. Bilancia, P. Fanghella, «Functional design of a hybrid leg-wheel-track ground mobile robot,», Machines 9 (10) (2021) 1–11, https://doi.org/10.3390/machines9010010, n°.

[105] Y. Zhu, Y. Fei, H. Xu, «Stability analysis of a Wheel-Track-Leg hybrid mobile robot,», Journal of Intelligent & Robotic Systems 91 (2018) 515–528, https://doi.org/10.1007/s10846-017-0724-1.

[106] B. Li, S. Ma, J. Liu, M. Wang, T. Liu, Y. Wang, «Amoeba-I: a shape-shifting modular robot for urban search and rescue,», Advanced Robotics 23 (9) (2009) 1057–1083, https://doi.org/10.1163/156855309X452485, n°.

[107] N. Li, S. Ma, B. Li, M. Wang, Y. Wang, «An online stair-climbing control method for a transformable tracked robot,», in: IEEE International conference on Robotics and Automation, RiverCentre, 2012, https://doi.org/10.1109/ICRA.2012.6224819.

[108] Z. Guanghua, D. Zhicheng, W. Wei, «Realization of a modular reconfigurable robot for rough terrain,», in: 2006 IEEE International Conference on Mechatronics and Automation, Luoyang, 2006, https://doi.org/10.1109/ICMA.2006.257529.

[109] W. Wang, W. Yu, H. Zhang, «JL-2: A mobile multi-robot system with docking and Manipulating Capabilities,», International Journal of Advanced Robotic Systems 7 (1) (2010) 009–018, https://doi.org/10.5772/7256, n°.

[110] X. Zhou, J. He, C. Ren, Y. Zhao, C. Peng, «Research on obstacle surmounting performance of all-terrain eight wheel drive robot,», in: 2018 Chinese Automation Congress (CAC), Xi`an, 2018, https://doi.org/10.1109/CAC.2018.8623525.

[111] B. Sim, K. Kim, K. Yu, «Development of body rotational wheeled robot and its verification of effectiveness,», in: 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, 2020, https://doi.org/10.1109/ICRA40945.2020.9197047.

[112] L. Yehezkel, S. Berman, D. Zarrouk, «Overcoming obstacles with a reconfigurable robot using reinforcement learning,», IEEE Access 8 (2020) 217541–217553, https://doi.org/10.1109/ACCESS.2020.3040896.

[113] Y. Chiu, N. Shiroma, H. Igarashi, N. Sato, M. Inami, F. Matsuno, «Fuma: Environment information gathering wheeled rescue robot with one-DOF arm,», in: IEEE International Workshop on Safety, Security and Rescue Robotics, Kobe, 2005, https://doi.org/10.1109/SSRR.2005.1501261.

[114] E. Kececi, «Design and prototype of mobile robots for rescue operations,», Robotica 27 (5) (2009) 729–737, https://doi.org/10.1017/S0263574708005109, n°.

[115] L. Bruzzone, P. Fanghella, G. Quaglia, «Experimental Performance Assessment of Mantis 2, Hybrid Leg-Wheel Mobile Robot,», Int. J. of Automation Technology 11 (3) (2017) 396–403, https://doi.org/10.20965/ijat.2017.p0396, n°.

[116] B. Seo, H. Kim, M. Kim, K. Jeong, T. Seo, «FlipBot: A new field robotic platform for fast stair climbing,», International Journal of Precision Engineering and

Manufacturing 14 (11) (2013) 1909–1914, https://doi.org/10.1007/s12541-013-0259-8, n°.

[117] G. Lan, S. Ma, «Step-climbing analysis of a novel tracked robot,», in: IEEE International Conference on Robotics and biomimetics, Shatin, 2005, https://doi.org/10.1109/ROBIO.2005.246326.

[118] Y. Huang, R. Meng, J. Yu, Z. Zhao, X. Zhang, «Practical obstacle-overcoming robot with a heterogeneous sensing system: design and experiments,», Machines 10 (289) (2022) 1–19, https://doi.org/10.3390/machines10050289, n°.

[119] M. Guarnieri, P. Debenest, P. Inoh, E. Fukushima, S. Hirose, «Development of Helios VII: an arm-equipped tracked vehicle for search and rescue operations,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, Sandai, 2004, https://doi.org/10.1109/IROS.2004.1389326.

[120] P. Ben-Tzvi, «Experimental validation and field performance metrics of a hybrid mobile robot mechanism,», Journal of Field Robotics 27 (3) (2010) 250–267, https://doi.org/10.1002/rob.20337, n°.

[121] M. Guarnieri, I. Takao, E. Fukushima, S. Hirose, «Helios VIII search and rescue robot: design of an adaptive gripper and system improvements,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems, San Diego, 2007, https://doi.org/10.1109/IROS.2007.4399372.

[122] M. Guarnieri, I. Takao, P. Debenest, K. Takita, E. Fukushima, S. Hirose, «Helios IX tracked vehicle for urban search and rescue operations: mechanical design and first tests,», in: IEEE/RSJ International Conference on Intelligent Robots and Systems Nice, 2008, https://doi.org/10.1109/IROS.2008.4651000.

[123] J. Serón, J. Martínez, A. Mandow, A. García-Cerezo, J. Morales, J. Reina, J. García, «Terrace climbing of the Alacrane mobile robot with cooperation of its onboard arm,», in: IEEE International Workshop on Advanced Motion Control, Sarajevo, 2012, https://doi.org/10.1109/AMC.2012.6197043.

[124] E. Jelavic, M. Hutter, «Whole-body motion planning for walking excavators,», in: 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, 2019, https://doi.org/10.1109/IROS40897.2019.8967631.

[125] J.M. García, J.L. Martínez, A. Mandow, A. García-Cerezo, «Caster-leg aided maneuver for negotiating surface discontinuities with a wheeled skid-steer mobile robot,», Robotics and Autonomous Systems 91 (2017) 25–37, https://doi.org/10.1016/j.robot.2016.12.007.

[126] C. O'Connor, «Five Things About NASA's Mars Curiosity Rover,» https://www.jpl.nasa.gov/news/five-things-about-nasas-mars-curiosity-rover, 2010 [accessed: 9 october 2023].

[127] G. Quaglia, D. Maffiodo, W. Franco, S. Appendino, R. Oderio, «The Epi.q-1 hybrid mobile robot,», The International Journal of Robotics Research 29 (1) (2009) 81–91, https://doi.org/10.1177/0278364909336806, n°.

[128] J.M. García, I. Medina, A.G. Cerezo, A. Linares, «Improving the static stability of a mobile manipulator using its end effector in contact with the ground,», IEEE Latin American Transactions 13 (10) (2015) 3228–3234, https://doi.org/10.1109/TLA.2015.7387226, n°.

[129] J.M. García, J.L. Martínez, A. Mandow, A. García-Cerezo, «Slide-Down Prevention for Wheeled Mobile Robots on Slopes,», in: 3rd International Conference on Mechatronics and Robotics Engineering, Paris, 2017, https://doi.org/10.1145/3068796.3068820.

[130] J.M. García, J.L. Martínez, A. Mandow, A. García-Cerezo, «Steerability analysis on slopes of a mobile robot with a ground contact arm,», in: Proc. 23rd Mediterranean Conference on Control and Automation, Torremolinos, Spain, 2015, https://doi.org/10.1109/MED.2015.7158761.