IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 2 May 2023, accepted 13 June 2023, date of publication 16 June 2023, date of current version 21 June 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3286871

SURVEY

Stair-Climbing Robots: A Review on Mechanism, Sensing, and Performance Evaluation

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This work was supported in part by the National Research Foundation of Korea under Grant NRF-2022R1A2C1007077, and in part by the National Research Foundation of Korea Grant funded by the Ministry of Science and Information Communication Technology (ICT) for Bridge Convergence Research and Development Program under Grant NRF-2021M3C1C3096807 and Grant NRF-2021M3C1C3096808.

ABSTRACT Indoor service robots have been widely introduced in the fields of cleaning, delivery, education, guidance, and healthcare, etc. in indoor environments. The mobility of an indoor service robot is essential to expanding its applications. However, the mobility of existing indoor service robots is highly limited by surrounding indoor environments. For example, a stair is one of the major obstacles that restrict the reachable areas of indoor service robots. Even though many studies have been performed to develop reliable and fast stair-climbing robots based on legged, tracked, wheel-legged and wheel-linkage mechanisms, a market-dominant stair-climbing robot remains unsolved. This review investigates the efforts of engineers devoted to stair-climbing robots. To this end, the locomotion mechanisms of stair climbing robots are classified and their sensing method are summarized. In this review, we also propose useful criteria for evaluating the stair-climbing ability of an indoor service robot. By virtue of these criteria, the stair-climbing performance of existing robots are qualitatively compared. We hope this review helps develop the reliable and fast stair-climbing robots and the reasonable criteria for their performances.

INDEX TERMS Stair-climbing, locomotion method, stair-sensing mechanism, performance evaluation of stair-climbing ability.

I. INTRODUCTION

A stair is one of the most difficult obstacles for indoor service robots to overcome. In the 2015 DARPA Robotics Challenge, the final mission for a robot to accomplish was stair-climbing. It is surprising that only 30% of all robots could complete this mission despite of long-term research. It is noteworthy that the shortest time for a robot to climb four steps is reported to be about 4 sec (typically one step in 1 sec), which is quite slower than the stair-climbing speed of a human [1], [2].

The variety of stairs makes it difficult for a robot to obtain the reliable stair-climbing ability. For example, the height and tread length of stair may be different according to the quality of construction techniques or countries. Moreover, shapes, materials, geometry, and environmental conditions such as the existence of a handrail may vary with the location and usage of a stair. To endow a robot with the reliable stair-climbing ability, the environments for a robot must be well-defined and its locomotion mechanism should be carefully designed to climb various stairs stably. In addition, the reliable control method and proper stair-sensing strategy become important in achieving the fast and stable stair-climbing.

Legged robots such as humanoids and quadruped robots may be an ideal solution for stair-climbing. Boston Dynamics released videos that demonstrated the excellent stair-climbing abilities of Atlas and Spot [3], [4]. Their stair-climbing abilities are very similar to or superior to human, but they must rely on the complex control method equipped with high-power motors, high-resolution sensors like LiDAR and

The associate editor coordinating the review of this manuscript and approving it for publication was Gerardo Flores.

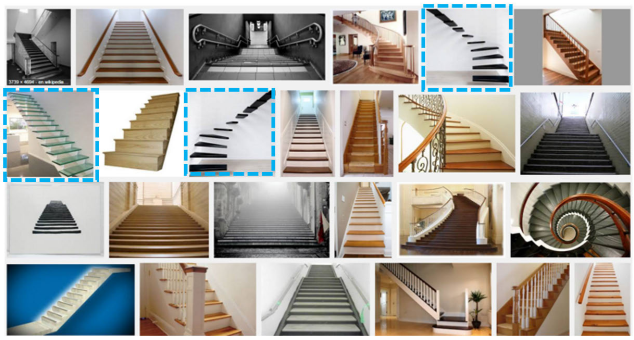

FIGURE 1. Various stairs in indoor environments (revised from [7]).

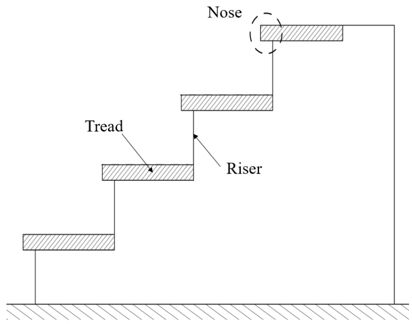

FIGURE 2. Typical structure of a stair.

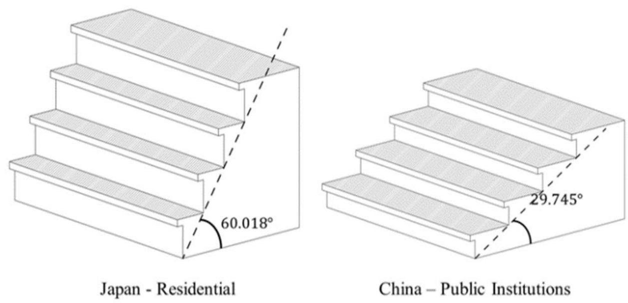

FIGURE 3. Two stairs with the steepest slopes in different countries.

cameras, etc. Even though the legged robots may ensure high performances under experimental set-ups, the economic cost and technical reason for the safety are still hurdles in using them as robotic platforms for wide indoor applications.

For decades, there have been other efforts to develop fast, reliable, and simple robotic mechanisms to overcome stairs. Commonly, modified tracked and wheeled mechanisms have been chosen for indoor service robots. For example, PackBot is used for reconnaissance [5] and Scalevo is designed for the handicapped [6]. Recently, wheel-legged, and wheel-linkage mechanisms have been suggested to guarantee both the high mobility of wheel and the adaptability of leg or linkage against stairs, for example, see [74], [106], [112], and [117].

There is a huge potential market for indoor service robots in various fields. However, a market-dominant solution with a high stair-climbing ability has not appeared yet. To the best of our knowledge, there has been no report to summarize fundamental studies related with stair-climbing robots. In this review, we investigate the main locomotion mechanisms, stair-sensing strategy, performance criteria and evaluation of and stair-climbing robots.

Section II briefly introduces types and size variations of stairs and issues considered for design of stair-climbing robots. Then, the main locomotion mechanisms for stair-climbing robots are classified into several categories and their main characteristics are discussed in Section III. In Section IV, the stair-sensing strategy with accompanying climbing method is presented. Section V introduces the candidates for evaluation of the stair-climbing ability of a mobile robot. In this review, the stair dimension of a stair and the vertical climbing speed of a mobile robot are suggested and evaluated with respect to the complexity of mechanism quantitatively. Section VI shows the recent research and future works shortly.

II. CONDITIONS OF STAIRS

The different shapes and sizes of stairs can be frequently encountered in indoor environments. As shown in Fig. 1, the dimensions, material, shapes, and geometry of stairs are very different according to their applications, which naturally makes a stair considered as the primary obstacle while designing an indoor robot. Note that there are curved stairs of different curvatures in indoor circumstances but in this review, we focus on the straight stairs.

Fig. 2 shows the typical structure of a stair. The tread is the horizontal part of a stair, and the riser is the vertical part between two treads of a stair, which determines the slope of a stair. It is noted that some stairs have no riser as shown in Fig. 1 (denoted by the blue dotted lines). The nose corresponds to a small rise in the tread. Typically, the dimensions of the tread and the riser, and the existence of the riser and the nose should be examined carefully for tracked and wheel-based robotic platforms since these factors may have the influence on the friction between the surface of a stair and their tracks or wheels.

It is noted that the regulations on the size of stair may vary according to the type of building as well as countries. Two stairs are compared in Fig. 3, where the left stair is the steepest one for residential buildings in Japan but the right stair is the steepest one for public institutions in China. As confirmed in Fig. 3, since the steepest slope of stair dramatically changes from approximately 30° to 60°, the design of a robotic solution to climb different stairs in different countries must be quite challenging. Please, refer to [8], [9], [10], and [11] for detailed information on the tread length and height of stairs in the International Building Code (IBC) for the US and Europe, as well as Eastern Asian countries with large construction markets like South Korea, Japan, and China. Recall that the regulation on the size of stair may provide the useful information for kinematic or dynamic constraints

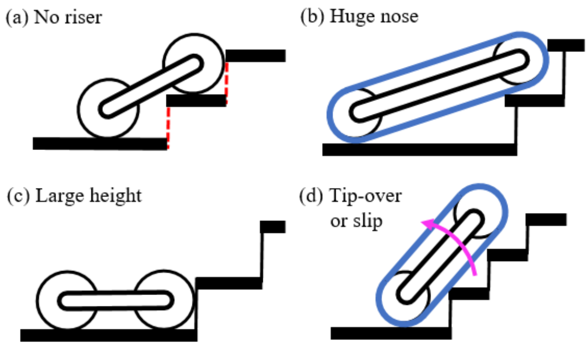

FIGURE 4. **Issues of stairs related with design of wheeled or tacked stair-climbing robot: (a) no riser, (b) huge nose, (c) large height and (d) tip-over or slip.**

on the stair-climbing robot such as wheel radius, length of link, minimum motor torque, required friction coefficient, etc [82], [108].

There are some issues to be considered for design of stair-climbing robot as shown in Fig. 4: first, stair-climbing robots may climb stairs without riser (e.g., the temporary stairs in construction sites). Note that they become huge hurdles to typical tracked or wheeled robots in that these robots cannot obtain the friction enough to climb those stairs [109], [115], [119]. Second, the nose of stair may be another obstacle to tracked and wheeled robots since these types of robots are more likely to be stuck in the nose during their stair-climbing [121]. Third, recall that theoretically the maximum height of stair for a wheeled robot to climb without any control is equal to its wheel radius, which implies that the stair-climbing ability of wheeled robot highly depends on its wheel radius [117], [132]. However, the size of wheel or track radius cannot be arbitrarily increased due to the manufacturing cost as well as its mobility in indoor environments. Finally, the tip-over or slip of tracked and wheeled stair-climbing robots is another important issue to be carefully handled, which usually occurs when a robot climbs a steep stair at a high speed [23], [108]. From these viewpoints, this review investigates how the mechanism of robot is designed and also the sensing/control strategy is built in order to improve its stair-climbing ability as well as mobile stability.

III. CLASSIFICATION OF STAIR-CLIMBING ROBOTS

In order to access wide spaces in indoor environments, the stair-climbing ability is essential since stairs extend a 2-dimensional (2D) space to a 2.5D space. Over the past decades, many studies have been carried out to develop reliable and high-performance robots. In this section, we classify the stair-climbing robotic mechanisms according to the locomotion method and compare their characteristics with respect to the issues discussed in the previous section.

In general, the robotic platforms are classified into four categories according to their locomotion method: tracked, legged, wheel-legged, and wheel-linkage robots.

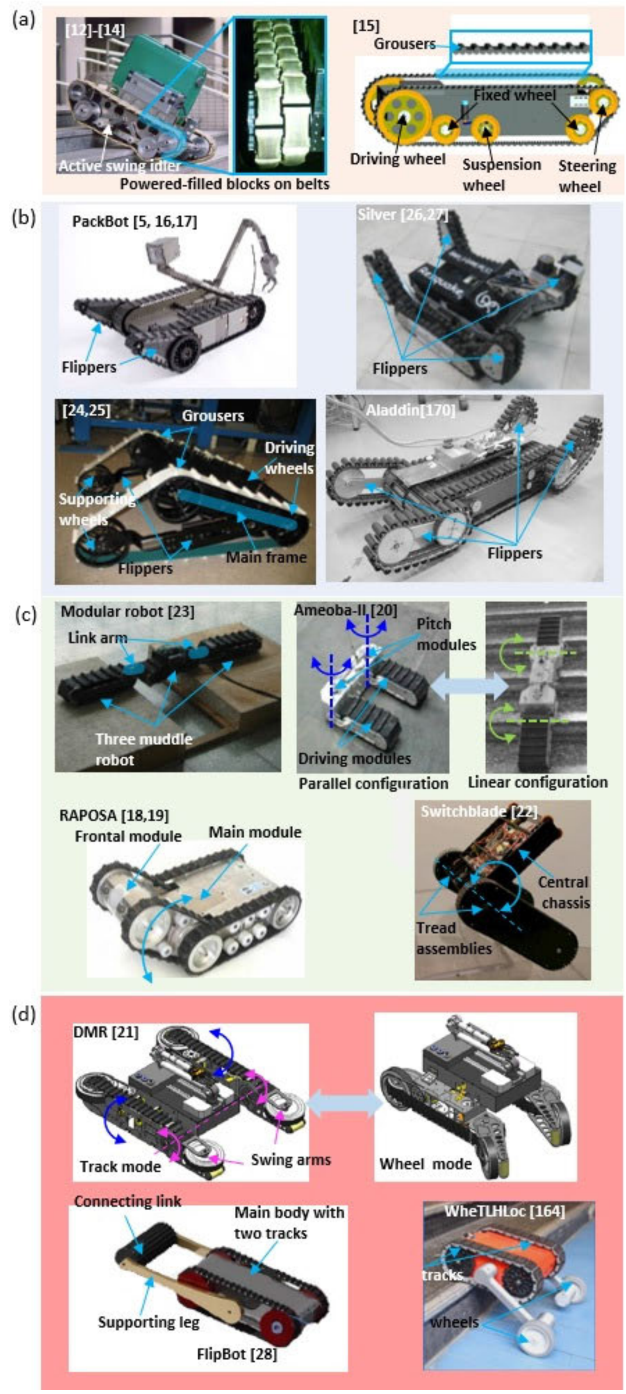

FIGURE 5. **Examples of tracked robots: (a) one body robots, (b) one body robots with flippers, (c) multi-body robots and (d) track-based hybrid robots.**

A. TRACKED ROBOT

A common method to climb stairs is to adopt a track-based design because the tracked robots are less susceptible to the size of stair so that the exact information of shape or size of a stair is not mandatory to the tracked robot. However, as discussed in the previous subsection, the tracked robot may have the difficulty in climbing a stair with a huge nose or a stair without a riser. Fig. 5 shows various types of tracked robot, where they are classified according to their structural characteristics.

1) ONE-BODY ROBOT

The simple way to cope with the slip phenomenon during stair-climbing is to increase the friction between the belt and a stair. For example, the belt of tracked robot has powder-filled blocks to reduce the slip. Also, the active swing idler mechanism is adopted to increase the contact area with a stair by adding the grounding pressure at the middle area of belt [12], [13], [14].

Similarly, the tracked robot in [15] has grousers in the track to prevent slip upon a stair, and also the suspension wheels are used to keep the track much tighter. It is noted that all tracks of tracked robots shown in Fig. 5 are basically equipped with grousers.

2) ONE-BODY ROBOT WITH FLIPPERS

On the other hand, dual and triple-body tracked design or additional links called the flipper is suggested not only to ensure sufficient friction by increasing the contact area between tracks and stairs but also to avoid the tip-over by manipulating body or flippers properly.

PackBot utilizes two or four flippers to rotate 360° freely, which enables the robot to climb even stairs without risers or stairs with noses effectively [5], [16], [17]. Also, by keeping in contact with the top of stairs, the flippers help the robot climb the last step of stair safely.

In [24] and [25], the shape of track can be changed by rotating the flippers located inside the track, which can rotate from $-90°$ to $180°$. By letting the flippers parallel to the main frame during stair-climbing, it can keep in contact with the stairs over a large area. Since Silver [26], [27] and Aladdin [170] have four independent flippers at the end of each track, they has the superb adaptability to various sizes of stairs.

3) MULTI-BODY ROBOT

RAPOSA consists of main/frontal modules and the frontal module can be tilted up to $\pm 90°$ with respect to the main module [18], [19]. During stair-climbing, it is properly tilted toward a stair just like the flipper of PackBot to increase the contact area between tracks and a stair.

On the other hand, Ameoba-II consists of three modules, i.e., main module equipped with two pitch modules and two other driving modules. By properly coordinating the motions of each module, Ameoba-II can reduce slip significantly during stair-climbing [20].

Switchblade is composed of the central chassis and two tread assembles for driving [22]. Since its tread assemblies can rotate 360° independently with respect to the central chassis, it enables to overcome a chasm or a stair safely by controlling its central chassis to keep its center of gravity stable.

The modular robot consists of multiple modules. By connecting the basic modules via link arms, its configuration can be arbitrarily chosen suitable for stair-climbing [23].

4) TRACK-BASED HYBRID ROBOT

The dual mobile robot (DMR) is equipped with two track-wheel driving modules that combine wheels with tracks to allow the real-time interchangeability so that it can choose wheels on planes and tracks on stairs, respectively [21]. In the track mode, the configuration of DMR is similar to that of PackBot by lifting up the swing arms.

On the contrary, the bio-inspired tracked solution called FlipBot tactfully utilizes the flipping motion to climb stairs. It is noteworthy that when the FlipBot climbs a stair via its successive flips, its supporting legs works as the supporting reaction force to the edge of stairs [28].

The wheel-track-leg hybrid locomotion robot (WheTLHLoc) combines the track mechanism with the wheel-legged mechanism to rotate 360° [164]. During its stair-climbing, the wheel-legged mechanism lifts up the frontal part of its body like the flippers, and then supports its body as shown in Fig. 5(d) as if the supporting legs supported the FlipBot.

B. LEGGED ROBOT

The legged locomotion, inspired by humans and animals, is a powerful way to climb stairs stably. It is noteworthy that in comparison with tracked robots, the legged robots have no difficulty in climbing a stair without riser and a stair with nose but need more degree-of-freedoms (DOFs) to produce the human-like motions so that they highly depend on the complex control method equipped with many actuators and sensors. With the development of accurate sensors as well as high-computing devices, legged robots achieve remarkable performance in stair-climbing. It is noted that as far as we know, one- and three-legged robots are not reported to climb stairs stably due to their asymmetrical structures. Therefore, this review examines two-, four- and six legged robots that are reported to climb a stair as shown in Fig. 6. Recall that it is important for legged robots to perceive a stair and to plan their motions, which will be discussed in Sec. IV.

1) TWO-LEGGED ROBOT

Two-legged robots are reported to perform excellent stair-climbing. For example, Boston Dynamics's Atlas was a 150 kg humanoid of 1.8 m in height with 28 hydraulically actuated degrees of freedom (DOF): 6 in each arm, 6 in each leg, 3 at the torso, and 1 in the neck [44], [45], [46], [47], [48], [49], [50], [51], [52]. Recently, its height and weight are significantly reduced to 1.5 m and 89 kg by virtue of 3D printing. Including stair-climbing, Atlas is reported to not only run but also leap, bound and backflip like an athlete.

DRC-Hubo+ is an 80 kg humanoid (with batteries) of 1.75 m in height with 32 DOF: 7 in each arm, 6 in each leg, 1 at the waist and the head, and 1 wheel at each knee [53],

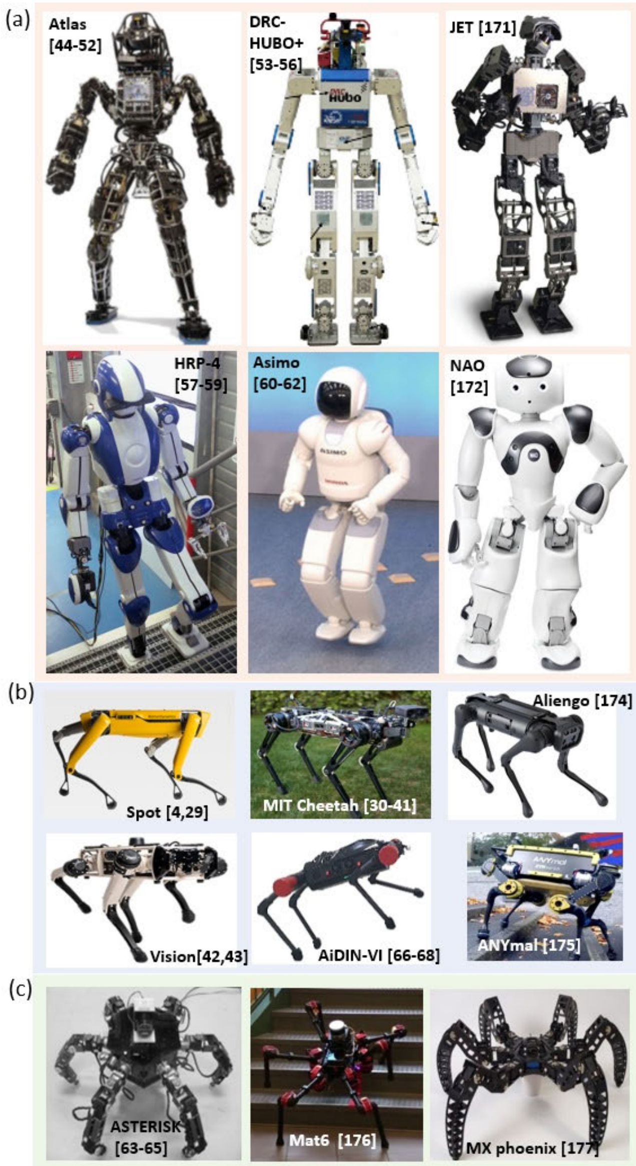

FIGURE 6. Examples of legged robots: (a) two-legged robots (bipedal), (b) four-legged robot (quadruped) and (c) six-legged robots (hexapod).

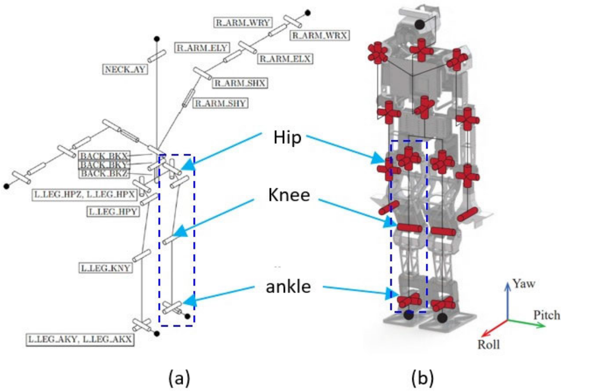

FIGURE 7. Joint configurations of humanoid's leg: (a) Atlas and (b) JET.

[54], [55], [56]. DRC-Hubo+ is known to win the first place in the 2015 DARPA Robotics Challenge by completing the given tasks such as door-opening, valve-turning and stair-climbing, etc.

JET is a 48 kg humanoid of 1.63 m in height with 32 DOF: 8 in each arm, 6 in each leg, 2 at the waist and 2 at the head. JET is reported to not only climb a stair but also perform complex tasks such as driving and exiting a vehicle [171].

HRP-4 is a 39 kg humanoid of 1.5 m in height with 34 DOF: 9 in each arm including 2 in the hand, 6 in each leg, 2 at the waist and 2 at the head [57], [58], [59]. HRP-4 is reported to climb a stair of 18.5 cm in height.

ASIMO is known the world's first bipedal robot with 28 DOF: 8 in each arm including 1 in the hand and 6 in each leg, whose height and weight are 1.3 m and 48 kg [60], [61], [62]. ASIMO performs tasks like shaking, jumping, obstacle-avoidance and stair-climbing/descending. ASIMO is used to develop a nuclear disaster robot for Fukushima nuclear power plant.

NAO is a 5.5 kg humanoid of 0.57 m in height with 24 DOF: 5 in each arm, 6 in each leg and 2 at the head [172]. NAO is used as the platform for the RoboCup Standard Platform League (SPL) and reported to climb a spiral stair of 7 cm in height [173]. In general, the DOF of leg of humanoid is chosen to be 6, which consists of 2 DOF motion of ankle, 1 DOF motion of knee and 3 DOF motion of hip as shown in Fig. 7.

2) FOUR-LEGGED ROBOT

Compared to two-legged robots, four-legged robots are easily balanced and much more suitable for carrying loads. However, they inevitably need the proper motion planning for their legs to achieve successful stair-climbing. Boston Dynamics' Spot is a 25 kg quadruped robot (up to 30 kg with a 6 DOF arm) capable of handling up to 14 kg payload [4], [29]. Unlike Atlas, Spot is fully driven by electrical motors. It is noted that Spot has a variety of gait such as crawling, walking, trotting and pacing. Spot is reported to climb stairs whose dimensions meet the US building code standards, for example, a stair of 25 cm∼28 cm in tread length and 17 cm in height.

On the contrary, there are many types of MIT Cheetah robots and Fig. 6(b) shows the MIT Cheetah 3, a 45 kg quadruped robot driven by high-performance electric motors to ensure broad force bandwidth and fast speed [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41]. MIT Cheetah 3 enables to move omnidirectionally in trotting, pronking, bounding and pacing gaits. MIT Cheeta 3 is well-known as the first quadruped robot to do a 360° backflip and reported to climb a stair blindly. Surprisingly, MIT Cheetah 3 can jump on/down from a desk of 0.76 m in height.

Ghost Vision 60 also achieves successful stair-climbing without any vision sensor [42], [43]. It is a 51 kg quadruped robot to handle up to 10 kg payload.

AiDIN-VI is a 33 kg quadruped robot with the battery of 4 kg, which is capable of 25 kg payload. AiDIN-VI is reported

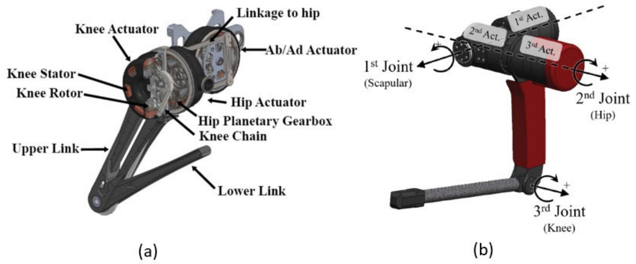

FIGURE 8. Joint configurations of quadruped robot's leg: (a) MIT Cheetah 3 and (b) AiDIN-VI.

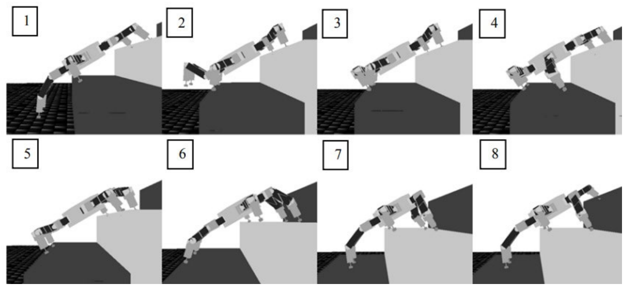

FIGURE 9. Continuous stair-climbing of ASTERISK.

to climb stairs of 21 cm in height with slope of 26.5° [66], [67], [68].

Aliengo is a 21.5 kg quadruped robot capable of 13 kg payload. Including stair-climbing, it is reported to walk, run and other high-performance gaits like backward running, left/right side shifting [174].

ANYmal is a 30 kg quadruped robot capable of a payload up to 10 kg [175]. Its leg can rotate 360° and also the leg configuration can be changed to crawl through tight spaces. Including stair-climbing, ANYmal can dance in a club, play a soccer and ice skate.

Generally, the leg DOF of quadruped robot is chosen to be 3, where 2 DOF motion is for hip abduction/adduction and flexion/extension and 1 DOF motion is for knee flexion/extension, respectively. It is noted that the low inertia of leg definitely ensures the agile and reliable gaits of quadruped robot. Therefore, instead of the serial mechanism where each actuator is located at each joint, the parallel mechanism is widely adopted for leg design of quadruped robot. For example, the MIT Cheetah 3 combines two motors coaxially and uses a chain for the knee joint [38]. As shown in Fig. 8, the joint configuration of leg of AiDIN-VI is similar to that of MIT Cheetah 3 [67]. Recently, rigorous studies have been performed to develop more compliant leg mechanisms that may be more suitable interacting with various environments under disturbances or uncertainties [178], [179].

3) SIX-LEGGED ROBOT

ASTERISK is a 4 kg hexapod robot whose height and leg length from its center of body to the end of leg are 0.18 m in standard posture and 0.42 m, respectively. Its leg consists of 4 rotational joints so that its total DOF is 24. It is reported to climb ladders and stair of 180 mm × 300 mm (height × tread) [63], [64], [65]. The gait of ASTERISK for stair-climbing is based on the wave gait, that is, its legs move left and right symmetrically in the moving direction and at least four legs support the body as shown in Fig. 9.

Mat6 is an 18 kg hexapod robot of 0.5 m in height and 1 m in width [176]. Its leg is composed of 3 rotational joints and its total DOF is 18. Mat6 is reported to climb a stair of 180 mm × 280 mm (height × tread) in the wave gait.

MX phoenix is a 4.8 kg hexapod robot whose leg consists of 3 rotational joints so that its total DOF is 18. Its most components are made by 3D printing to create unique 3D curved parts and to ensure the lightness. It is reported to climb a stair [177].

It is noted that the locomotion of hexapod robots become relatively slower than other legged robots due to their legs. Also, the gait for them must be carefully chosen. Similar to other legged robot, there is an issue to design legs of hexapod robots and the leg design of hexapod inspired by insects is discussed in [180].

C. WHEEL-LINKAGE ROBOT

The wheel-linkage mechanism in Fig. 10 may be possible candidate for locomotion on uneven and structural surfaces including stairs. However, as pointed out in Sec. II, its stair-climbing ability highly depends on the existence of nose and riser. The effort to overcome these shortcomings of wheel-linkage mechanism is explained below.

1) ROCKER-BOGIE BASED ROBOT

The well-known rocker–bogie design has been adopted as the basic platform for space rovers like Spirit, Opportunity and Curiosity due to their excellent load distribution and superb adaptability to the unstructured environments [108], [109], [110], [111].

In [108], the optimal design of rocker-bogie mechanism is done to reduce the oscillations of center of mass (CoM) of robot during stair-climbing. To ensure the stable posture of robot body during stair-climbing, the electrical cylinder is added to the rocker-bogie mechanism [109]. However, this rocker-bogie based mechanism still has the defect that it must move backward when starting to overcome a stair.

Shrimp is proposed to cope with this defect of rocker-bogie mechanism by combining a passive front fork with a parallel bogie mechanism. As a result, it can climb a step whose height is twice larger than its wheel diameter as shown in Fig. 10(a) [112], [113].

For the rescue in disaster environment, the rocker-based larger robot is designed [114], which connects two bodies with a free joint. Its six wheels can be independently driven and steered. Unfortunately, due to its large size (1690 × 810 × 1140 mm^3, length ×height × width), its usage is significantly restricted in indoor environments.

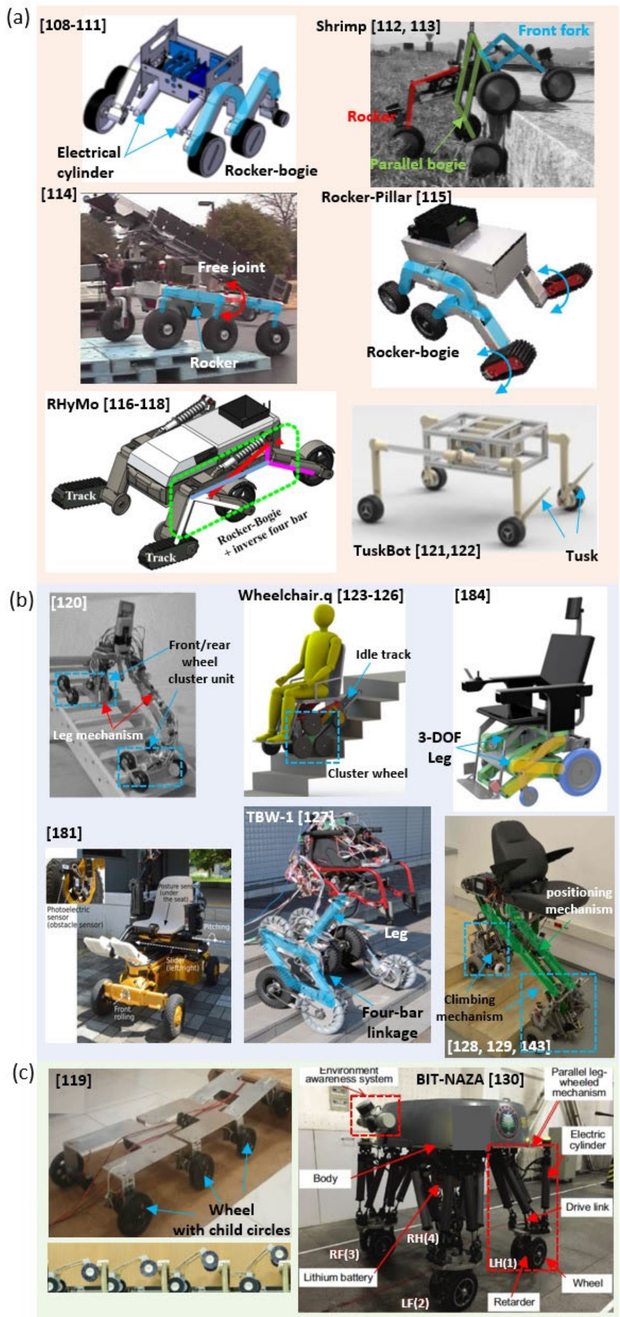

FIGURE 10. Examples of wheel-linkage robots: (a) rocker-bogie based robots, (b) wheelchairs and (c) multi wheel-linkage robots.

Recently, in order to minimize the effect of nose and riser of a stair, some studies replace the wheel of rocker-bogie mechanism with tracks [115], [116], [117], [118] or adopt the additional device like tusk [121], [122]. While the rocker-pillar just replaces its front wheel with a track, the RHyMo combines the inverse four-bar mechanism with the rocker-bogie and the track to reduce the oscillations of its CoM during stair-climbing and the resulting oscillation of its CoM is evaluated via the new metric posture variation index (PVI) [117]. The wheel-track hybrid version of TuskBot installs the tusk at the front wheel and also adds the track at the rear wheel.

2) WHEELCHAIRS

While the rocker-bogie mechanism and Shrimp are based on passive links, the wheel-linkage based wheelchair adopts the active links to guarantee the safety of their passengers during stair-climbing up and down.

In [120], the concept of wheelchair for stair-climbing has been verified, which consists of front and rear wheel-clusters combined with leg mechanisms of four leg actuator units. It climbs a stair by lifting up the chair through extension of leg mechanism and then, rotating the front/rear wheel-clusters asynchronously.

Similarly, Wheelchair.q climbs a stair by rotating the cluster wheel composed of three wheels [123], [124], [125], [126]. Also, the idle track is adopted to enhance the static stability so that during stair-climbing, it keeps in contact with the stair as shown in Fig. 10(b).

In TBW-1, two wheel-clusters are connected by the four-bar mechanism driven by DC servo motors so that the wheel-cluster can rotate by transforming its mode from straight to dogleg or parallelogram [127].

The wheelchair consists of two climbing mechanisms and the positioning mechanism driven by multiple DC motors, which surpasses the obstacle and ensures the verticality of chair, respectively [128], [129], [143]. When it climbs up/down a stair, the rack of climbing mechanism plays the role of supporting the weight of wheelchair instead of wheels.

Unlike existing wheelchairs, the four-wheeled wheelchair is proposed in [181]. Since its legs have additional DOFs, the proposed wheelchair can climb a stair in the pace gait as if legged robots climb a stair.

Also, the wheelchair climbs stairs by using two 3-DOF legs with boomerang-shaped feet [184]. The leg mechanisms are folded into the wheelchair body when the wheelchair moves over flat surfaces.

In comparison with other mechanisms for stair-climbing, the mobile safety of wheelchair is important in that a human utilizes a wheelchair. Therefore, to ensure the safe operation during stair-climbing, the structures of wheelchairs become inevitably complicated with many actuators and sensors. Also, their climbing motions are typically slower than those of other mechanisms due to intricate algorithms for sensing and locomotion. However, it is noteworthy that the stair-climbing ability of most wheelchairs has nothing to do with the existence of nose and riser.

3) MUTLI-WHEEL-LINKAGE ROBOTS

In [119], the multi-wheel-linkage mechanism is presented, which can climb a stair by virtue of passive links between each module and a modified wheel composed of parent and child circles. However, due to the passivity of connection, some of its wheels may lose contact with the surface of a stair.

In [130], BIT-NAZA is designed for the high load capacity and the smooth behavior in various environments. It has four wheel-linkages based on the Stewart platform consisting of six electrical cylinders. When it climbs a stair, its wheels are locked and its wheel-linkages behaves like legs. Since the workspace of its wheel-linkage is restricted, the height of stair for BIT-NAZA to climb is relatively lower and its tread length needs to be longer.

In general, wheel-linkage based platforms not only keep in good contact with various stairs but also ensure the stable locomotion on the ground. Most of wheelchairs suffer from low stair-climbing speed but their stair-climbing abilities are not affected by the existence of nose and riser. As for large-sized robots in [114] and [130], the size of stairs for them to climb are limited. To enhance the stair-climbing ability of rocker-bogie or Shrimp-based robots, additional device like tracks and tusk may be simple solutions to stairs with a nose or without risers.

D. WHEEL-LEGGED ROBOT

The wheel-leg design has been recently studied since they have the merits of wheeled robots and legged robots that not only move quickly on flat grounds but also overcome various obstacles with the high adaptability.

1) LEG-TYPE WHEEL BASED ROBOT

Multiple spoke-based wheel-legged designs have been widely adopted due to their good stair-climbing abilities: For example, ASGUARD is a 9.5 kg hybrid quadruped robot inspired by insect locomotion [69], [70], [71], [72], [73]. Five compliant legs are mounted around each hip shaft with an angular distance of $2\pi/5$ and the legged wheel radius is 22 cm. It is reported to climb a stair without fixed motion pattern.

The curved-spoke tri-wheel robot is designed to climb a stair efficiently, whose size and weight are 500 $\times$ 600 (width $\times$ length) mm^2 and 6 kg. While it can climb different stairs quickly with the help of stopper mechanism, its locomotion on flat surfaces may suffer from oscillations [82].

Another bio-inspired RHex-style robot is designed, whose length and height are 0.47 m and 0.14 m, respectively. It is equipped with six two-thirds circular spokes similar to the cockroach [81]. It is reported that on the basis of tripod walking gait, this robot climbs a step of 25 cm in height but it may need different stair-climbing algorithm depending on the height of a stair.

RHex is the most popular robot equipped with six half-circular spokes similar to an insect's leg, whose weight and length are 7.5 kg and 0.5 m, respectively [83], [84], [85], [86], [87], [88], [89]. Based on the back-to-front metachronal wave gait, RHex is reported to climb various stairs successfully. It is noted that the spoke shape of RHex is fixed so that its gait must be carefully designed according to conditions where it moves. So is the gait of other leg-type wheel-based robots.

IONS is a 7.5 kg quadruped robot equipped with four compliant leg-type wheels called Wheg [79], [80]. Through the simple open-loop gait planning, it can climb up and down a stair of 18 cm in height.

GerWalk is a large, lightweight and simple robot, which consists of a buoyant balloon body containing helium and two elastic spoke rimless-wheels [77], [78]. Its body is based on truss structure and made by aluminum and bamboo. As a result, its weight with the balloon is just 78 g. It is reported to climb a stair of 28 cm $\times$ 17 cm (tread $\times$ height).

It is noted that the non-smooth locomotion of spoke-based robots such as ASGUARD, RHex and IONS, etc may occur even on flat grounds, which is caused by their discontinuous contact with the ground.

2) TRANSFORMABLE WHEEL-BASED ROBOT

To cope with this undesired phenomenon, reconfigurable wheel-based robots have been suggested, which can change the shapes of wheels into the legged shapes if necessary.

A new wheel-leg transformation mechanism in Fig. 12(a) is proposed in TurboQuad [74], [75], [76], which enables the robot to transform its wheel shape even in its motion. Furthermore, it does not need additional actuator for wheel-leg transition since the transformation is done by its own driving actuation system. Its previous version Quattroped is reported to climb a stair with a tread length between 25 and 30 cm and height within 15-17 cm [76].

A new segmented wheel-based robot is developed [101], [102], [103], [104], [105]. When travelling on flat ground, the shape of wheel is a perfect and full circle. However, when climbing a stair, its shape is transformed into a starfish-like shape to enable the circular segment to touch down tangentially on the surface of stair as shown in Fig. 11(b). It is reported to climb a stair of 11 cm $\times$ 6.4 cm (tread length $\times$ height).

STEP is a novel 2-DOF transformable wheel-based robot, whose wheel is built on five-bar PRRRP mechanism [106]. As shown in Fig. 12(c), the lobe angle and radius of proposed wheel can be adjusted independently so that STEP can overcome various obstacles connected in series. STEP is reported to successfully climb a stair of (26, 30) cm $\times$ (10, 18) cm (tread $\times$ height).

α-WaLTR is a new adaptive wheel-and-leg transformable robot, whose length and weight are 0.72 m and about 11 kg, respectively. The transformation between the wheel mode and the leg mode in Fig. 12(b) is passively done by using a gear teeth with a mechanical lock at the end. It is reported to climb a stair of 29 $\times$ 18 cm^2 (tread $\times$ height). In comparison with the STEP and Turboquad whose transformation are actively done, the structure of α-WaLTR is much simpler but its transformed wheel shape is fixed so that the size of stair for α-WaLTR to climb may be limited.

3) STAR-WHEEL BASED ROBOT

MSRox is a hybrid mobile robot with four star-wheels consisting of three sub-wheels and a tri-lobe as shown in Fig. 11(c) [96], [97]. When it traverses on flat surface, two sub-wheels of each star-wheel rotates but when it climbs a stair, all star-wheels themselves rotate. It is reported to climb a stair of 37 $\times$ 14 cm^2 (tread $\times$ height).

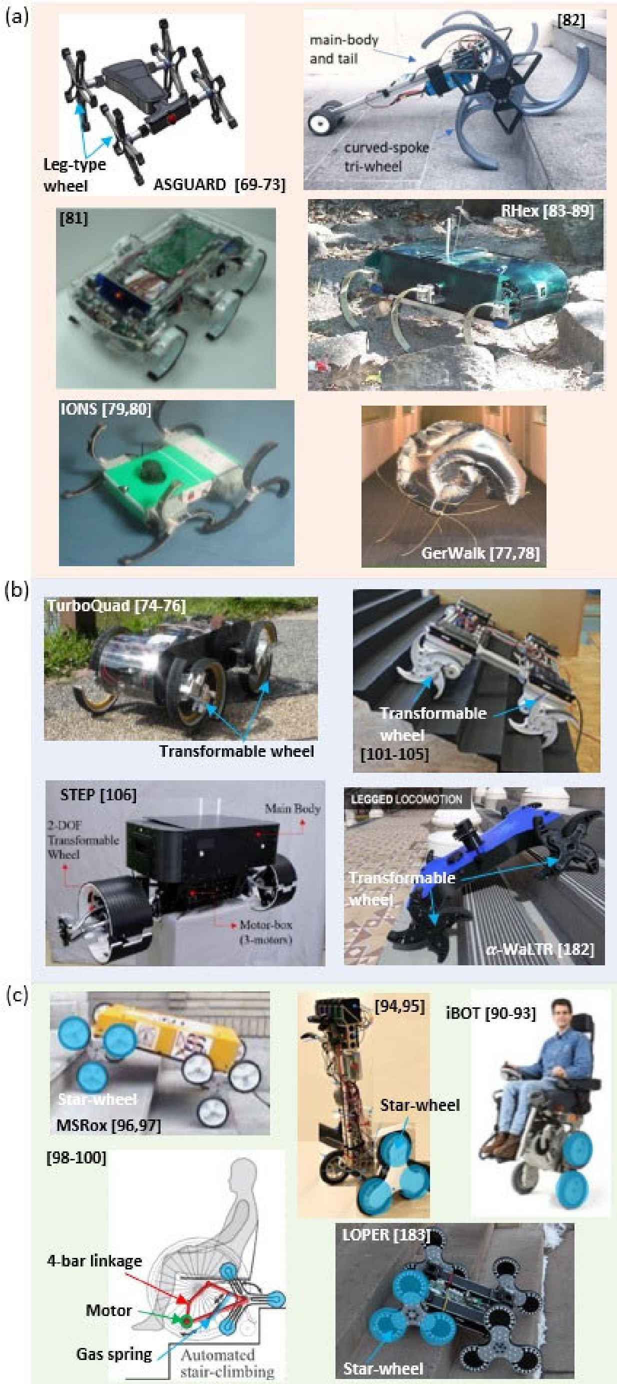

FIGURE 11. Examples of wheel-legged robots: (a) leg-type wheel-based robots, (b) transformable wheel-based robots and (c) star-wheel based robots.

In [94] and [95], the 76 kg automatic erect stair-climbing robot is described. It is based on triangular modules similar to the star-wheel of MSRox. It is reported to climb up and down a stair autonomously.

The iBot is the well-known personal mobility of 126 cm in height and 127 kg in weight, which is driven by two wheel modules to rotate around each other for stair-climbing [90], [91], [92], [93]. It moves on flat ground in the self-balancing mode as shown in Fig. 11(c). It is reported to climb a stair of about 10 cm in height.

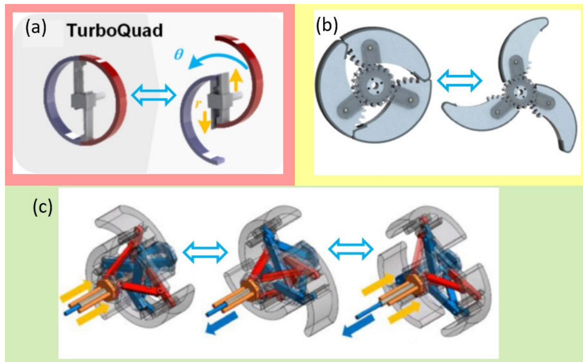

FIGURE 12. Examples of transformable wheels: (a) Turboquad, (b) α-WaLTR and (c) STEP.

In [98], [99], and [100], a new mobility vehicle is presented, which can climb a stair by virtue of the 4-bar linkage driven by the gas spring (called active rotary-legs mechanism). It is reported to climb a stair of 30 $\times$ 12.5 cm^2 (tread $\times$ height).

LOPER is a quadruped-hybrid stair climbing robot with tri-lobe wheel similar to those of MSRox [183]. However, unlike the wheel of MSRox, the tri-lobe wheel of LOPER always rotates irrespective of surrounding environment.

It is obvious that the stair-climbing ability of wheel-legged robots is superior to those of wheel-linkage or tracked robots in that wheel-legged robots are less affected by the existence of nose and riser. However, it is also true that the wheel-leg design achieves high-speed stair climbing with a simple design but the adaptability to various sizes and shapes of stairs remains an issue to be solved.

IV. STAIR-SENSING AND CLIMBING STRATEGY

Other important issues for stair-climbing robot are how to endow a robot with the ability of recognizing the geometry of stair like the tread length and height, the existence of the riser or the nose, and how to manipulate a robot with given (limited) information of stair effectively, for example, to keep its balance and moving direction for avoiding collision, stuck or falling down from stairs. To this end, various sensors have been adopted to obtain the precise information of a stair in combination with estimation algorithms.

A. TRACKED ROBOT

1) STAIR-SENSING

Most tracked robots do not use the sensors to detect a stair or recognize its size because this information has little effect on the stair-climbing performance of tracked robots. Some tracked robots driven remotely by a human operator may be equipped with the visual sensors to measure the information of surrounding environments, for example, RAPOSA uses webcams [18] and PackBot has the stereo camera [16]. Also, the tracked mobile robot and WheTLHLoc adopt the cameras [15], [164].

On the other hand, Amoeba-II uses the range sensor to distance to the riser of the first step because its configuration must be changed into linear one before stair-climbing [20]. Silver adopts two Laser range finder (LRF) to scan

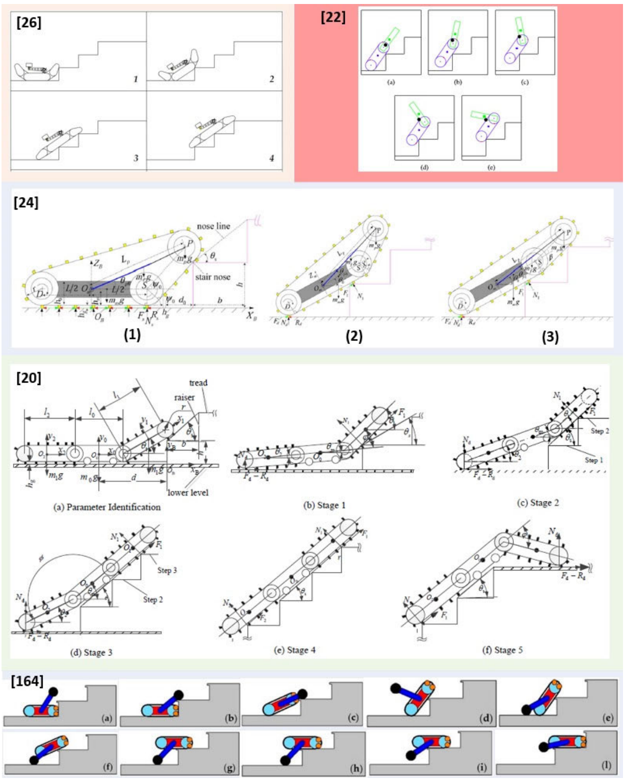

FIGURE 13. Examples of stair-climbing strategies of tracked robots.

vertically and horizontally for stair-detection and posture correction [26].

2) STAIR-CLIMBING STRATEGY

In [15], the entire procedure of stair-climbing of mobile tracked robot is divided into six stages and at each stage, the required torque for the driving wheel is calculated through the dynamic analysis. Moreover, the degree of stability is suggested to evaluate the stair-climbing ability of mobile tracked robot, which is defined as the ratio of variations of potential energies for tumbling on the flat ground and tumbling during stair-climbing: the more the robot is likely to fall from a stair, the lower degree of stability it has.

Similarly, in [24], the interaction between the track and a stair is analyzed at three steps of stair-climbing, which can be distinguished by the shape of track as confirmed in Fig. 13. Furthermore, the online tip-over prediction algorithm is proposed for each step of stair-climbing.

The arm configuration of Silver during stair-climbing is described in Fig. 13 [26]. The behavior of Aladdin climbing a stir seems quite similar to that of Sliver [170].

The stair-climbing process of modular robot is divided into three stages and at each stage, its mobility is analyzed for its kinematic and dynamic factors [23].

The stair-climbing procedure of Amoeba-II is shown in Fig. 13 [20]. Through the force analysis at each stage in Fig. 13, the stair-climbing criterion is built. It is noteworthy that its configuration is very similar to that of self-reconfigurable tracked robot in [24]

The stair-climbing procedure of Switchblade is given in Fig. 13 [22]. As shown in Fig. 13, Switchblade climbs a stair with keeping the balance by properly adjusting the angle of central chassis.

The stair-climbing process of WheTLHLoc is also shown in Fig. 13 [164]. Note that two legs of WheTLHLoc raises its main body effectively so that it does not need to flip unlike the Flipbot which must need to flip for stair-climbing.

B. LEGGED ROBOT

1) STAIR-SENSING

The legged robots inevitably depend on the exteroceptive sensors to obtain the information of environment due to their instability. For example, Atlas's primary sensing is done by the multi-sense SL sensor composed of a binocular stereo camera and a rotating planar LiDAR [135]. DRC-Hubo combines two regular cameras with a rotating 2D LiDAR for stair recognition [55]. Similarly, JET adopts a rotating 2D LiDAR [171]. Instead of using a LiDAR, ASIMO and NAO utilize multiple cameras for stair detection [60], [185]. NAO uses four sonar rangefinders. In the case of HRP-4, a RGB-D camera is added for stair-detection [59].

On the other hand, the quadruped robot, Spot's perception system consists of five pairs of stereo cameras to recognize obstacles [139]. Of course, additional sensors including LiDAR can be installed at Spot's main body to improve its perception range and accuracy. Ghost Vision 60 utilizes multiple RGB-D cameras and thermal cameras for surround-sensing [43]. Similar to Spot, Ghost Vision 60 can be equipped with additional sensors for inspection. AiDIN-VI collects vision data from the RGB-D camera [67] and Aliengo adopts two depth cameras and a visual odometer camera for geometry information [174]. In the case of MIT Mini-Cheetah, a tracking camera and a depth camera are adopted together [141]. As range sensors, ANYmal uses a laser range sensor and a stereo camera mounted in its front and back [175].

The six-limb based robot ASTERISK detects the position and posture of stair by using a 2D laser range finder to rotate for 3D range scanning [65]. Mat6 uses a LiDAR-inertial odometry with two RGB-D cameras for stair-sensing [176].

It is noteworthy that unlike two legged robots, quadruped or hexapod robots are less sensitive to various disturbances caused by the structural characteristics of stairs. As a result, MIT Cheetah 3 and Ghost Vision 60 are reported to climb up and down stairs even without the use of external environment sensors [38], [42]. Examples of sensing systems used in legged robots for stair-climbing/detection are shown in Fig. 14.

2) CONTROL STRATEGY FOR STAIR-CLIMBING

a: TWO-LEGGED ROBOTS

It is noteworthy that the main goal of two-legged robots is to reproduce the motion of a human naturally so that unlike tracked robots, the control strategies for two-legged robots

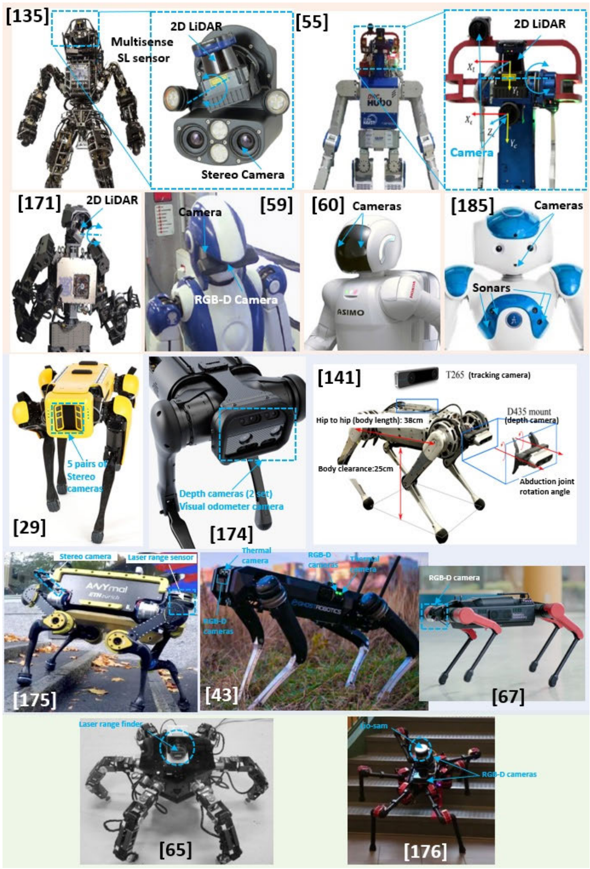

FIGURE 14. Examples of sensing systems used in legged robots for stair-climbing/detection.

are very complicated and not limited to only stair-climbing. Therefore, in this review, the common control strategy of two-legged robots is first examined, which can perform tasks including stair-climbing. Subsequently, the specific methods for legged robots to climb a stair are explained.

Fig. 15(a) shows the overall procedure of common control strategy of two-legged robots. Also, Fig. 15(b) describes the different stabilization approaches according to the stability criteria, which corresponds from motion generation to two-legged robot denoted by the green line in Fig. 15(a). For example, in the case of zero moment point (ZMP) approach, the reference footsteps generated from the path planner are transferred to the motion generation in Fig. 15(a), which corresponds to the ZMP generator in Fig. 15(b). Then, the desired ZMP trajectory is given to the ZMP controller in Fig. 15(b) corresponding to the feedback control (stabilizer) in Fig. 15(a). The desired feet force distribution and CoM motion are given to a two-legged robot through the whole-body and low-level joint controllers.

The motion of ATLAS is built based on its footstep motion and its motion stability is ensured by finding the desired contact wrenches at each contact point via the stabilizer [187]. As the whole-body control for ATLAS, the inverse dynamics-based control [188] and the momentum-based controls in a QP fashion [51], [189] and in a MPC fashion [44] are reported, respectively.

Similarly, the motion of DRC-Hubo is designed on the footstep motion and stabilized by the ZMP controller [54]. The inverse kinematics-based whole-body control is applied to DRC-Hubo [190].

In [59], the desired footsteps of HRP-4 are stabilized by the DCM feedback controller in the similar manner to the case (2) in Fig. 15(b). The inverse kinematics-based whole-body controller is chosen for the stair-climbing of HRP-4. It is noteworthy that in [59], the desired contact wrenches are computed by the DCM controller to track the walking pattern well and the admittance control is combined with the whole-body controller to realize the desired contact wrenches.

The motion of JET is also given from the footstep motion and then stabilized by the ZMP controller supported by the MPC to reduce the CoM velocity fluctuation. The inverse kinematics-based whole-body controller is adopted for stair-climbing [171].

The footstep motion of NAO is stabilized by the ZMP controller equipped with the QP-based preview control of CoM [191].

ASIMO' motion is also constructed on its footstep motion stabilized by the ZMP controller and the momentum-based whole-body control is used to cope with such disturbances as the irregularities of ground and the misalignment of torso [60].

b: FOUR-LEGGED ROBOTS

It is noteworthy that in addition to footstep planning, there is another thing to be considered for motion planning of four-legged robots unlike two-legged robots, that is, the gait of four-legged robot which is a manner of walking or running on foot. For a four-legged robot to climb a stair, its footstep planning and gait scheduling must work together in harmony. Figs. 16(a), 16(b) and 16(c) show the control frameworks for two-legged robots MIT Cheetah3 [38], ANYmal [175] and Aliengo [174], respectively.

As confirmed in Fig. 16(a), the desired CoM reference trajectory is designed on the user input in the combination with the gait scheduler. The MPC-based force control and the swing leg control work alternately according to the gait phase to compute the optimal ground force and to track the swing trajectory, respectively.

The sequence of footsteps of ANYmal is designed from the goal pose and current stance. Considering the condition of terrain, the feasible footsteps are searched while checking the stable robot configuration as shown in Fig. 16(b). Then, the swing trajectory is generated by the swing leg planner to connect the current foot position and the optimized foothold target. The QP-based whole-body control is used to stabilize the robot's behavior around the desired trajectories [192].

Assuming the periodic gait with fixed step sequence and step timing, the footsteps of Aliengo are planned upon

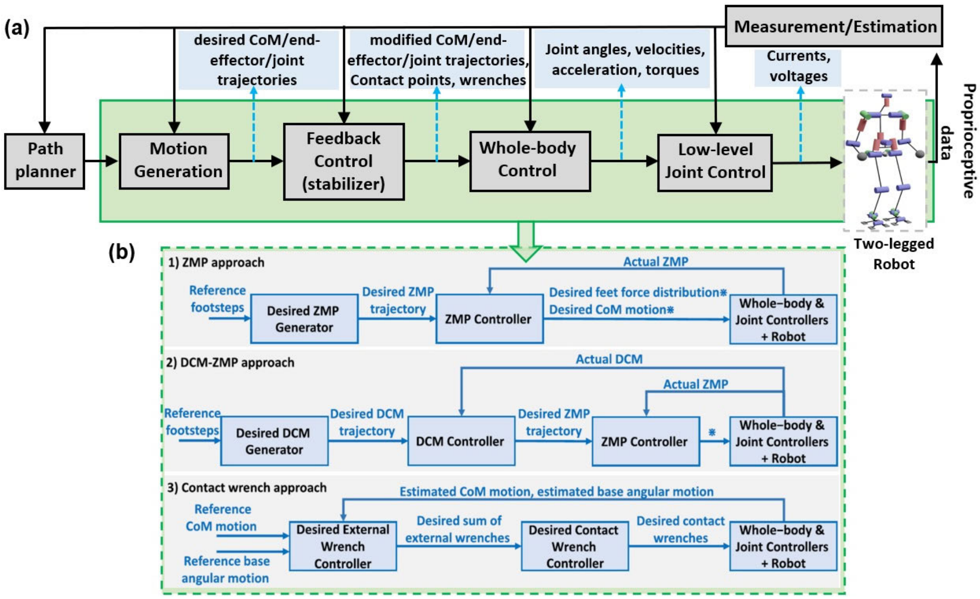

FIGURE 15. **(a) Overall procedure for common control strategy of two-legged robots and (b) different approaches according to the stability criteria [49].**

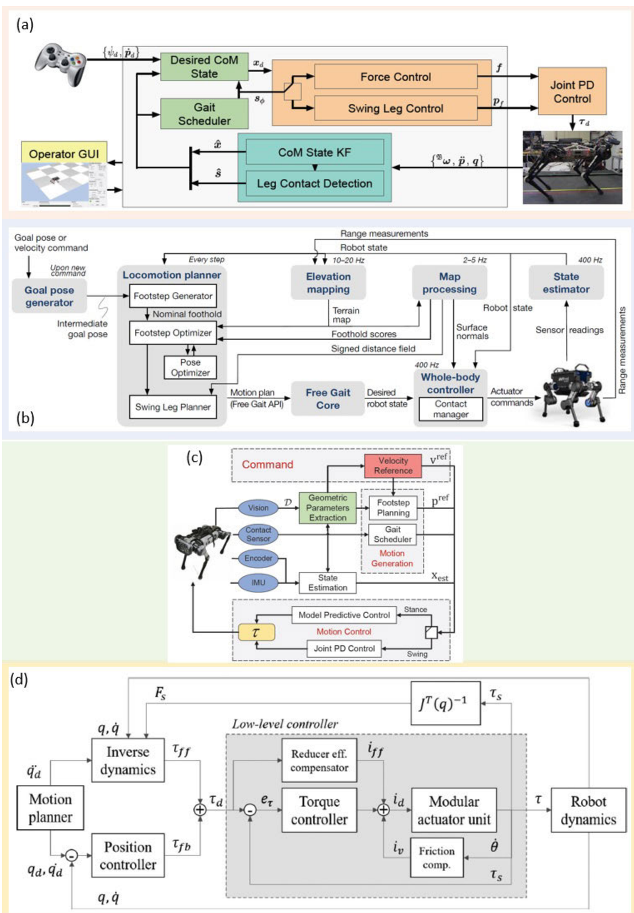

FIGURE 16. **Examples of control frameworks for two-legged robots.**

the velocity reference and the geometric information of stair as shown in Fig. 16(c). Similar to MIT Cheetah 3, the switching control is adopted between the MPC-based force control for stance and the joint PD control for leg swing.

For static walking of AiDIN-VI, the force-based ZMP planner and modified preview control are combined with the landing force control to reduce the rate of change of angular momentum. For its dynamic gaits, the composite control consisting of inverse dynamics-based control and position control is implemented as shown in Fig. 16(d).

c: SIX-LEGGED ROBOTS

After the detection for vertical lines and rise surfaces of a stair is completed based on the 3D range data, ASTERISK climbs a stair in the wave gait in Fig. 9 [64]. To ensure its mobile stability, the normalized energy stability margin is examined together with checking that its center of gravity is placed within the area of supporting legs.

Compared to the stair-climbing procedure of ASTERISK, the procedure of MAT6 seems quite similar to those of two-legged robots [176]. First, the pose planner generates the intermediate pose towards the user-specified goal. Next, a set of footholds are selected on the terrain map and then via the direct collocation optimizer, the optimal trajectories for body pose, foot position and reaction force are computed. Finally, the low-level controller converts the whole-body motion trajectory into joint angle and torque trajectories to command motors.

C. WHEEL-LINKAGE ROBOT

1) STAIR-SENSING

Among the wheel-linkage robots, the wheelchairs utilize various sensors to obtain the precise information of their positions and postures on stairs in addition to recognizing the size or shape of stairs for the safety of human operator.

In [120], the proximity sensors are used as the stair/stair-edge sensors to detect a stair and to detect having crossed over the edge of a step during its stair-climbing up/down, respectively.

In [184], laser distance sensors are utilized to estimate the shape of a stair by simple fact that the distance increases abruptly when the edge of stair is detected.

In [181], three photoelectric sensors per wheel are adopted to detect an obstacle during stair-climbing.

In [128], two laser distance sensors are used to estimate the dimension of a stair. They can rotate by being coupled with the pivot axis to scan the architectural barrier in forward and backward directions.

On the other hand, there are few rocker-bogie based robots and multi-wheel-linkage robots with sensors to obtain the information of a stair.

2) CONTROL STRATEGY FOR STAIR-CLIMBING

Recall that most rocker-bogie based robots have no special strategies for stair-climbing: for example, Shrimp utilizes the front fork to naturally produce an elevation of its front wheel if an obstacle is encountered [112]. Similarly, other robots in [108], [109], [110], [111], and [114] can climb a stair without special strategies. However, for the velocity control, the position and pose of a robot on stairs may be necessary; for example, the contact angles between a stair and wheels are used to estimate the position and pose of a robot on a stair by comparing the relation between the tilting angles of rocker and bogie [108], [109], [110], [111]. Unfortunately, they are vulnerable to the existence of nose or riser because the nose is another hurdle to overcome and their stair-climbing highly depends on the friction between wheels and the riser. To improve these shortcomings of rocker-bogie based robots, front wheels of some robots are replaced with the tracks that can be tilted with active joints [115], [116], [117], [118] or additional device like tusk is used to lift the front of robot easily [121], [122].

For a wheelchair to climb a stair, there are usually the specific procedures to be followed, which may be completely automatic or not: during stair-climbing/descent, the speed of wheel cluster is controlled by a user via joystick [120] or the stair-climbing/descent starts after the wheelchair is placed properly in front of a stair by the user [127], [143], [181], [184].

Unlike other wheel-linkage robots, BIT-NAZA climbs a stair by walking so that a sequence of its footholds and the trajectory of its center of gravity (COG) is searched by the heuristic search method for given kinematic and geometric constraints [130]. Then, the low-level controller activates the joint locomotion to follow given optimal footholds and COG trajectory with ensuring the static equilibrium and smooth walking.

D. WHEEL-LEGGED ROBOT

1) STAIR-SENSING

The bioinspired RHex-style robot in [81] is equipped with two infrared range (IR) sensors on its front side in order to detect the presence of a step and its heading orientation. During its step-climbing, the inclinometer is used to measure the height of a step.

IONS has the IR sensor and the IP camera for obstacle detection and indoor navigation [79].

α-WaLTR is equipped with the RGB-D camera for stair detection and the 2D LiDAR to extract line segments of surrounding environment for real-time navigation [182].

MSRox has the photoelectric sensor to detect a stair [97].

In [95], the Kinect sensor is placed at the top front of the erect structure to get 3D data of surrounding environment. In Combination with the acceleration measurement from the IMU, a stair is recognized and its size is estimated for stair-climbing.

2) CONTROL STRATEGY FOR STAIR-CLIMBING

The trajectory of wheel-leg of ASGUARD on a stair is generated and modified by an independent pattern generator based on the direct coupling between the measured motor torque and the stiffness of the position controller driven by the position error of a wheel-leg [72]. To ensure the ground contact of ASGUARD, a rotational degree of freedom (DOB) along the body axis is added, which serves as an elastic spinal column.

The curved-spoke tri-wheel robot uses a stopper at each wheel to avoid the slipping on a stair [82].

The bioinspired RHex-style robot adopts the so-called ‘‘rearing/rising strategy’’ similar to step-climbing locomotion of the cockroach [81].

The stair-climbing gait of RHex is based on a back-to-front metachronal wave gait [85]. Especially, leg trajectories, phase times and the sequence of leg motion are determined by the geometry of a stair.

For IONS to traverse various terrains including stairs, different types of gaits such as walking, turning and stair-climbing/descent are chosen [79]. Also, the Whegs of IONS are separately controlled for its synchronized motion.

Based on the workspace of leg and geometrical interaction between legs and a stair, the leg trajectory of Quattroped for stair-climbing is designed, which is the previous version of TurboQuad [193]. The gait/mode generation and transition of TurboQuad are controlled by the central pattern generator (CPG) and coupled oscillator networks [75].

From the kinematic viewpoint, the required tilting angle of wheel lobe and wheel radius of STEP are determined by the prior knowledge of tread length and height of a stair [106].

It is noteworthy that when the stair-climbing locomotion of mobile robots is based on a so-called star-wheel consisting of three wheels, special control strategy for stair-climbing is not indispensable: when the star-wheel increases the wheel

TABLE 1. Summary of tracked robots.

Type	Name	Stair size (tread×height) (mm^2)	Weight (kg)	Vertical Speed (cm/sec)	Payload (kg)	Sensor for stair detection
One-body tracked robot	Stair climber [12]-[14]	270 × 160	65	5.33	60	-
	Tracked mobile robot [15]	220 × 150	62	33.8	-	Camera
One-body tracked robot with flippers	PackBot [16], [17]	250 × 170 [estimated]	24	4.25	20	Stereo camera
	RLMA [24], [25]	260 × 185	6.6	1	22	-
	Silver [26], [27]	320 × 180	25	4.32	-	Laser range finder (LRF)
	Aladdin [170]	240 × 110, 240 × 120 [estimated]	20	-	-	-
Multi-body tracked robot	RAPOSA [18]	230 × 170 [estimated]	27	28.71	-	Webcam
	Amoeba-II [20]	248 × 180	10.58	2.2	-	Range sensor
	Switchblade robot [22]	200 × 190 [estimated]	5.58	7	-	-
	Tracked modular robot [23]	210 × 110, 250 × 130, 300 × 160	3	20	-	-
Track-based hybrid robot	DMR [21]	178 × 178	65	17.8	50	-
	FlipBot [28]	300 × 100, 240 × 200	7.8	-	-	-
	WheTLHLoc [164]	200 × 180 [estimated]	-	-	-	Camera

TABLE 2. Summary of legged robots.

Type	Name	Stair size (tread×height) (mm^2)	Weight (kg)	Vertical Speed (cm/sec)	Total DOF/ leg DOF	Sensor for stair detection
Two-legged robot	Atlas [44]-[52]	600 × 400 [estimated]	89	16	28 / 6	Stereo camera, LiDAR
	DRC-Hubo [53]-[56]	275 × 120	80	1.5	32 / 6	Regular camera, LiDAR
	JET [171]	300 × 230	48	-	32 / 6	LiDAR
	HRP-4 [57]-[59]	240 × 185	39	5.14	34 / 6	RGB-D camera
	ASIMO [60]-[62]	246 × 164 [estimated]	48	16.4	28 / 6	Camera
	NAO [172], [173]	240× 70 [estimated]	5.5	-	24 / 6	Camera
Four-legged robot	Spot [4], [29]	320 × 200 [estimated]	30	20	12 / 3	Stereo Camera
	MIT Cheetah 3 [30]-[41]	279 × 178 [estimated]	43	11.87	12 / 3	-
	Aliengo [174]	300 × 150, 260 × 160	21.5	-	12 / 3	Depth camera, visual odometer camera
	Vision 60 [42], [43]	198 × 198 [estimated]	51	-	12 / 3	RGB-D camera, thermal camera
	AiDIN-VI [67]	420 × 210 [estimated]	33	1.05	12 / 3	RGB-D camera
	ANYmal [175]	210 × 210 [estimated]	30	20	12 / 3	Laser range sensor, stereo camera
Six-legged robot	ASTERISK [63]-[65]	300 × 180	4	0.281	30 / 5	Laser range finder
	Mat6 [176]	280 × 180	18	-	18 / 3	LiDAR-inertial odometry, RGB-D camera
	MX phoenix [177]	-	4.8-	-	18 / 3	-

radius of mobile robot, its stair-climbing ability has naturally improved [95], [97], [100], [183].

Tables 1, 2, 3 and 4 summarize the characteristics of tracked, legged, wheel-linkage and wheel-legged robots, respectively. For all types of robots, the following common factors are investigated: the weight of robot, the vertical speed of robot, the step size and the sensor for stair-detection. The vertical speed of a robot means the total height of stair divided by the time taken for a robot to climb a stair. The step size corresponds to the tread and height of a stair known for a robot to climb. For the tracked robot, the payload for a robot to carry out is examined. For the legged robot, the total degree of freedom (DOF) of their motions and DOF of their legs are searched. For the wheel-linkage robots, the number of wheels is added and for the wheel-legged robots, the main structures of their locomotion are given.

It is noted that although some robots are reported to climb stairs in papers or video files, numerical information such as the exact size of a stair for robots to climb and their vertical speed is not sometimes provided in detail. Therefore, in this review, we have first estimated the size of a stair for robot to climb by the proportional relation between the measured lengths of stair in the figure or captured video file and the known overall length of robot. Then, their vertical speeds are calculated by dividing the estimated or real height of a stair with the time taken for the robot to climb it, which can be easily measured from the video file.

V. PERFORMANCE EVALUATION OF STAIR-CLIMBING ROBOTS

The quantitative evaluation of stair-climbing ability is essential for reliable robotic solutions. Several criteria for stair-climbing robots have been proposed; for example, the difference between the trajectory of CoM of a robot and the straight line determined by the slope of stair [20], [28], [82], [115], [116], [117], [118], the acceleration during stair-climbing [131], the required friction coefficient [108], [118], [132] have been used to evaluate the stair-climbing performance of mobile robots.

On the other hand, a new metric versatility is introduced to allow a comparison among mobile robot designs [133]. It is noteworthy that the versatility of mobile robot is evaluated with respect to the complexity defined as the product of the number of their actuators and the number of their joints. Also, the versatility is segmented into the obstacle mobility and the maneuverability. From this viewpoint, the stair-climbing

TABLE 3. Summary of wheel-linkage robots.

Type	Name	Stair size (tread×height) (mm^2)	Weight (kg)	Vertical Speed (cm/sec)	# of wheels	Sensor for stair detection
Rocker-bogie based robot	Rocker-bogie based robot [108]-[111]	300 × 200, 210 × 160, 300 × 100	14.5	26.67	6	-
	Shrimp [112], [113]	210 × 170	3.1	1.2	6	-
	Six-wheel robot with rocker (large robot) [114]	630 × 150	420	25.74	6	-
	Rocker-Pillar [115]	400 × 150	25	15	4 wheels / 2 tracks	-
	RHyMo [116]-[118]	300 × 160	53	16.67	4 wheels / 2 tracks	-
	TuskBot [121], [122]	360 × 180, 300 × 120	-	6.92	4 wheels / 2 tracks	-
Wheelchair	Wheelchair [120]	260 × 180	80	6.67	8	Proximity detectors
	Wheelchair. q [123]-[126]	-	-	-	6 wheels / 1 track	
	Wheelchair [184]	255 × 255	70	-	4 wheels / 2 legs	Laser distance sensor
	RT-Mover [181]	280 × 170	92	-	4	Photoelectric sensor
	TWB-1 [127]	300 × 110	154	0.05	8	
	SCMS [128], [129], [143]]	300 × 150	72	-	4	Laser distance sensor
Multi-wheel-linkage robot	Modular robot [119]	305 × 178, 292 × 190, 280 × 203	-	14.51	8	
	BIT-NAZA [130]	220 × 80	-	0.17	8	LiDAR, camera

TABLE 4. Summary of wheel-legged robots.

Type	Name	Stair size (tread×height) (mm^2)	Weight (kg)	Vertical Speed (cm/sec)	Main structure	Sensor for stair detection
Leg-type wheel-based robot	ASGUARD [69]-[73]	300 × 170	9.5	13.91	4 legged wheels	-
	Curved-spoke tri-wheel robot [82]	300 × 160	6	22.86	2 spoke wheels	-
	Bioinspired RHex-style robot [81]	250 × 270	-	1.56	6 Whegs	Infrared range (IR) sensors, inclinometer
	RHex [83]-[89]	295 × 189	8.6 ~ 9.5	2.87	6 Whegs	-
	IONS [79], [80]	300 × 180 [estimated]	7	6.75	4 Whegs	IR sensor, IP camera
	GerWalk [77], [78]	280 × 170	0.075	42.5	2 rimless wheels	-
Transformable wheel-based robot	TurboQuad [74]-[76]	300 × 160	18.5	5.14	4 transformable leg-wheels	-
	Segmented wheel-based robot [101]-[105]	110 × 64	-	-	4 segmented wheels	-
	STEP [106]	300 × 160	35	18	2 transformable wheels	-
	α-WaLTR [182]	290 × 180	-	-	4 transformable wheels	RGB-D camera, 2D LiDAR
Star-wheel based robot	MSRox [96], [97]	150 × 100	-	13.33	4 star-wheels	Photoelectric sensor
	Automatic erect stair-climbing robot [94], [95]	260 × 180	76	3.6	2 tri-wheel modules	Kinect sensor, IMU
	iBOT [90]-[93]	290 × 160	80.7	3.2	4 wheels	-
	New mobility vehicle [98]-[100]	300 × 125	24	1.14	2 wheels + 2 rotary legs	-
	LOPER [183]	-	-	-	4 tri-lobe wheels	-

ability of a mobile robot is obviously one specific example of obstacle mobility. Although the obstacle mobility is handled in [133], the practical points such as the difficulty of climbing steeper stairs and the efficiency of climbing stairs quickly is not reflected properly because the obstacle mobility in [133] just determines the weighting according to the given conditions.

Therefore, in this review, the vertical speed of a mobile robot and the stair dimension are selected as the performance criteria, which are graphically explained in Fig. 17. Note that the stair dimension is defined as $\phi \times (e^{ch} - 1)$, where ϕ and h are the slope [deg] and the height [mm] of a step, respectively and c is a constant chosen to modify the score of stair dimension into a visible scale. In order to reflect the fact that the stair-climbing becomes difficult in proportion to the height of stair, the stair dimension is adopted instead of the stair size and the exponential function is applied for the height of stair. Recall that the stair dimension is zero when the height of stair is zero, which means that a mobile robot moves on a flat ground. When the slope and height of a stair varies from 30 to 60 deg and from 0 to 220 mm, the resulting stair dimension is given in Fig. 18, where c is chosen as 0.007.

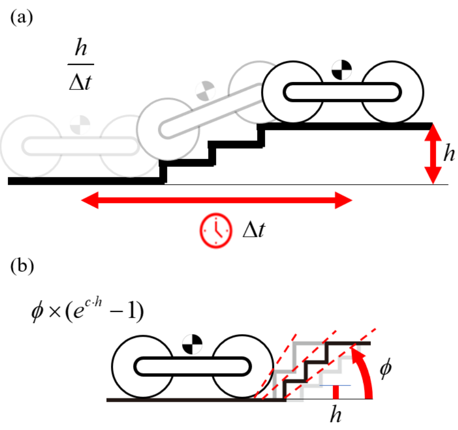

FIGURE 17. Candidates for performance evaluation of stair-climbing robots: (a) vertical speed and (b) stair dimension.

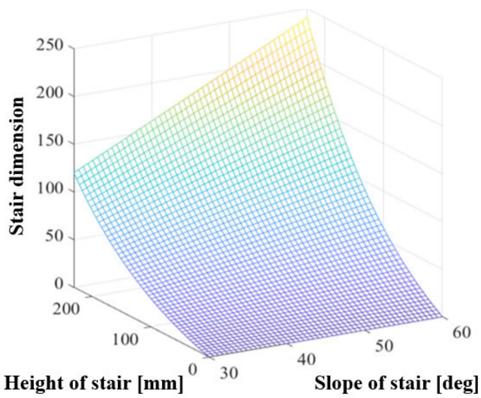

FIGURE 18. Example of stair dimension defined as $\phi(e^{ch} - 1)$ with scaling constant c = 0.007.

Similar to [133], these criteria are evaluated with respect to the complexity of a mobile robot as shown in Fig. 19, where tracked, legged, wheel-legged and wheel-linkage robots are denoted by the blue circle, the red triangle, the green rhombus and the black square, respectively. Note that full colored circle/triangle/rhombus/square denote tracked/legged/wheel-legged/wheel-linkage robots that cannot climb a stair without a riser.

The average values of stair dimensions for tracked/legged/wheel-legged/wheel-linkage robots are about between 70 and 140 as shown in Fig. 19(a). While the averaged stair dimension value of wheel-linkage robot is the lowest as 70, the averaged stair dimension value of legged robot is the highest as 140. Recall that it is possible to score the stair dimensions of existing stairs from [8], [9], [10], and [11], for example, the steepest IBC standard stairs score 80.5, whereas the steepest stairs from IBC residential groups score 112.3. Therefore, it can be said that robots scoring the stair dimensions ranging between 80 and 120 in Fig. 19(a) can climb the commonly used stairs.

With respect to the complexity, most legged robots are located at the right side of Fig. 19(a) while tracked and wheel-linkage robots are located at the middle of Fig. 19(a), which implies that the legged robots have more complicated structures due to their actuators and joints. On the other hand, the wheel-legged robots are widely located at Fig. 19(a) due to such quite simple wheel-legged robots as GerWalk [77], curved-spoke tri-wheel robot [82] and soft-material based Loco-sheet [107]. Exceptionally, the multi-wheel-linkage robot BIT-NAZA requires relatively many actuators and joints owing to its Stewart platform-based leg structure [130].

Atlas's stair dimension is much higher than other robots, which implies that Atlas can climb much higher and steeper stairs. As the wheel-legged robot, the bioinspired RHex-style robot [81] takes the 2nd place in the stair-dimension and as the wheel-linkage robot, the wheelchair [184] is in the 3rd place. ANYmal and Vision 60 are in the 4th and 5th places, respectively. As the tracked robot, switchblade robot [22] is in the 6th place. The stair climbing ability of most legged robots except for Atlas seems similar to other robots but recall that the existence of a riser does not have the effect on the stair-climbing ability of all legged robots at all. To the contrary, some wheel-legged and tracked robots depend on the riser of a stair, for example, star-wheel based robots need the riser for stair-climbing [90], [91], [92], [93], [94], [95], [98], [99], [100]. However, as given in Fig. 19(a), most wheel-linkage robots except for inevitably depend on the riser of a stair, which may restrict the wide application of wheel-linkage robots.

As shown in Fig. 19(b), the tracked robots not only have the simple mechanism but also ensure the relatively fast vertical speed, which may be because their stair-climbing procedures are similar to moving on a ramp. The rankings of averaged vertical speeds of mobile robots are in the order of tracked, wheel-legged, legged and wheel-linkage robots. It is not surprising that the vertical speed of wheel-legged robot GerWalk [77] is the highest in that its weight is just 0.075 kg.

In comparison with tracked and wheel-legged robots, the vertical speeds of wheel-linkage robots are relatively slow owing to wheelchairs with complex structures [127], [128], [129], large sized BIT-NAZA [130] and rocker-bogie based Shrimp [112], [113]. It is noted that most the wheel-linkage robots must keep in contact with both the riser and the tread of a stair during their stair-climbing, which is absolutely time-consuming. The averaged vertical speeds of legged robots are similar to those of wheel-legged robots despite of the complex mechanisms of legged robots. The vertical speed of Spot is slightly higher than those of other legged robots due to its ability to generate a gait suitable for stair-climbing [4], [29]. On the other hand, the vertical speed of ASTERISK is quite slower than other legged robots due to the inherent characteristics of six legged locomotion.

It is true that except for legged robots, other mechanisms suffer from the adaptability to the size and shape of stair, for example, the wheel-linkage based design like the rocker-bogie and Shrimp cannot climb a stair without a riser because they depend on the friction to climb stairs by contacting the riser. Wheel-legged robots with wheels at the

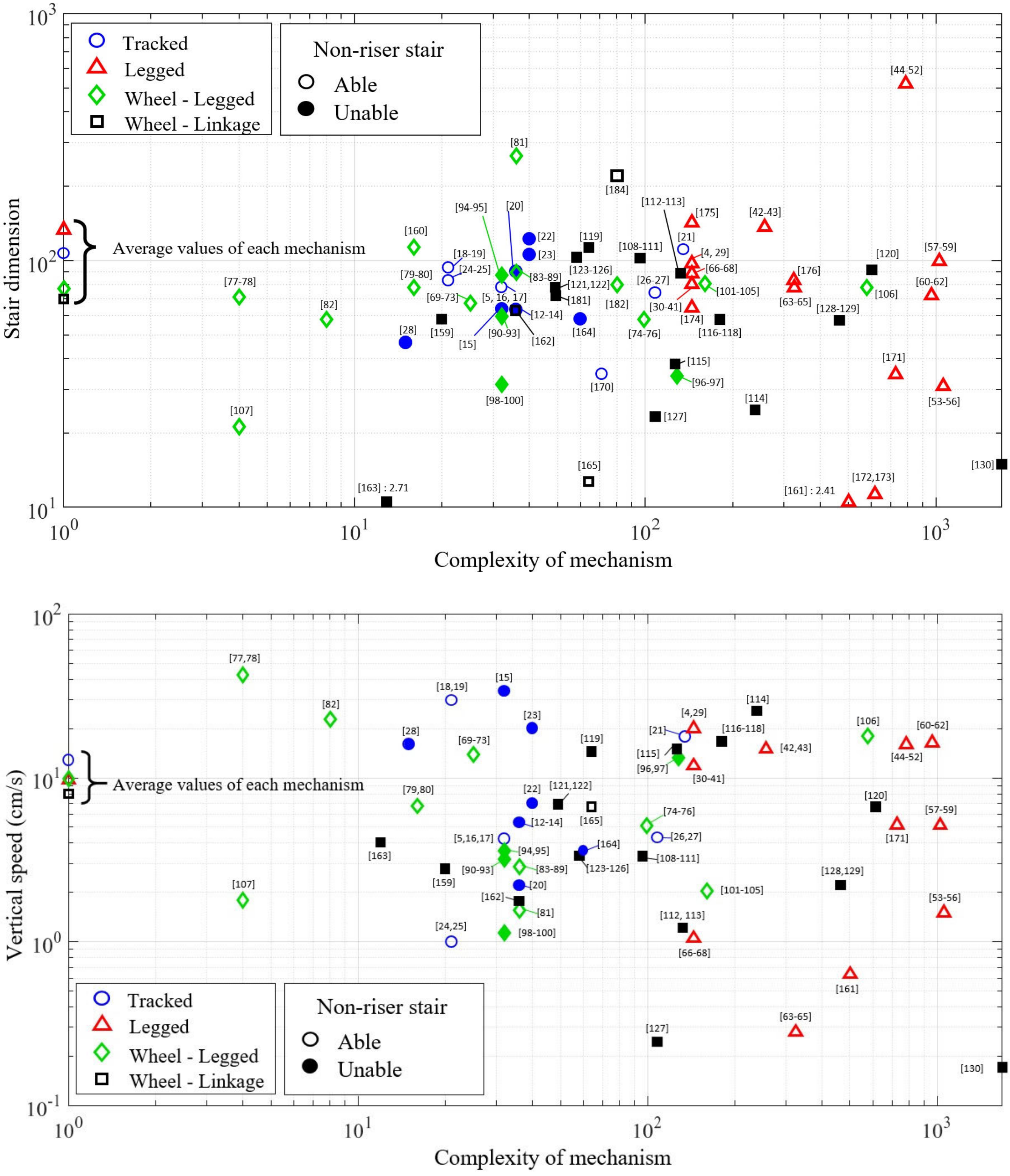

FIGURE 19. **Qualitative evaluations of a robot design via (a) stair dimension and (b) vertical speed of mobile robot with respect to complexity.**

end of spokes also need to contact with the riser of a stair for the same reason. It is noted that while climbing the stairs, the first step of wheel-based and tracked robots is to contact with the riser. In order to reduce this dependency on the riser of a stair, the one-body tracked robot with flippers and the multi-body tracked robots have been proposed, which can adjust the contact angle between their tracks and the riser by tilting the articulated tracks properly. Similarly, some of wheel-linkage robots are equipped with tracks instead of front wheels.

VI. RECENT RESEARCH AND FUTURE WORKS

As discussed, the stair-climbing seems a challenging issue in the research of robotic platform. In recent years, there have been some notable studies on robotic design and control to overcome the limitations of the existing mechanisms.

For legged robots, one of important issues is sensing. If the sensing information is incorrect, the legged robot usually falls down or are stuck during stair-climbing [147]. The convolution neural network (CNN), the well-known deep learning architecture, is adopted to increase the sensing and segmentation accuracy with vision sensors [148], [149]. In order to cope with the issue related with sensing, the MIT Cheetah 3 is tested in the novel way to climb a stair blindly without external sensors [38]. Recently, the practical method to train a neural network policy in simulation and transfer it to a legged robot has been applied to the quadruped ANYmal and as a result, it is reported to run faster than before and to recover from falling even in complex environments [153]. From the viewpoint of the legged robot design, the stair-climbing ability is considered for the design of legged robot with the aim of avoiding undesired interferences between its legs and stairs [166]. Also, the benchmark studies have been conducted by using a set of performance indicators for two legged robots with various environmental conditions and the whole-body control algorithms [167], [168].

The robotic mechanisms have been recently designed in a way to properly combine the merits of existing mechanisms. Unlike existing rocker-bogie based robotic mechanisms, the damper-driven rocker-bogie (DDRB) mechanism utilizes only two motors on its front wheels by combining the rotary damper and the tensile spring with the pivot of bogie [159]. As a result, even under lower friction condition, the proposed DDRB mechanism enables to overcome different obstacles efficiently via the simple velocity control. The wheelchair with a tri-wheel is combined with a linkage mechanism to change its center of mass (CoM) for stable stair-climbing [100]. Also, a new two-wheeled robot with four rotational (4R) and two prismatic (2P) joints is proposed to climb different stairs by following a four-step cycle of approaching, lifting, putting and retraction [162]. A three wheeled robot is proposed to climb various stairs by simply adjusting the length between front and rear wheels [163].

Some two legged and quadruped robots add wheels at the end of their legs to improve the performance on flat surfaces. For example, the wheel-legged robot is proposed to climb a step or two steps effectively, which can adjust its leg lengths so as to lift up its wheels [161]. However, it may have the difficulty in climbing common size stairs due to its long body length. A new wheel-legged robot is designed by combining four legs with the wheel on the end of each leg, whose legs are composed of linkages and sliders for dynamic leg motion suitable to stair-climbing [165]. Similarly, two wheel-legged robot is suggested for stair-climbing [150]. By combining the principle of tracked, legged, wheel-leg, and wheel-linkage mechanisms, a completely new robot can be designed. The STEP mechanism adopts two degrees-of-freedom (DOF) wheels to adjust its wheel radius as well as the tilting angle of limb simultaneously for stair climbing [106]. For the perfect autonomous navigation of STEP, the sensing and control issues should be solved. Similar to STEP, the involute-curve-shaped mechanism (ICSM) uses the involute-curve-shaped wheel that has the merit of overcoming the stair in that its rotational axis can be lifted easily above the stair height [160]. However, the size of stair for the proposed ICSM to climb may be restricted owing to its fixed shape. Similarly, a new hexapod Q-Whex is designed on the basis of so-called quasi-wheels [194]. Recently, a modular 2-DOF transformable wheel is designed, whose size and mass are significantly reduced in comparison with the STEP by adopting a flat BLDC motor [158].

Also, Soft materials have been used to adapt the robots according to the size and shape of stairs; this has been referred to as physical intelligence [107].

Up to date, most of studies related with stair-climbing has focused on climbing only a linear stair not a curved or rotating stair. This topic must be handled as one of future works for stair-climbing robotic platforms. Also, the physical intelligence on soft materials and structures has been widely studied. For example, the flexible wheel with a novel structure is designed for stair climbing [151]. The physically intelligent structure of soft robotics has been mainly achieved by using the origami method, which is well known to achieve the desired deformation [154], [155]. However, it is true that the softness of material may be a huge hurdle to applying the soft robotic platform to various practical applications. Recently, the payload of transformable wheeled vehicle is significantly improved in [156] but it cannot be used for stair-climbing due to its heavy weight. In the near future, physically intelligent design of soft robotic platform with good payload capacity will be achieved by considering material compliance and structural deformation. For more detailed research issues of soft robotics, refer to [157].

VII. CONCLUSION

In this review, we have examined the conditions of stairs, the mechanism design, the sensing and control methods and proper performance criteria for stair-climbing robots. There have been a lot of studies to develop a reliable and fast stair-climbing robot based on the track, leg, wheel and wheel-linkage based designs; however, due to various types and shapes of stairs as well as the economical reason, there is no market-dominant design of a stair-climbing robot. For fair comparison, the quantitative criteria are suggested and the characteristics of four types of mobile robots are compared in details. Also, some recent results are introduced, where a soft morphing or wheel transformation are discussed. We hope that this review serves as the guidance to development of reliable and fast stair-climbing robotic platform.

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