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Review

Watch the Next Step: A Comprehensive Survey of Stair-Climbing Vehicles

Antonio Pappalettera †, Francesco Bottiglione †, Giacomo Mantriota † and Giulio Reina *,†

Dipartimento di Meccanica, Matematica e Management, Politecnico di Bari, 70126 Bari, Italy; antonio.pappalettera@poliba.it (A.P.); giacomo.mantriota@poliba.it (G.M.)
* Correspondence: giulio.reina@poliba.it
† These authors contributed equally to this work.

Abstract: Stair climbing is one of the most challenging tasks for vehicles, especially when transporting people and heavy loads. Although many solutions have been proposed and demonstrated in practice, it is necessary to further improve their climbing ability and safety. This paper presents a systematic review of the scientific and engineering stair climbing literature, providing brief descriptions of the mechanism and method of operation and highlighting the advantages and disadvantages of different types of climbing platform. To quantitatively evaluate the system performance, various metrics are presented that consider allowable payload, maximum climbing speed, maximum crossable slope, transport ability and their combinations. Using these metrics, it is possible to compare vehicles with different locomotion modes and properties, allowing researchers and practitioners to gain in-depth knowledge of stair-climbing vehicles and choose the best category for transporting people and heavy loads up a flight of stairs.

Keywords: stair-climbing vehicles; mobile robotics; obstacle negotiation; assistive technology; mobility impairment; architectural barriers

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1. Introduction

The number of people affected by any form of physical disability represents a significant part of the world population, from children to adults alike. It is estimated that approximately 131 million or 1.85% of people require wheelchairs in the world [1]. Almost 1% of United States population currently uses a wheelchair. Half of them must overcome steps to enter and exit their homes. A similar fraction report having difficulty entering or leaving the home [2]. In any case, there are also people without disabilities to consider. According to the National Center for Health Statistics (Hyattsville, MD, USA), only in the USA, the percent of adults aged 18 and over with any difficulty walking or climbing steps in 2020 is 18.0%, almost 60 million of people [3].

Despite that, the worldwide number of people who find it difficult to overcome architectural barriers daily has not yet been estimated. Because the world population is aging, the people mobility problems are of increasing importance. In Italy, many multi-story residential buildings are not accessible by people with disabilities or walking problems because in them there is no elevator (or similar) for connection to the upper floors. The situation in schools is no better. The ISTAT (The Italian National Institute of Statistics) sources reveal that only 32% of them are barrier-free. In 63% of cases, the reason for the lack of accessibility is the lack of an elevator or the presence of a lift that is not suitable for the transport of people with motor disabilities [4].

Ground vehicles can help to solve these problems [5,6]. They face many challenges, including the negotiation of obstacles [7,8], stairs [9,10] and uneven terrain [11–14]. Recently, much attention has been attracted by solutions that allow to overcome a series of steps towards stair-climbing platforms [15]. In order to design a ground vehicle that can successfully transport people and heavy loads up a flight of stairs, we started to look at existing solutions to obtain useful information for design purposes. However, the stair-climbing literature is very sparse and poorly organized. In this paper, an attempt to survey the state-of-the-art in this field is pursued. Since all the solutions proposed entail a rather high level of automation, we will refer throughout the paper interchangeably to stair-climbing robots or vehicles. However, some of the prototypes included in the survey are human operated and not fully autonomous. One common aspect is that all the proposed solutions use a fully electric propulsion system.

Stair climbing is a very challenging task for a mobile robot. It is now necessary to define what is meant by robots that climb stairs. The idea is to look at those vehicles that have the ability to overcome, without the human muscular help, an architectural barrier such as the one shown in Figure 1, adapting itself effectively to different lengths of rise, run, tread and respecting the presence of nosing. During the whole obstacle negotiation stage, safety and tip over stability need to be guaranteed while avoiding immobilization conditions.

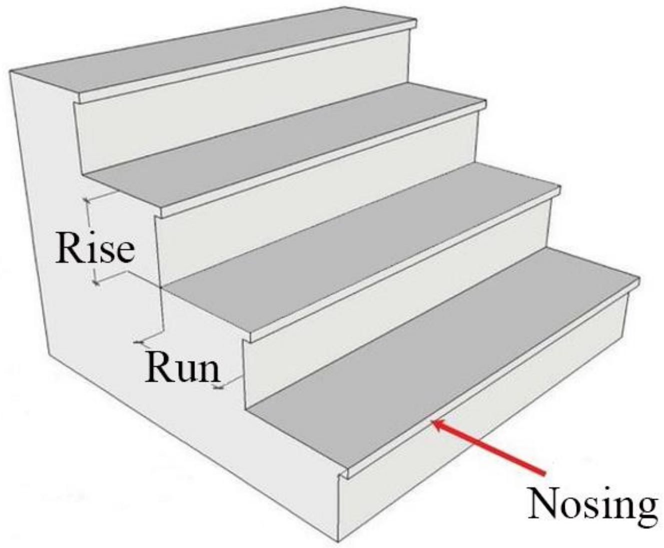


Figure 1. Staircase nomenclature. Typical values for run are 22.8–27.9 cm, rise 20.3 cm, nosing 2.5 cm.

Many climbing systems configurations, which include legged-type, crawler-type, wheeled-type, or combination of the previous, have been proposed in the literature as effective solutions to climb a flight of stairs in addition to driving on regular flat surfaces. These mobile robots can be manually controlled, semi-automated or fully automated using software algorithm combined with embedded CPUs, sensors and cameras [16].

This paper surveys the current state of the art of stair-climbing robots to provide an at-a-glance view of the vast literature, including both commercial and research examples. Another important contribution refers to the introduction of metrics to quantitatively evaluate the climbing performance and allow vehicles with heterogenous properties and locomotion types to be fairly compared. While the previous literature reviews have focused on specific aspects, including step-climbing ability of power wheelchairs [17], traction characteristics of explosive ordnance disposal (EOD) robots [18], tracked locomotion systems [19] and load carriage assistive devices [20], here a comprehensive overview covering a wide range of stair-climbing vehicles is presented.

This work is intended to be prescriptive for the readers. The proposed methodology of analysis, based on quantitative measurable metrics such as allowable payload, maximum climbing speed, maximum crossable slope and transport ability, can be used as an effective criterion to obtain important robot features that cannot be deduced a priori through a single qualitative analysis of the stair-climbing systems. Researchers and engineers can choose exactly the most suitable stair climbing solution to meet the project requirements based on and learning from the results presented in the following when designing new stair-climbing vehicles.

The article is organized as follows. Section 2 proposes a general categorization of climbing vehicles considering payload capacity and locomotion mode. Next, a detailed description of the different families of robots is provided in Section 3. Section 4 presents performance measures and a side-by-side comparison among the various vehicle type, along with a discussion of cost and complexity. Finally, Section 5 concludes this survey providing relevant conclusions as to which category of robot is best able to transport people and heavy loads up a flight of stairs.

2. Categorization of Stair-Climbing Vehicles

Many examples of stair-climbing vehicles have been proposed and demonstrated. They can be divided into broad categories according to the scheme shown in Figure 2. One of the main aspects to consider is whether the robot is designed to carry a payload. Therefore, the first main classification can be made by differentiating "payload robots" from "no payload robots". In this classification, we consider payload may be people, animals or goods that should be carried safely by the robot through a desired path. On the contrary, equipment attached to the robot and not directly involved in the motion ability, such as additional sensors and cameras, robotic arms and tools, are not considered as payload but rather part of the robots itself.

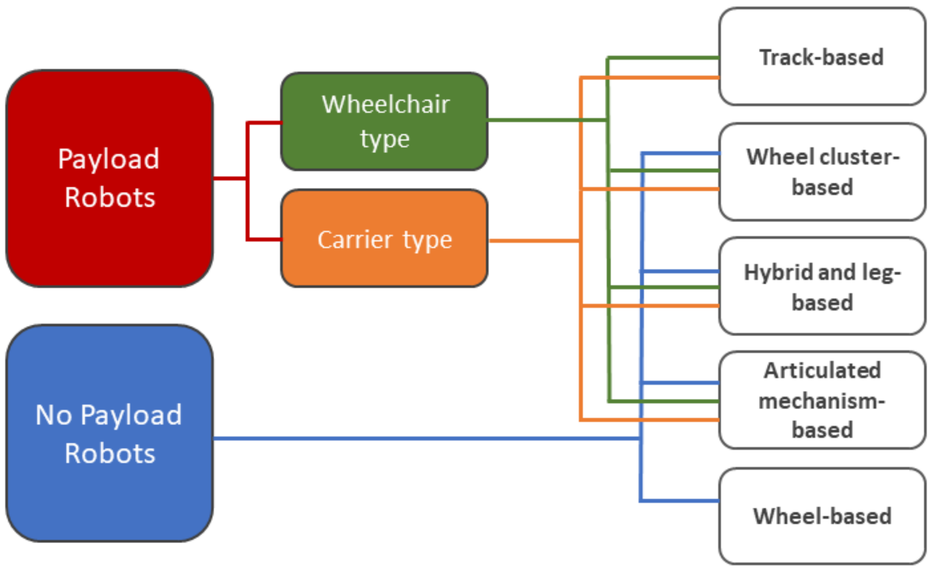


Figure 2. Categorization chart for Stair-Climbing Vehicles.

Payload robots can be further divided into wheelchair and carrier type. Wheelchair types are systems in which a wheelchair for the transport of a person is used. In carrier types, a container is used instead to allocate goods.

Finally, wheelchair type, carrier type and no payload robots can be divided according to the stair-climbing mechanism used. These mechanisms belong to five main categories: track-based, wheel cluster-based, articulated mechanism-based, hybrid and leg-based and wheel-based systems.

(1) *Track-based mechanisms* have the largest ground contact surface and are very stable due to a lower center of gravity. To facilitate the stair-climbing process, tracks can be equipped with teeth. Track-based mechanisms enable robots to climb up or down the stairs at a constant speed in a stable manner due to the interlocking effect between the track's outer teeth and the steps' sharp corner. There are no problems regarding the different length of rise, run, tread and noising of the stair steps' shape. The track-based mechanisms are widely adopted.

(2) *Wheel cluster-based mechanisms*: A wheel cluster is a component with multiple wheels uniformly distributed in the same plane around a common center. While using a stair-

climbing mechanism, the wheels rotate around the central axis of the wheel cluster and propel the robot up or down the stairs. Often, wheel cluster-based mechanism robots are not able to overcome all type of stair, so a range of available step lengths are given. Wheel cluster-based robots are characterized by speed fluctuation during the ascending and descending motion.

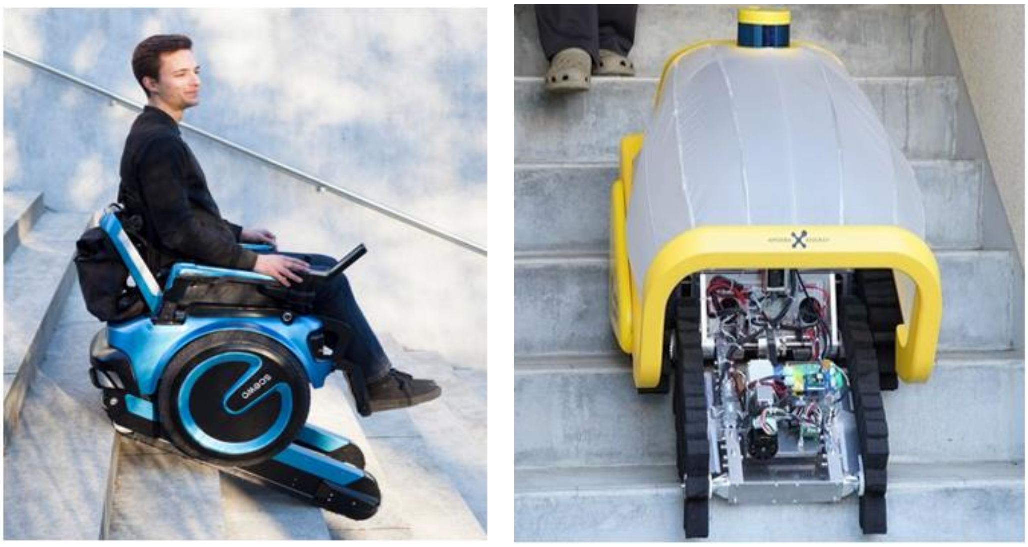
(3) *Articulated mechanism-based systems*: This type of stair-climbing robots uses an articulated mechanism in combination with wheels to accomplish the stair-climbing task.

(4) *Hybrid and leg-based mechanisms*: This type of stair-climbing mechanism originates from the imitation of humans' and animals' stair-climbing techniques, using legs and feet to walk on various steps. Theoretically they can adapt to all type of stairs provided that the control system is sufficiently developed.

(5) *Wheel-based mechanisms*: Two or more wheels are used to perform the stair-climbing task. They can be suspended respect to the robot's frame, using mechanical suspension, or not. Wheeled robots can reach high speeds with low power consumption.

3. Payload Robots

These types of vehicles are designed to carry a load during staircase negotiation. They can be divided into wheelchair type (please refer to Figure 3a), where the person transported is seen as a payload, or carrier type (see Figure 3b). Both families are described in detail in the remainder of this section.



(**a**) (**b**)

Figure 3. (**a**) Scewo wheelchair in action. Adapted with permission from ref. [21]. 2023 Preeta Chatterjee 24 September 2021; (**b**) Amoeba Go-1 in action [22].

3.1. Wheelchair Type Robots

Since the 1990s, many research results on wheelchair-type stair climbing robots have been achieved and a variety of commercial wheelchairs and prototypes have been developed [23]. Many examples of wheelchair-type stairs have been demonstrated at Cybathlon [24]. Cybathlon is a non-profit project of ETH Zurich (Zurich, Germany) who acts as a platform that challenges teams from all over the world to develop assistive technologies suitable for everyday use with and for people with disabilities. Different disciplines comprise the competitions. They apply the most modern powered devices such as prostheses, wearable exoskeletons, wheelchairs and functional electrical stimulation, as well as novel brain–computer interfaces to remove barriers between the public, people with disabilities and science. In the Powered wheelchair race competition, the most modern solutions compete with each other. Among the different tasks there is precisely that of overcoming a small series of steps.

Some examples of wheelchair type robots are now presented using classification shown in Figure 2. Track-based robots are reported in Table 1.

Table 1. Track-based wheelchair type robots list.

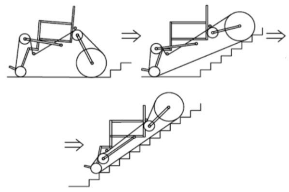
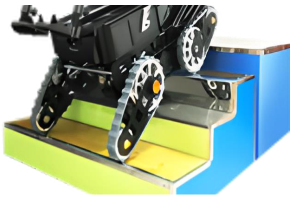
Name	Solution	Features
Scewo Bro [25]		Commercial solution, automatic stair-climbing system, self-balancing software control, high safety
TopChair-S [26]		Commercial solution, automatic stair-climbing system, self-balancing software control
WT Wheelchair [27,28]		Prototype solution, manual stair-climbing system, no self-balancing control system
Tao [29]		Prototype solution, manual stair-climbing system, self-balancing software control
B-Free Ranger [30]		Commercial solution, automatic stair-climbing system, self-balancing software control
ZED evolution [31]		Prototype solution, manual stair-climbing system, no self-balancing control system
Caterwil GTS5 Lux [32]		Commercial solution, automatic stair-climbing system, self-balancing software control, high speed

Table 1. *Cont.*

Name	Solution	Features
Fortissimo [33]		Prototype solution, manual stair-climbing system, no self-balancing control system
Hkust [33]		Prototype solution, manual control, no self-balancing control system
All-Terrain Wheelchair [34]. Adapted with permission ref. [34] 2017 Janez Podobnik		Prototype solution, automatic stair-climbing system, self-balancing software control, Chebyshev-based linkage mechanism for lifting and lowering the tracks

Most of the solutions [25,26,29,30,33,34] use wheels as preferred locomotion mode on regular flat ground while the track-based system is stowed under the carriage. Obstacle negotiation is performed in track locomotion mode: the position of the tracks is changed so that they are lowered to the ground while wheels detach from the ground. Instead, in [27,30,33] a reconfigurable track-based system is proposed to prepare the robot to negotiate stairs: in WT-Wheelchair internal linkages, positions are changed while front and rear flipper angulation are used in B-Free Ranger and Fortissimo. The wheelchair-type robots that participated in the Cybathlon are: Scewo Bro [25], B-Free Ranger [30], ZED evolution [31], Caterwil GTS5 Lux [32], Fortissimo [33], Hkust [33], All-Terrain Wheelchair [34].

The wheel cluster robots are reported in Table 2.

Table 2. Wheel cluster-based wheelchair type robots list.

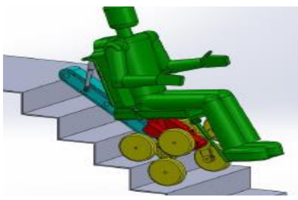
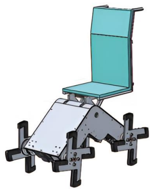
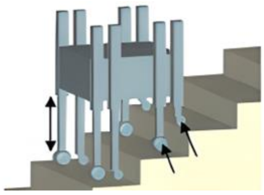
Name	Solution	Features
iBOT 4000 [35,36]		Commercial solution, automatic stair-climbing system, self-balancing software control, good driving range
Wheelchair.q [37,38]. Adapted with permission from ref. [37] 2017 Giuseppe Quaglia, Matteo Nisi		Prototype solution, manual control, no self-balancing control system, good performance

Table 2. *Cont.*

Name	Solution	Features
Castillo [39]. Adapted with permission from ref [39] 2017 Basilio Dobras Castillo		Prototype solution, manual control, self-balancing control system, low comfort

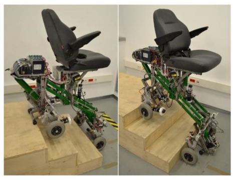
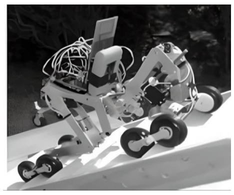
Each solution has very different features from others. iBOT 4000 [35] has inverted pendulum-type dynamic stability control to go up and down stairs while holding the seat stable. Wheelchair.q [37] is composed of a pair of locomotion units and a retractable track that guarantees the rear support point. Finally, Castillo [39], uses four X-shaped wheels to climb and descend stairs while the seat angle of the wheelchair can be changed to hold the center of gravity close to the center of the supporting polygon. Hybrid and leg-based robots are reported in Table 3.

Table 3. Hybrid and leg-based wheelchair type robots list.

Name	Solution	Features
Wang [40]. Adapted with permission from ref [40] 2014 Hongbo Wang		Prototype solution, manula stair-climbing system
Zero Carrier [41,42]. Adapted with permission from ref. [41] 2004 Jianjun Yuan		Prototype solution, automatic stair-climbing system, low speed
JWCR-1 [43,44]. Adapted with permission from ref. [44] 2007 Jiaoyan Tang		Prototype solution, manual control, low safety
WL-16 II [45,46]. Adapted with permission from ref. [45] 2006 Y. Sugahara		Prototype solution, manual control

Wang [40] and Zero Carrier [41,42] have chain-driven legs that move vertically and wheels at the end of each leg. Some are driven to provide forward locomotion while other are passive wheels. Lee wheelchair [47] (not shown in Table 3) climbs stairs using the two 3-DOF legs with boomerang-shaped feet. The leg mechanisms are folded into the compact wheelchair body when the wheelchair moves over flat surfaces. JWCR-1 [43,44] and WL-16 II [45] simulate humanoid walking to going up and down stairs. The first uses 12-DOF mechanism to replicate a human leg while the second has 6-DOF parallel mechanism for each leg. Articulated Mechanism-based robots are reported in Table 4.

Table 4. Articulated mechanism-based wheelchair type robots list.

Name	Solution	Features
RT-Mover PType WA [48–50]		Prototype solution, automatic stair-climbing system, self-balancing software control
Morales [51]		Prototype solution, automatic stair-climbing system, self-balancing software control, low speed
Lawn [52]. Adapted with permission from ref. [52] 2003 M.J. Lawn		Prototype solution, automatic stair-climbing system, self-balancing software control
TBW-I [53]. Adapted with permission from ref. [53] 2010 Yusuke Sugahara		Prototype solution, manual control, no self-balancing control system
HELIOS-V [54]. Adapted with permission from ref. [54] 1999 Y. Uchida		Prototype solution, manual control, no self-balancing control system
Chen [55]. Adapted with permission from ref. [55] 2012 Chun-Ta Chen, Hoang-Vuong Pham		Prototype solution, manual control, no self-balancing control system, low stability
RPWheel [56]		Prototype solution, manual control, no self-balancing control system

In general, they use a wheel or wheels mounted on a structure whose position changes during stair climbing. Chen [55] and TBW-I [53] use simple rotation to change the shape of the mechanism, Morales [51] and Lawn [52] use deployable rigid supports to lift the device and a secondary mechanism to place the wheels on the new support surface. Finally, RT-Mover PType WA [48] has two leg-like axle mechanism and a seat slider. Four wheels are mounted at the leg tips. Every leg-like mechanism possesses two shafts: one for roll adjustments and one for steering adjustment. RT-Mover PType WA [48–50] and RPWheel [56] wheelchair type robots participated at the 2020 Cybathlon edition.

3.2. Carrier Type Robots

One goal of robotics is to replace human operators in daily tasks. Mobile robots for goods delivery represent an important application area. The challenge that these robots must face is to climb a flight of stairs (up and down) of a building carrying a load. With reference to the classification proposed in Section 2, examples of carrier-type stair-climbing vehicles will be introduced and discussed.

Track-based robots are reported in Table 5.

Table 5. Track-based carrier type robots list.

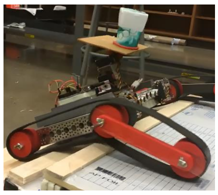
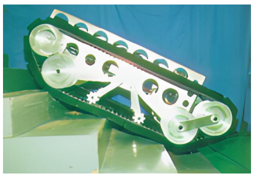
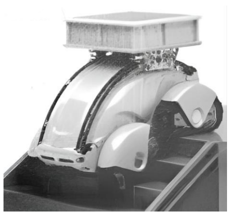
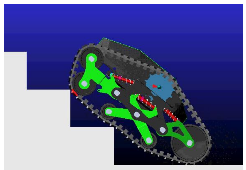
Name	Solution	Features
Zhang [57,58]		Prototype solution, autonomous driving, self-balancing control system, small dimensions
Amoeba Go-1 [22]		Commercial solution, autonomous driving, self-balancing control system, soft rubber tracks
Yoneda [59]		Prototype solution, manual control, no self-balancing control system
TAQT Carrier [60]. Adapted with permission from ref. [60] 1992 S. Hirose		Prototype solution, manual control, self-balancing system
HELIOS-VI [61]		Prototype solution, manual control, no self-balancing control system

Table 5. *Cont.*

Name	Solution	Features
Haulerbot [62]		Commercial solution, autonomous driving, self-balancing control system, high payload capacity
iRobt 710 Kobra [63]		Commercial solution, autonomous driving, self-balancing control system
Polibot [64]		Prototype solution, manual control, no self-balancing control system

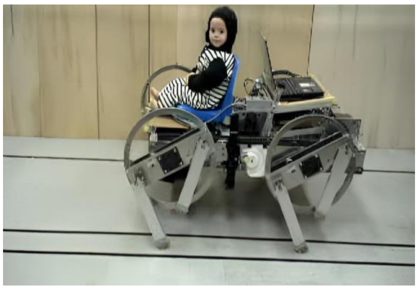
Solutions that adopt a reconfigurable track-based are: [65] (not shown in Table 5), [66] (not shown in Table 5) and [57,61,67] (not shown in Table 5) and [60,62,63] feature front and rear moving flippers. Amoeba Go-1 [22] does not use a traditional track, while it is equipped with a pair of soft crawlers in place of a classic track with grousers. Finally, Polibot [64] refers to an example of suspended tracked robot where the ground wheels can move with respect to the chassis using independent swing arms, showing remarkable mobility over challenging environments that include staircases. A wheel cluster-based robot is reported in Table 6.

Table 6. Wheel cluster-based carrier type robots list.

Name	Solution	Features
Deshmukh [68]		Prototype solution, manual control, no self-balancing control system

It has four wheel-cluster units to perform the stair climbing task [68]. To hold the payload horizontally, a simple mechanism is used to raise and lower the platform. Hybrid and leg-based robots are reported in Table 7.

Table 7. Hybrid and leg-based carrier type robots list.

Name	Solution	Features
Wen [69]		Prototype solution, autonomous driving, automatic stair-climbing system
PEOPLER-II [70,71]		Prototype solution, autonomous driving, no self-balancing control system

Wen [69] has driven legs which move vertically, and four wheels attached to the body frames. Moreover, [72] (not shown in Table 7) uses driven legs as Wen [69] but a different system to appreciate stairs corners. Peopler-II [70,71] has perpendicularly oriented planetary legged wheels that are used to climb and descend stairs. Finally, Yeping [73] (not shown in Table 7) is a four-legged stair-climbing robot. Each leg has 4-DoF and support a roller at their own end. An articulated mechanism-based robot is reported in [74]. It uses deployable rigid supports to lift the device and a secondary mechanism for placing the wheels on the new support surface. The front wheels can change shape to paws.

3.3. No Payload Robots

This type of robot has been designed without foreseeing any payload capacity. They usually employ less complicated systems to perform the ascent and descent of the flight of stairs. Referring to Figure 2, no payload robots can be categorized based on the specific climbing mechanism. It should be noted that the hybrid and leg-based platforms can be further divided into three subcategories: biped, quadruped and hexapod.

Track-based robots are reported in Table 8.

Table 8. Track-based robots list.

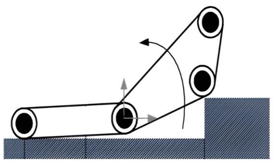
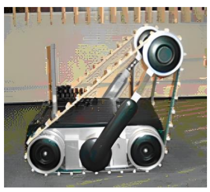
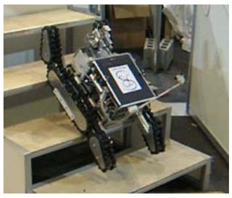
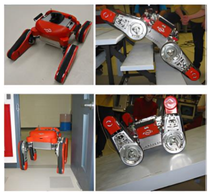
Name	Solution	Features
ROBHAZ-DT3 [75]. Adapted with permission from ref. [75] 2004 Woosub Lee		Prototype solution, teleoperated control
Variable configuration articulated tracked vehicle [76]. Adapted with permission from ref. [76] 2007 Pinhas Ben-Tzvi		Prototype solution, teleoperated control, self-balancing control system

Table 8. *Cont.*

Name	Solution	Features
MACbot [77]		Prototype solution, automatic stair-climbing system
Silver [78]. Adapted with permission from ref. [78] 2006 S. Ali A. Moosavian		Prototype solution, mobile rescue robot automatic stair-climbing system, teleoperated control, self-balancing control system
Azimut [79]. Adapted with permission from ref. [79] 2003 F. Michaud		Prototype solution, flat diamond-shape tracks, local perception system

All solutions use reconfigurable track-system to negotiate stairs. The Robhaz-dt3 [75] track is divided into two parts that can rotate one with respect to the other. Reference [76] changes internal linkages positions to modify the track shape. Finally, [77–79] have front and rear moving flippers to perform the stair climbing task. Wheel-cluster-based robots are reported in Table 9.

Table 9. Wheel cluster-based robots list.

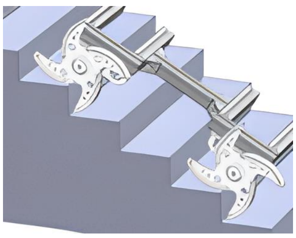
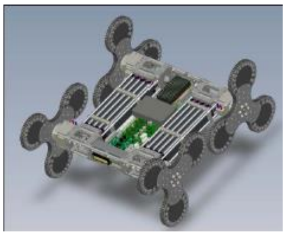
Name	Solution	Features
The Tri-Wheel [80,81]. Adapted with permission from ref. [81] 2015 Lauren M. Smith		Prototype solution
Asguard [82,83]		Prototype solution, mobile rescue robot, motion control software
Krys [84,85]		Prototype solution, segmented stair-climbing wheels

Table 9. *Cont.*

Name	Solution	Features
Looper [86]. Adapted with permission from ref. [86] 2008 Sam D. Herbert		Prototype solution

Most of the solutions [80–82,86] use rotating wheels to perform stair climbing. The Tri-Wheel [80,81] has two locomotion units at the front of the robot, Asguard [82,83] and Looper [86] four. Krys [84,85] possess special wheels for movement on stairs: its rotary segments are capable of smooth driving on stairs without oscillation of the chassis center of mass. Articulated mechanism-based robots are reported in Table 10.

Table 10. Articulated mechanism-based robots list.

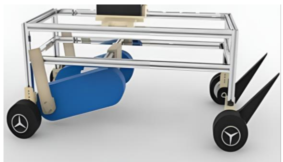
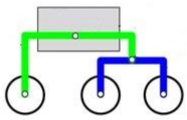
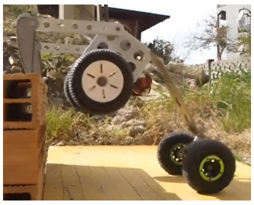
Name	Solution	Features
TuskBot [87]. Adapted with permission from ref. [87] 2017 Jonghun Choe		Prototype solution, indoor operations, length-adaptable platform
Rocker-Bogie [88]. Adapted with permission from ref. [88] 2012 Dongmok Kim, Heeseung Hong, Hwa Soo Kim, Jongwon Kim		Prototype solution, automatic stair-climbing system
Rocker-Pillar [89]. Adapted with permission from ref. [89] 2012 Dongkyu Choi		Prototype solution, automatic stair-climbing system
Octopus [90]		Prototype solution, automatic stair-climbing system
WheTLHLoc [91]		Prototype solution, all-terrain mobile robot, automatic stair-climbing system

Table 10. *Cont.*

Name	Solution	Features
Mantis [92]. Adapted with permission from ref. [92] 2014 Luca Bruzzone		Prototype solution, teleoperated control

They present very different systems to perform the stair-climbing task. Mabuchi [93] (not shown in Table 10) has arms to hook onto the tread of stairs. TuskBot [87] has rear assistive track mechanisms to accommodate stairs and front a protruded structure to climb the stair. Rocker-Bogie [88] and Rocker-Pillar [89] derive their structures from strong mobility in an unexpected terrain vehicle. Octopus [90] has many parallel suspension architectures that lead to a very smooth slope of the center of gravity when overcoming vertical slopes. Finally, WheTLHLoc [91] and Mantis [92] are characterized by a main body equipped with actuated wheels and two protruded structures to allow for climbing stairs. The biped types of hybrid and leg-based robots are reported in Table 11.

Table 11. Biped-based robots list.

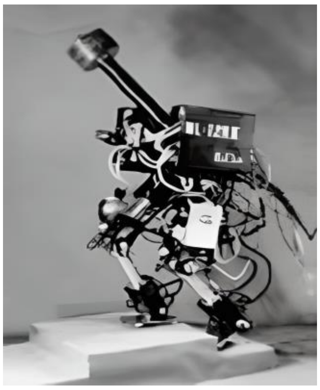
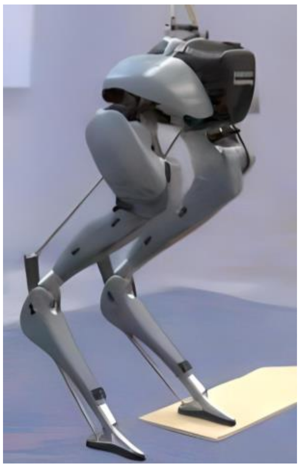
Name	Solution	Features
WL-12RIII [94]		Prototype solution, ZMP (Zero Moment Point) stability control, teleoperated system
RoboSapien [95]		Prototype solution, ZMP (Zero Moment Point) stability control, teleoperated system

Table 11. *Cont.*

Name	Solution	Features
Cassie [96,97]. Adapted with permission from White, J.; Swart, D.; Hubicki, C.; Force-based Control of Bipedal Balancing on Dynamic Terrain with the "Tallahassee Cassie" Robotic Platform. 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, France, 2020, pp. 6618–6624, 2020 J. White		Prototype solution, autonomous walking

WL-12RIII [94] and RoboSapien [95] are inspired by humanoid locomotion. Cassie [96,97] is the most recent robot of the three listed. Its mechanical structure resembles more the hindlimbs of a gazelle. In all the solutions presented, it is of fundamental importance the use of a control for standing and walking without tipping. Quadruped type of hybrid and leg-based robots are reported in Table 12.

Table 12. Quadruped-based robots list.

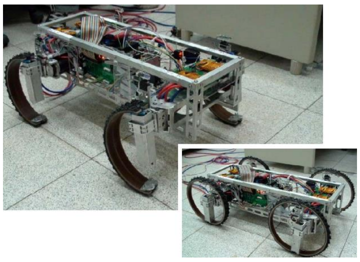
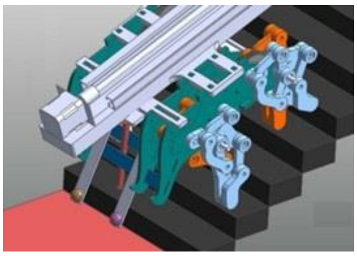
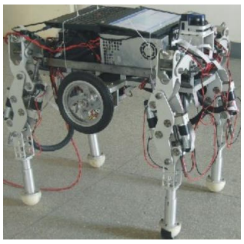
Reference	Solution	Features
Quattroped [98,99]. Adapted from permission from ref. [98] 2011 Shen-Chiang Chen		Prototype solution, teleoperated system
Liu [100]. Adapted with permission from ref. [100] 2017 Chih-Hsing Liu		Prototype solution, teleoperated system, balancing control system
Cheetah 3 [101]		Prototype solution, autonomous walking without use of cameras

Table 12. *Cont.*

Reference	Solution	Features
Spot [102]		Commercial solution, autonomous walking
ANYmal [103]. Adapted with permission from ref. [103] 2016 Marco Hutter		Prototype solution, autonomous walking
HyTRO-I [104]. Adapted with permission from ref. [104] 2013 Dongping Lu		Prototype solution, manual control

In recent years these solutions have been increasingly developed with special attention to the walking gait control. With their structure, Cheetah 3 [101], Spot [102], ANYmal [103] and HyTRO-I [104] simulate the movements of a four-legged mammalian animal. Labib [105] (not shown in Table 12) uses a simpler solution and uses a reconfigurable Klann linkage mechanism to perform the stair climbing task. Finally, Quattroped [98] has a "transformation mechanism" to modify wheels as legs. Specifically, each leg has 2-DoF and can rotate and move linearly with respect to the hip, which is defined as the connecting point from the body to the leg/wheel and is fixed on the body. A hexapod type of hybrid and leg-based robot is reported in Table 13. Rhex [106] is inspired by cockroach locomotion to traverse highly fractured and unstable terrain, as well as to ascend and descend a particular flight of stairs. It has 6 rotational DoFs, one for each leg.

Table 13. Hexapod-based robots list.

Name	Solution	Features
RHex [106]. Adapted with permission from ref. [106] 2002 E.Z. Moore		Prototype solution, automatic stair-climbing system

The only wheeled-based robot is reported in Table 14. Two large wheels are used to perform the stair-climbing task. They are suspended respect to the robot's frame by two parallel elastic jumping mechanisms. Ascento Pro can overcome full flights of stairs, drive at up to 12 km/h and all this for up to 8 h per battery charge.

Table 14. Wheeled-based robots list.

Name	Solution	Features
Ascento Pro [107]		Commercial solution, autonomous drive, outdoor surveilliance service

4. Analysis and Comparison

In this section, various performance metrics are presented that consider allowable payload, maximum climbing speed, maximum crossable slope, transport ability and their combinations. By referring to these metrics, it is possible to compare vehicles with different locomotion modes and properties, highlighting the advantages and disadvantages of each.

4.1. Performance Metrics

Various metrics, suggested by Binnard [108], are introduced to quantitatively evaluate the performance of a given stair-climbing vehicle. Special attention has been given to the normalization of the metrics allowing heterogeneous platforms to be fairly compared. Metrics were estimated based on the specifications stated in related scientific papers or technical sheets. Where data are not available, corresponding metrics are not calculated.

The first performance metric is the payload capacity, *PC*, defined as the percentage ratio of the maximum payload mass to the robot mass:

$$PC = \frac{payload\ mass}{robot\ net\ mass} \times 100 \quad (1)$$

As a second metric, the normalized speed, *NS*, can be defined as the ratio of the robot maximum climbing speed to the robot body length.

$$NS = \frac{Maximun\ Speed}{Body\ length} \quad (2)$$

As an overall performance metric, the Normalized Work Capability, *NWC*, can be considered. It is suggested by Binnard [108] and it is defined as the product of the Normalized Speed (*NS*) and Payload Capacity (*PC*).

$$NWC = PC \times NS \quad (3)$$

Figure 4 shows a bar chart where the Normalized Work Capability is estimated for the wheelchair type vehicles presented in Sections 3.1 and 3.2. Details can be found in the Appendix A Tables A1–A3 where the numeric value of *PC*, *NS* and *NWC* are provided for each platform. Red refers to track-based, blue to wheel cluster-based, green to hybrid and leg-based and yellow to articulated mechanism-based robots.

It can be said that *NWC* quantifies the robot general performance, as it considers both the ability to carry payload and the climbing speed. As seen from the bar charts, the *NWC* metric well defines the different robot categories: track-based, wheel cluster-based, hybrid and leg-based and articulated mechanism-based. In fact, each category has a characteristic range of *NWC*. Articulated mechanism-based robots are mainly concentrated in the range of values that varies between 0 and 3 [s^{-1}]. Even legged robots have low *NWC* values, ranging between 0 and 5 [s^{-1}]. Wheel cluster-based robots have high *NWC* values and are mostly concentrated in the range between 5 and 15 [s^{-1}]. Finally, the track-based stair-climbing robots are distributed evenly over the entire range of *NWC* values, where the most recent robots have NWC values ranging from 6 to 18 [s^{-1}].

The *NWC* of carrier type robots is presented in Figure 5.

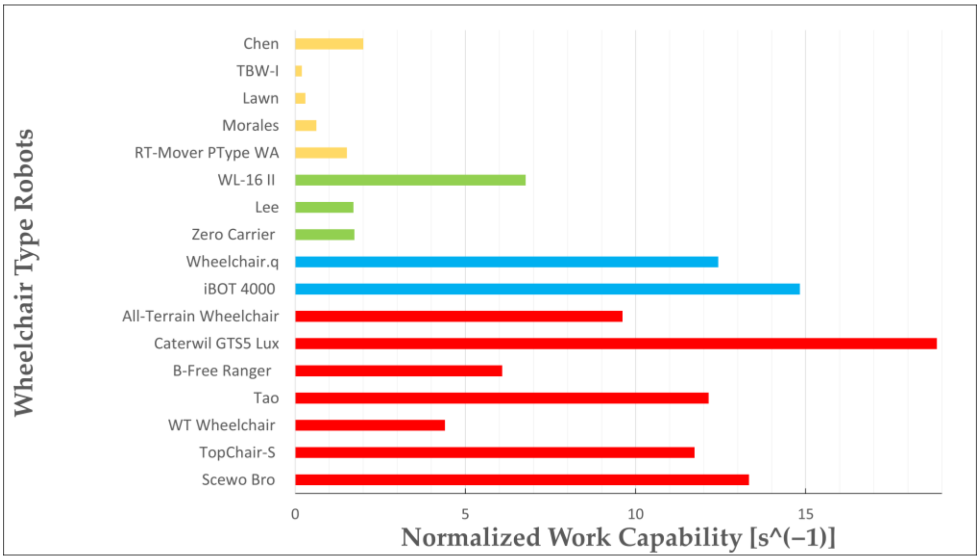


Figure 4. Normalized Work Capability comparison for wheelchair type robots; Chen [55]; TBW-I [53]; Lawn [52]; Morales [51]; RT-Mover PType WA [48–50]; WL-16 II [45,46]; Lee [47]; Zero Carrier [41,42]; Wheelchiar.q [37,38]; iBOT 4000 [35,36]; All-Terrain Wheelchair [34]; Caterwill GTS5 Lux [32]; B-Free Ranger [30]; Tao [29]; WT-Wheelchair [27,28]; TopChair-S [26]; Scewo Bro [25].

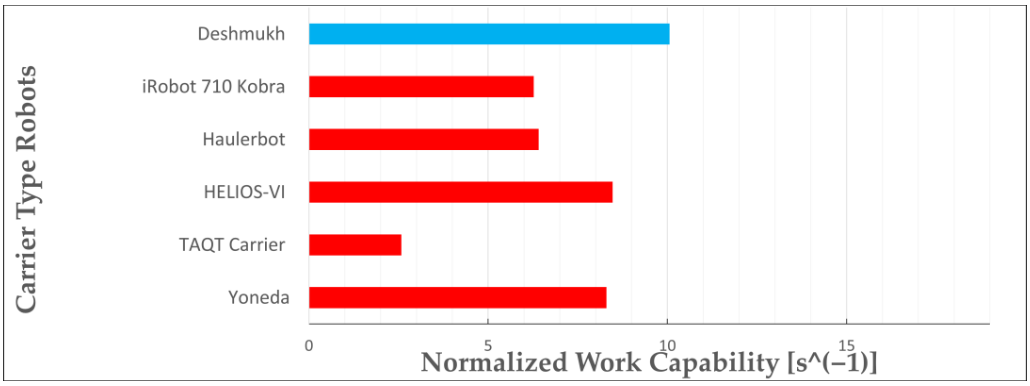


Figure 5. Normalized Work Capability comparison for carrier type robots; Deshmukh [68]; iRobot 710 Kobra [63]; Haulerbot [62]; HELIOS-VI [61]; TAQT Carrier [60]; Yoneda [59].

Normalized Work Capability is not the only metric to measure the performance of payload stair-climbing robots. To evaluate the versatility of use of one robot compared to another, the maximum crossable step height and stair slope are also used as performance metrics. Maximum crossable step height and stair slope are reported in Appendix A Table A4 for each existing vehicle. A graphical representation of the maximum crossable height and slope is given below. Figure 6 refers to wheelchair-type robots while Figure 7 refers to carrier-type robots. Based on these two metrics, different categories do not cluster clearly. Each single robot may be designed in such a way to match desired values of maximum step height and slope regardless of the category it belongs.

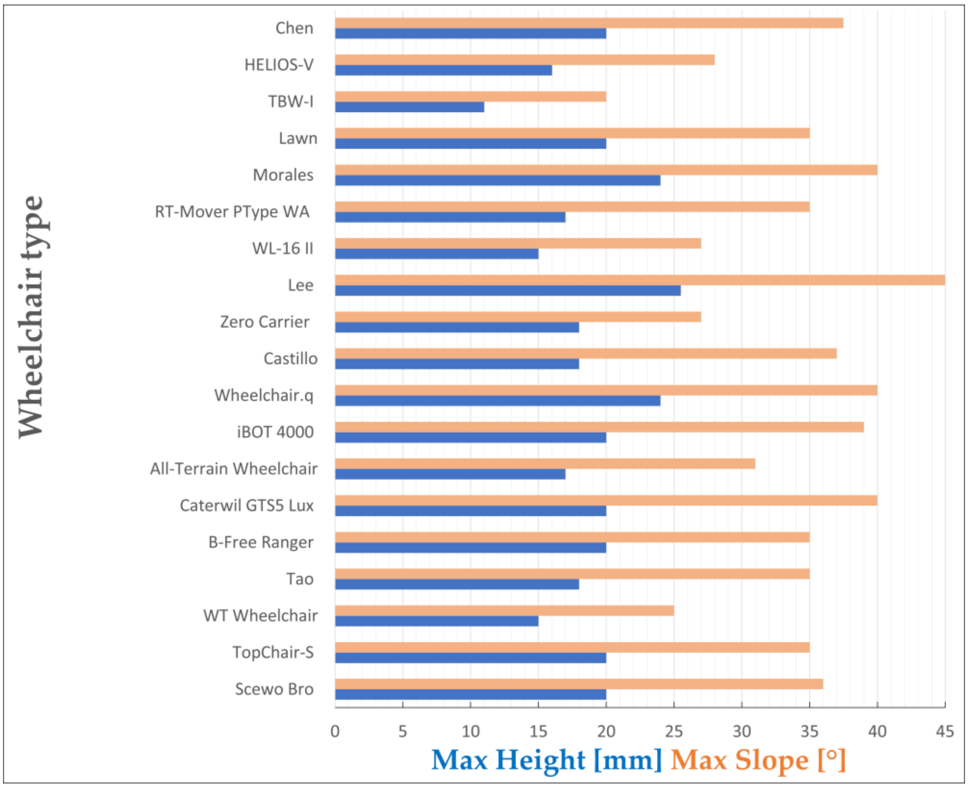


Figure 6. Max crossable height and slope comparison for wheelchair type robots; Chen [55]; HELIOS-V [54]; TBW-I [53]; Lawn [52]; Morales [51]; RT-Mover PType WA [48–50]; WL-16 II [45,46]; Lee [47]; Zero Carrier [41,42]; Castillo [39]; Wheelchiar.q [37,38]; iBOT 4000 [35,36]; All-Terrain Wheelchair [34]; Caterwill GTS5 Lux [32]; B-Free Ranger [30]; Tao [29]; WT-Wheelchair [27,28]; TopChair-S [26]; Scewo Bro [25].

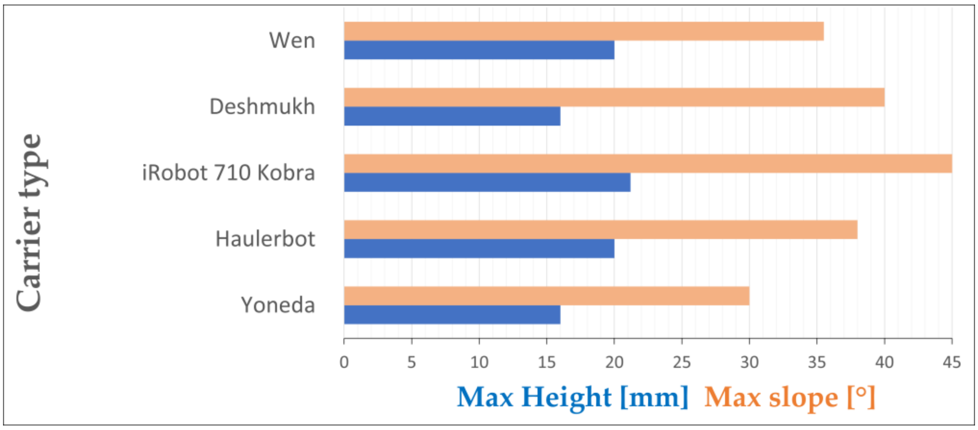


Figure 7. Max crossable height and slope comparison for carrier type robots; Wen [69]; Deshmukh [68] iRobot 710 Kobra [63]; Haulerbot [62]; Yoneda [59].

Here, the Transport Ability (*TA*) is introduced to quantify how effective the robot is at carrying payload during stair-climbing operation. We defined it as the ratio of the payload mass to the maximum robot power.

$$TransportAbility\ (TA)\ [\mathrm{kg/W}] = \frac{Payload\ mass}{Robot\ power} \quad (4)$$

The value of *TA* represents how many kilograms of payload the robot can transport using a unit quantity of power, and so how effective the robot is during transport operation.

Again, the values calculated for different robots are reported in Appendix A Table A5. When data are not provided, the metrics are not reported. A comparison bar chart of Transport Ability values is provided in Figure 8 for wheelchair-type robots and in Figure 9 for carrier-type robots. Red is used to indicate track-based robots, blue to wheel cluster-based, green to hybrid and leg-based and yellow to articulated mechanism-based robots. The most transport-effective categories appear to be track-based and wheel cluster-based because they reach higher value of *TA*. In fact, they combine a good carrying capacity with a small number of actuators. In contrast, the articulated mechanism-based robots and hybrid and leg-based categories, using many actuators to move the system, exhibit lower transport effectiveness because they reach lower values of *TA*.

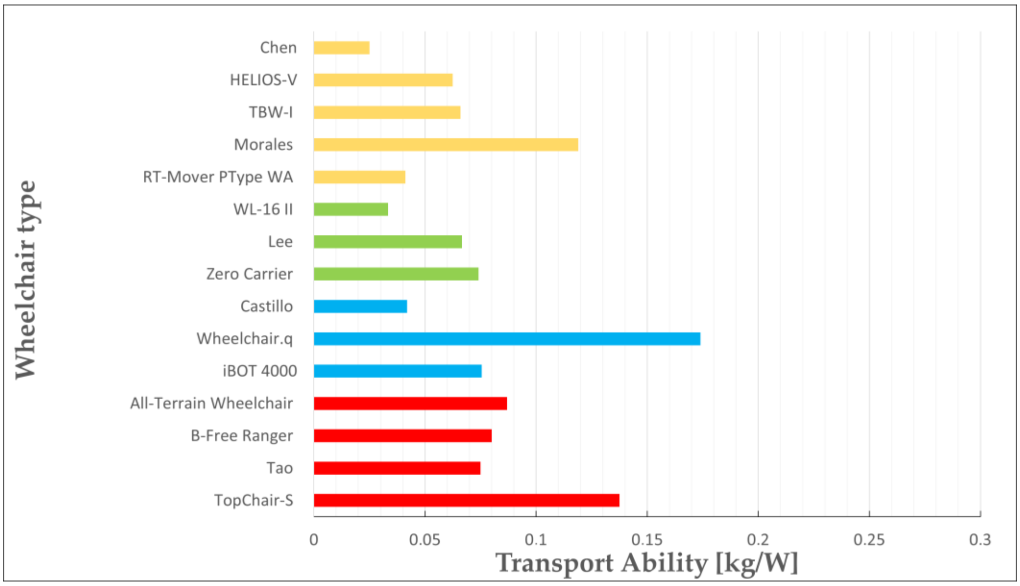


Figure 8. Transport Ability comparison for wheelchair type robots; Chen [55]; HELIIOS-V [54]; TBW-I [53]; Morales [51]; RT-Mover PType WA [48–50]; WL-16 II [45,46]; Lee [47]; Zero Carrier [41,42]; Castillo [39]; Wheelchiar.q [37,38]; iBOT 4000 [35,36]; All-Terrain Wheelchair [34]; B-Free Ranger [30]; Tao [29]; TopChair-S [26].

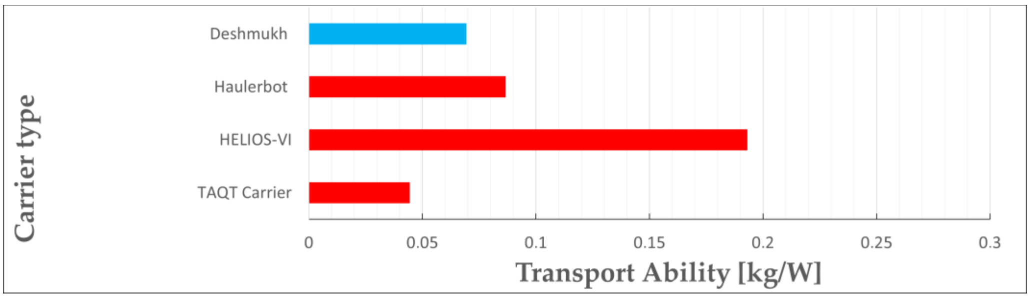


Figure 9. Transport Ability comparison for carrier type robots; Deshmukh [68]; Haulerbot [62] HELIOS-VI [61]; TAQT Carrier [60].

4.2. Comparison Charts

To have a graphical representation of the various performance metrics and their correlation, several scatter plots are provided. Track-based robots are reported with red points, wheel cluster-based robots are reported in blue, hybrid and leg-based robots are reported in green, and articulated mechanism-based robot with yellow points. Figure 10 relates the two independent metrics: the Payload Capacity and the Normalized Speed. It can be observed that most of the points fall below an imaginary diagonal that from the top left to the bottom right cuts the graph into two parts. This highlights the intuitive inverse proportionality that exists between the payload and the transport speed. The lower the payload, the higher the speed of the robot. On the contrary, when the payload to be transported is very heavy, the speed of the robot decreases considerably. Articulated mechanism-based robots deviate from this behavior. Indeed, the normalized speed is almost independent on the payload capacity of each robot, as a result of a technical limitation of the gate-based walking strategy typical for this category.

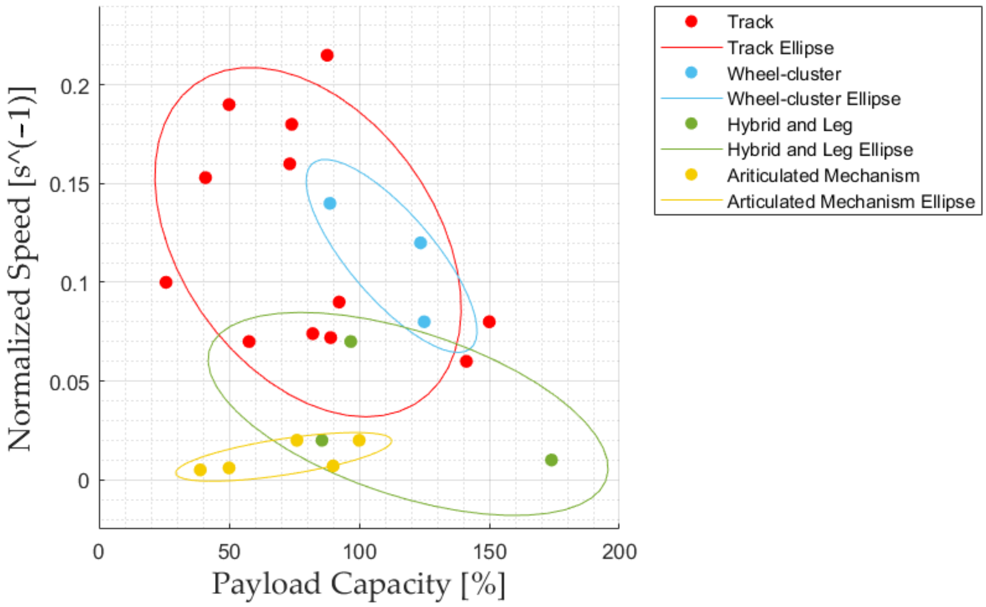


Figure 10. Payload Capacity—Normalized speed scatter plot.

It is important to observe the distribution of the various types of robots in the graph of Figure 10. For the two-dimensional data ([*NS*, *PC*]) pertaining to a given category, a standard deviational ellipse can be defined centered on the mean center and considering one standard deviation. These ellipses were created using the Gaussian Ellipsoids function of the MatLab® software (MathWorks, Natick, MA, USA). It can be seen how the ellipse of the articulated mechanism-based robots (marked in yellow) lies in an area at the bottom of the graph. These vehicles cannot carry a load greater than the robot's own weight and never exceed a Normalized Speed of 0.02 s^{-1}. Hybrid and leg-based robots (green ellipse), despite being able to carry a wide range of payloads, never exceed an *NS* value greater than 0.1 s^{-1}. Wheel cluster-based vehicles are always able to carry a payload comparable to the weight of the robot and at a speed higher than both that of articulated mechanism-based robots and that of hybrid and leg-based robots. Finally, the track-based robots are distributed in the central area of the graph. It is thus evident that they can carry a payload comparable to the weight of the robots. In addition, the arrangement of the ellipse on the graph shows that track-based robots on average have a higher transport speed than the other categories.

In Figure 11, the *NWC* is shown as a function of the *PC* for the four types of vehicles. The distribution in this plane is significant. Again, to better highlight the arrangement of the different categories within the chart, it is also possible to add the already mentioned Gaussian ellipses to the graph. These ellipses are based on the statistical values of the *PC* and *NWC* parameters. Recall that the *NWC* is an index of the total performance of the vehicle, as it considers the load transported and the speed of transport [104]. Once a *PC* value is calculated, it is possible to identify which category of robot has better performance based on the position of the ellipses in the chart plan. Track-based and wheel cluster-based robots are more suitable for carrying a load on stairs because their ellipses reach higher values of *NWC* than the articulated mechanism-based and hybrid and leg-based robots.

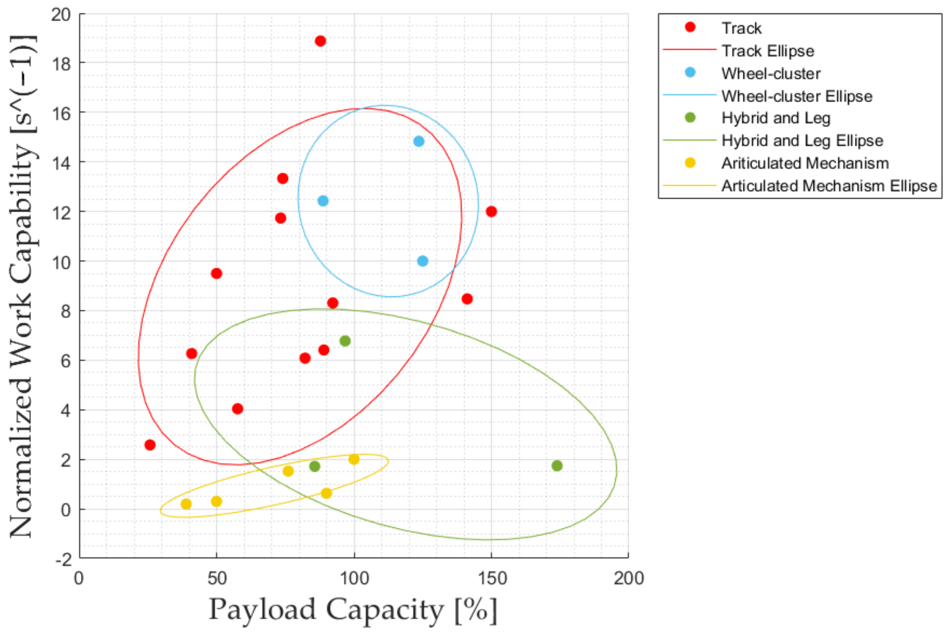


Figure 11. Normalized Work Capability—Payload Capacity scatter plot.

We define the stairs slope as the inclination respect the horizontal of the notional line connecting the nosings of all treads in a flight. Compared to the step height, the slope considers not only the height of the step, but also the depth of the same. For this reason, when comparing the performance of different robots, it is preferable to use the maximum slope of the stairs. Then, Figure 12 illustrates the maximum stairs slope to payload capacity scatter plot. It can be seen which slope of stairs can overcome the different categories of robots. It emerges that most categories of robots are able to overcome values of stairs slope included in the range 25–45°. These are the typical slope values of stairs for most real applications.

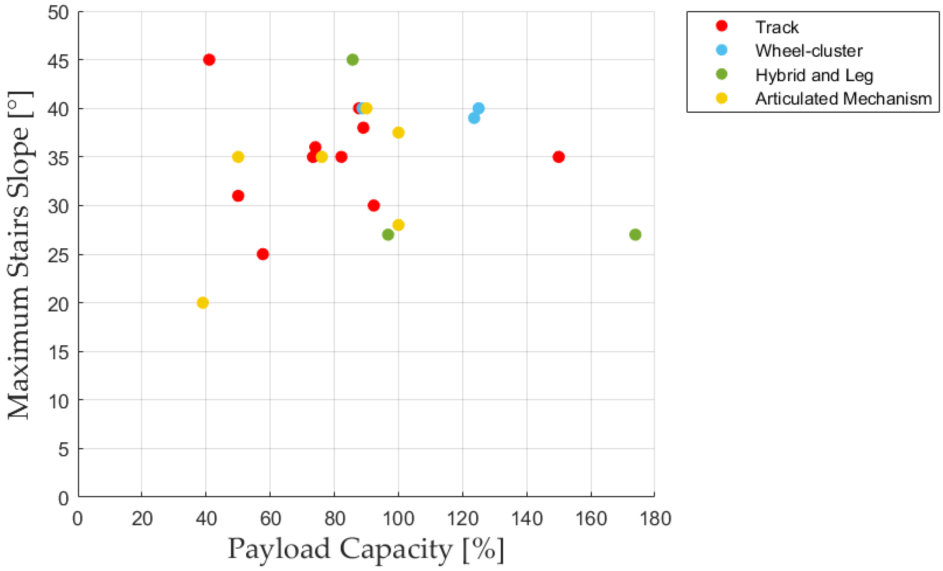


Figure 12. Maximum stairs slope—Payload Capacity scatter plot.

In Figure 13 the maximum stairs slope values for the different robots are diagrammed as a function of Normalized Work Capability instead of Payload Capacity. The maximum slope range of stairs is always between 25° and 45°. The graph shows that the two categories that have the highest total performance are track-based and wheel cluster-based, as they have higher Normalized Work Capability values in that range, so that they are most suitable to perform the stair-climbing task respect to articulated mechanism-based and hybrid and leg-based robots.

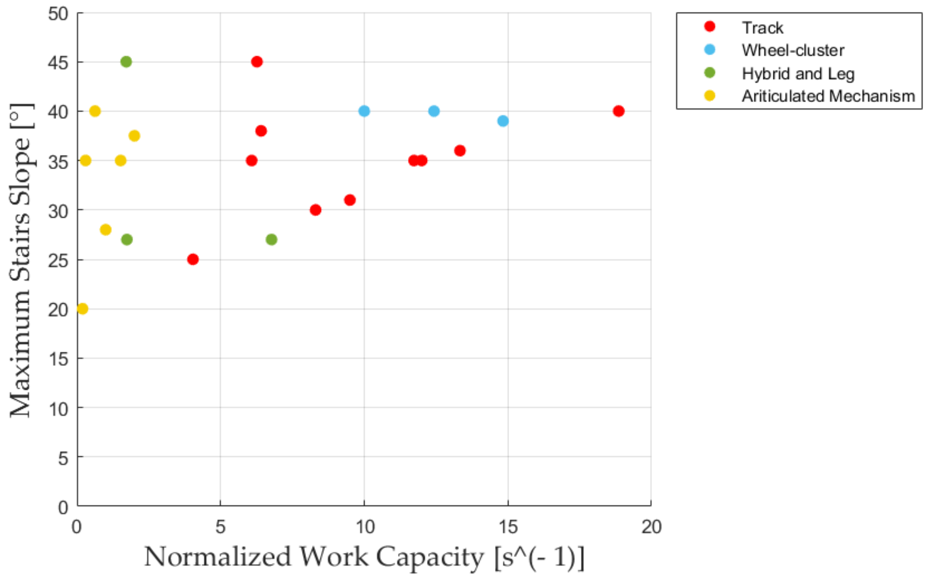


Figure 13. Maximum Stairs Slope—Normalized Work Capability scatter plot.

Figure 14 shows the Transport Ability versus Payload Capacity scatter plot. Again, to better highlight the arrangement of the different categories within the chart, it is also possible to add the already mentioned Gaussian ellipses to the graph. These ellipses are based on the statistical values of the *TA* and *PC* parameters. Hybrid and leg-based robot ellipse is almost horizontal, sign that the Transport Ability varies little as the load carried varies. Moreover, hybrid and leg-based category has the lowest transport ability for all payload capacity values. On the contrary, wheel cluster-based robot ellipse is almost vertical, sign that the Transport Ability varies greatly depending on the climbing mechanism used. The most high transport ability value belongs to track-based robots category.

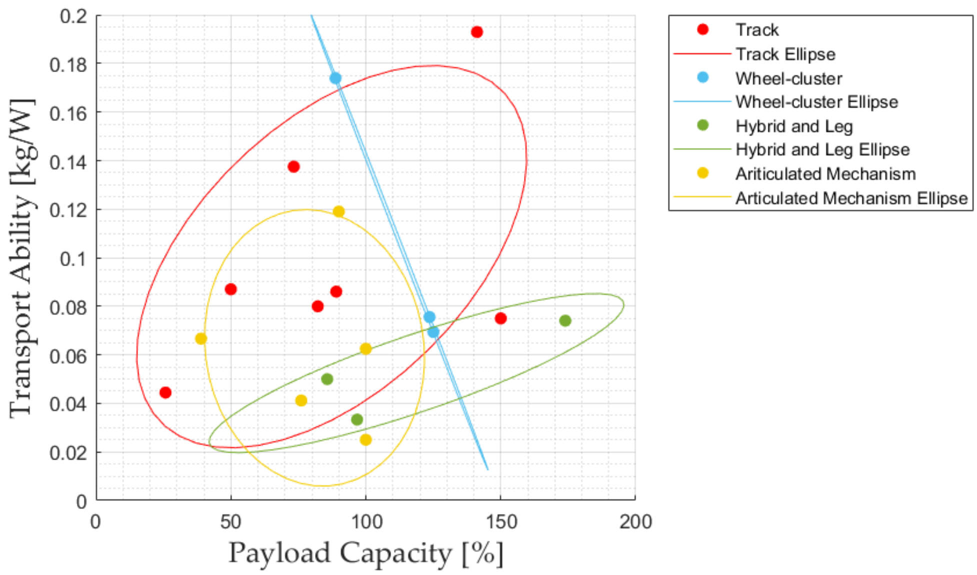


Figure 14. Transport Ability to Payload Capacity scatter plot.

At the end, Figure 15 relates the two independent metrics: the Transport Ability and the Normalized Work Capability. As we have already said, the *NWC* is an index that reflects a bit the overall performance of the robot, since it considers both the load capacity and the transport speed of the robot. Similarly, *TA* is an index that considers how much power the robot needs to carry a unit load. Based on these two parameters, the Transport Ability-Normalized Work Capability graph can be divided into four zones: (1) in the top right the area of the robots with high overall performance and high transport ability, (2) in the bottom right the area of the robots with high overall performance but with low transport ability, (3) in the top left the area of the robots with high transport ability but with low overall performance, (4) in the bottom left the area of the robots with low transport ability and low overall performance. Moreover, in this case, to highlight the arrangement of the points of the different categories, the ellipses have been added.

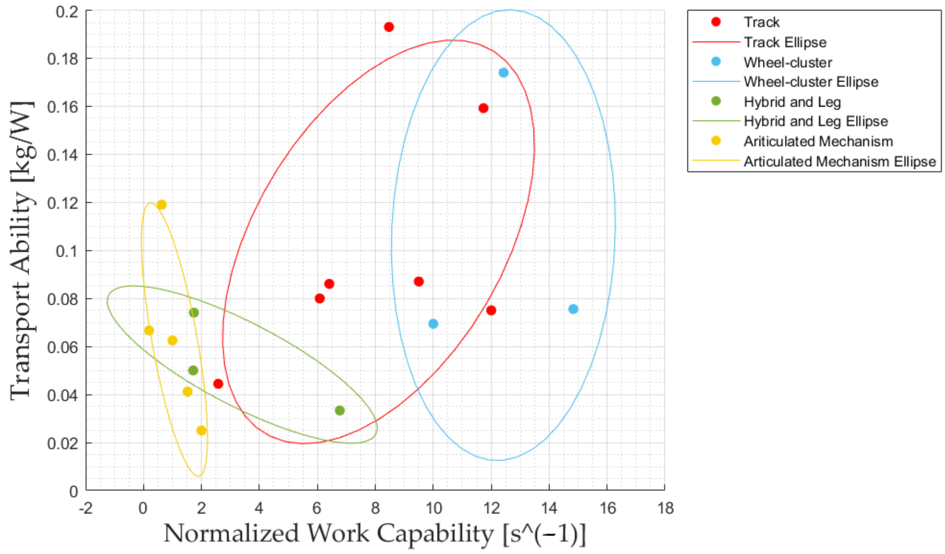


Figure 15. Transport Ability to Normalized Work Capability scatter plot.

So, from the position of the ellipses in the *TA-NWC* plan in the figure, it is possible to have important indications on the different categories of robots that cannot be deduced a priori through a single qualitative analysis of the systems. Articulated mechanism-based robots are shown to have variable transport ability depending on the climbing mechanism used. However, they demonstrate low overall performance by positioning themselves in the leftmost area of the graph plane in Figure 15. Wheel cluster-based and track-based robots are the categories that come closest to the area of the plan with high overall performance and high transport ability, proving to be the most suitable categories for transporting a payload on a flight of stairs. In contrast, the hybrid and leg-based robots category clusters in an area with low transport ability and low overall performance.

4.3. Complexity and Cost Issues

Drawing from [109], fundamental design choice criteria in mobile robotics are mechanical and control complexity, as also underlined in [5].

Mechanical complexity has a considerable influence on the reliability of robot operation. Track-based and wheel cluster-based robots are apparently simple and robust, while robots with complicated mechanical designs, such as legged and articulated mechanism-based robots are complex and delicate. Control complexity has significant influence on the robot motion control. It is higher for solutions involving legs and a sophisticated mechanism due to gait planning requirements.

Mechanical and control complexity can be used to evaluate the simplicity of realization of one robot compared to another. Therefore, in addition to the performance metrics of Section 4.1, it is decided to develop a qualitative evaluation scale of mechanical complexity (MC) and control complexity (CC) for the robots analyzed in this paper. Detailed numeric data are presented in Appendix A Table A6. Scores start from low and continue with medium-low, medium, medium-high, high and very-high.

Another fundamental design parameter is the overall cost. From mechanical and control complexity, it is possible to obtain an idea of the possible cost of the robot. It is plausible that an expensive solution has very high complexity. Therefore, cost is used to evaluate the simplicity of realization of one robot compared to another, and how much a robot can be easily sold compared to another one.

It is also decided to draw up a qualitative evaluation scale of cost for the robots in this paper. Cost evaluation scores are presented in Appendix A Table A7. Scores start from low and continue with low-medium, medium, medium-high and high. To have a graphical representation of the results obtained, a cost scale graph is provided below in Figure 16. The five cost grades and the total number of robots belonging to each grade are reported on the abscissa and ordinate axis, respectively.

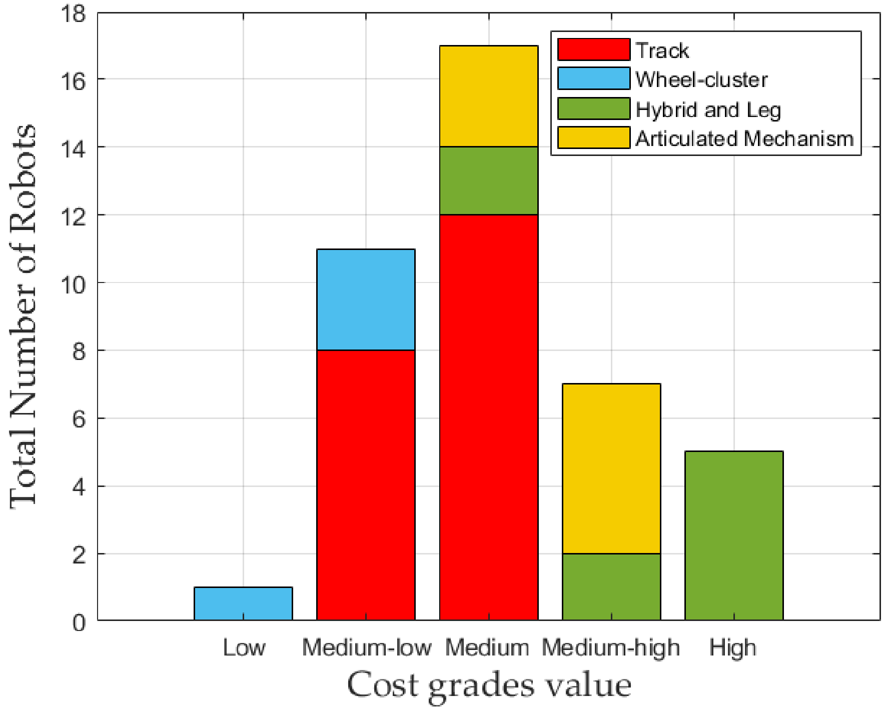


Figure 16. Cost scale graph.

It is useful to say that the wheelchair type track-based robots Scewo Bro [25] and B-Free Ranger [30] are now available for $40,536 and $17,688, respectively. Wheel cluster-based robot iBOT 4000 Mobility System [35] was available for $26,000 in the period from 1999 to 2016.

Figure 16 provides information on how robots type affects the cost. Due to the elaborate mechanical structure, the presence of numerous actuators and sensors and the complexity of the control system, the most expensive robots are the legged ones, immediately followed by the articulated mechanism-based ones. Track-based robots have an average system cost, while wheel-clustered robots are the cheapest type to make.

5. Discussion

This paper surveyed the current state-of-the-art in stair-climbing vehicles to obtain useful information about which category of robot is best able to transport people and heavy loads up a flight of stairs. In the first part of the article, a brief description of the stair-climbing existing mechanisms and method of operation are provided. Then, based on the capability of carrying payload and the type of locomotion mechanism, we propose a general stair-climbing system categorization. Next, to compare the different payload robots, several quantitative performance metrics are defined and calculated on the purpose, namely: payload capacity, normalized speed, normalized work capability, maximum step height, maximum stairs slope and transport ability. Correlations among previous performance metrics are sought by plotting one metric against the other, providing the reader with an in-depth understanding of the stair climbing problem. Then, complexity and cost issues are addressed. As a conclusion of the work, we tried to identify what to look at to choose the best category for transporting people and heavy loads up a flight of stairs. The normalized work capacity parameter is chosen to quantify the overall performance of different climbing robots and the respective categories. A complete overview of the different stair-climbing system performance is obtained when expressing Transport Ability as a function of Normalized Work Capability. Since hybrid and leg-based robots are located in the lower left area of the *TA-NWC* plan (Figure 15) and have a high cost, they prove to be the least suitable category for transporting a payload on a flight of stairs. Moreover, articulated mechanism-based robots do not seem suitable for stair-climbing operations. This is because they have low overall performance, low transport ability, complicated mechanical structure and control strategy. On the contrary, track-based and wheel cluster-based robots prove to be the most suitable categories to perform the transport of a load during the ascent of a flight of stairs. This is because they combine good overall performance and good transport ability, positioning in the right part of the *TA-NWC* plan (Figure 16), with low mechanical complexity, simple control strategy and low construction cost. With these results it will be possible to design a track-based or wheel-cluster based robot that better than articulated mechanism-based robots and hybrid and leg-based robots can transport people and heavy loads up a flight of stairs. The posture control categorization, the control algorithm categorization, the gait planning categorization, the driving force distribution categorization and highlighting the advantages and disadvantages of them are work understudied issues and future development. They have not been dealt with so as not to make the paper too heavy to read.

Author Contributions: Conceptualization, A.P., F.B., G.M. and G.R.; methodology, A.P.; writing—original draft preparation, A.P. and G.R.; writing—review and editing, G.R. and F.B.; funding acquisition, G.R. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

In this appendix, performance metrics introduces in Section 4.1 are calculated for the robots analyzed in this document. WT and CT indicate wheelchair type and carrier type robots, respectively. When technical data are not provided, metrics are omitted. Tables A1 and A2 show the Payload Capacity and Normalized speed, respectively. Normalized Work Capability is calculated in Table A3. Maximum crossable step height and stairs slope are reported in Appendix A Table A4. Then, Transport Ability values are calculated in Table A5.

Table A1. Robot's Payload Capacity.

Name	Type	Category	PC [%]	Payload/Robot
Scewo Bro Errore. [25]	WT	Track	74.07%	120 kg/162 kg
WT Wheelchair [27,28]	WT	Track	57.69%	75 kg/130 kg
TopChair-S [26]	WT	Track	73.33%	110 kg/150 kg
Tao [29]	WT	Track	150%	75 kg/50 kg
B-Free Ranger [30]	WT	Track	82.19%	120 kg/146 kg
Caterwil GTS5 Lux [33]	WT	Track	87.71%	100 kg/114 kg
All-Terrain Wheelchair [34]	WT	Track	50%	80 kg/160 kg
iBOT 4000 [35,36]	WT	Wheel cluster	123.63%	136 kg/110 kg
Wheelchair.q [37,38]	WT	Wheel cluster	88.77%	87 kg/98 kg
Zero Carrier [41,42]	WT	Hybrid and Leg	173.91%	80 kg/46 kg
Lee [47]	WT	Hybrid and Leg	85.71%	60 kg/70 kg
WL-16 II [45,46]	WT	Hybrid and Leg	96.77%	60 kg/62 kg
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	76.08%	70 kg/92 kg
Morales [51]	WT	Articulated Mechanism	90%	90 kg/100 kg
Lawn [52]	WT	Articulated Mechanism	50%	80 kg/160 kg
TBW-I [53]	WT	Articulated Mechanism	38.96%	60 kg/154 kg
HELIOS-V [54]	WT	Articulated Mechanism	100%	50 kg/50 kg
Chen [55]	WT	Articulated Mechanism	100%	80 kg/80 kg
Yoneda [59]	CT	Track	92.30%	60 kg/65 kg
TAQT Carrier [60]	CT	Track	25.80%	80 kg/310 kg
HELIOS-VI [61]	CT	Track	141.17%	120 kg/85 kg
Haulerbot [62]	CT	Track	89.04%	130 kg/146 kg
iRobt 710 Kobra [63]	CT	Track	40.96%	68 kg/166 kg
Deshmukh [68]	CT	Wheel cluster	125%	10 kg/8 kg

Table A2. Robot's Normalized Speed.

Name	Type	Category	NS [s^{-1}]	Speed/Length
Scewo Bro [25]	WT	Track	0.18 s^{-1}	21 cm/s/113.5 cm
WT Wheelchair [27,28]	WT	Track	0.07 s^{-1}	10 cm/s/131 cm
TopChair-S [26]	WT	Track	0.16 s^{-1}	19 cm/s/115 cm
Tao [29]	WT	Track	0.08 s^{-1}	7.3 cm/s/90 cm
B-Free Ranger [30]	WT	Track	0.074 s^{-1}	8.3 cm/s/112 cm
Caterwil GTS5 Lux [33]	WT	Track	0.21 s^{-1}	22 cm/s/102 cm
All-Terrain Wheelchair [34]	WT	Track	0.19 s^{-1}	30 cm/156 cm
iBOT 4000 [35,36]	WT	Wheel cluster	0.12 s^{-1}	10 cm/s/81.3 cm

Table A2. *Cont.*

Name	Type	Category	NS [s^{-1}]	Speed/Length
Wheelchair.q [37,38]	WT	Wheel cluster	0.14 s^{-1}	10 cm/s/70.9 cm
Zero Carrier [41,42]	WT	Hybrid and Leg	0.01 s^{-1}	1 cm/s/60 cm
Lee [47]	WT	Hybrid and Leg	0.02 s^{-1}	2 cm/s/85.5 cm
WL-16 II [45,46]	WT	Hybrid and Leg	0.07 s^{-1}	5 cm/s/70 cm
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	0.02 s^{-1}	2.2 cm/s/110 cm
Morales [51]	WT	Articulated Mechanism	0.007 s^{-1}	1 cm/s/145 cm
Lawn [52]	WT	Articulated Mechanism	0.006 s^{-1}	1 cm/s/170 cm
TBW-I [53]	WT	Articulated Mechanism	0.005 s^{-1}	0.5 cm/s/108 cm
Chen [55]	WT	Articulated Mechanism	0.02 s^{-1}	2 cm/s/82 cm
Yoneda [59]	CT	Track	0.09 s^{-1}	10.2 cm/s/118 cm
TAQT Carrier [60]	CT	Track	0.10 s^{-1}	14 cm/s/130 cm
HELIOS-VI [61]	CT	Track	0.06 s^{-1}	7 cm/s/105.5 cm
Haulerbot [62]	CT	Track	0.072 s^{-1}	8.3 cm/s/115 cm
iRobt 710 Kobra [63]	CT	Track	0.15 s^{-1}	14 cm/s/91.4 cm
Deshmukh [68]	CT	Wheel cluster	0.08 s^{-1}	6.28 cm/s/78 cm

Table A3. Robot's Normalized Work Capability.

Name	Type	Category	NWC[s^{-1}]
Scewo Bro [25]	WT	Track	13.33 s^{-1}
WT Wheelchair [27,28]	WT	Track	4.40 s^{-1}
TopChair-S [26]	WT	Track	11.73 s^{-1}
Tao [29]	WT	Track	12.14 s^{-1}
B-Free Ranger [30]	WT	Track	6.08 s^{-1}
Caterwil GTS5 Lux [33]	WT	Track	18.85 s^{-1}
All-Terrain Wheelchair [34]	WT	Track	9.61 s^{-1}
iBOT 4000 [35,36]	WT	Wheel cluster	14.83 s^{-1}
Wheelchair.q [37,38]	WT	Wheel cluster	12.43 s^{-1}
Zero Carrier [41,42]	WT	Hybrid and Leg	1.74 s^{-1}
Lee [47]	WT	Hybrid and Leg	1.71 s^{-1}
WL-16 II [45,46]	WT	Hybrid and Leg	6.77 s^{-1}
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	1.52 s^{-1}
Morales [51]	WT	Articulated Mechanism	0.62 s^{-1}
Lawn [52]	WT	Articulated Mechanism	0.3 s^{-1}

Table A3. *Cont.*

Name	Type	Category	NWC[s^{-1}]
TBW-I [53]	WT	Articulated Mechanism	0.195 s^{-1}
Chen [55]	WT	Articulated Mechanism	2 s^{-1}
Yoneda [59]	CT	Track	8.30 s^{-1}
TAQT Carrier [60]	CT	Track	2.58 s^{-1}
HELIOS-VI [61]	CT	Track	8.47 s^{-1}
Haulerbot [62]	CT	Track	6.41 s^{-1}
iRobt 710 Kobra [63]	CT	Track	6.27 s^{-1}
Deshmukh [68]	CT	Wheel cluster	10.06 s^{-1}

Table A4. Crossable step height and stairs slope.

Name	Type	Category	Step Height [cm]	Stairs Slope [°]
Scewo Bro [25]	WT	Track	20 cm	36°
WT Wheelchair [27,28]	WT	Track	15 cm	25°
TopChair-S [26]	WT	Track	20 cm	35°
Tao [29]	WT	Track	18 cm	35°
B-Free Ranger [30]	WT	Track	20 cm	35°
Caterwil GTS5 Lux [33]	WT	Track	20 cm	40°
All-Terrain Wheelchair [34]	WT	Track	17 cm	31°
iBOT 4000 [35,36]	WT	Wheel cluster	20 cm	39°
Wheelchair.q [37,38]	WT	Wheel cluster	24 cm	40°
Castillo [39]	WT	Wheel cluster	18 cm	37°
Zero Carrier [41,42]	WT	Hybrid and Leg	18 cm	27°
Lee [47]	WT	Hybrid and Leg	25.5 cm	45°
WL-16 II [45,46]	WT	Hybrid and Leg	15 cm	27°
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	17 cm	35°
Morales [51]	WT	Articulated Mechanism	24 cm	40°
Lawn [52]	WT	Articulated Mechanism	20 cm	35°
TBW-I [53]	WT	Articulated Mechanism	20 cm	20°
HELIOS-V [54]	WT	Articulated Mechanism	16 cm	28°
Chen [55]	WT	Articulated Mechanism	20 cm	37.5°
Yoneda [59]	CT	Track	16 cm	30°
Haulerbot [62]	CT	Track	20 cm	38°

Table A4. *Cont.*

Name	Type	Category	Step Height [cm]	Stairs Slope [°]
iRobt 710 Kobra [63]	CT	Track	21.2 cm	45°
Deshmukh [68]	CT	Wheel cluster	16 cm	40°
Wen [69]	CT	Hybrid and Leg	20 cm	35.5°

Table A5. Transport Ability values.

Name	Type	Category	TA [kg/W]	Power [W]	Payload [kg]
TopChair-S [25]	WT	Track	0.137	800 W	110 kg
Tao [29]	WT	Track	0.075	1000 W	75 kg
B-Free Ranger [30]	WT	Track	0.08	1500 W	120 kg
All-Terrain Wheelchair [34]	WT	Track	0.087	920 W	80 kg
iBOT 4000 [35,36]	WT	Wheel cluster	0.075	1800 W	136 kg
Wheelchair.q [37,38]	WT	Wheel cluster	0.174	500 W	87 kg
Castillo [39]	WT	Wheel cluster	0.041	1430 W	60 kg
Zero Carrier [41,42]	WT	Hybrid and Leg	0.074	1080 W	80 kg
Lee [47]	WT	Hybrid and Leg	0.06	1200 W	60 kg
WL-16 II [45,46]	WT	Hybrid and Leg	0.033	1800 W	60 kg
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	0.041	1700 W	70 kg
Morales [51]	WT	Articulated Mechanism	0.119	840 W	100 kg
TBW-I [53]	WT	Articulated Mechanism	0.066	900 W	60 kg
HELIOS-V [54]	WT	Articulated Mechanism	0.062	800 W	50 kg
Chen [55]	WT	Articulated Mechanism	0.025	3200 W	80 kg
TAQT Carrier [60]	CT	Track	0.044	1800 W	80 kg
HELIOS-VI [61]	CT	Track	0.193	622 W	120 kg
Haulerbot [62]	CT	Track	0.086	1500 W	130 kg
Deshmukh [68]	CT	Wheel cluster	0.069	144 W	10 kg

Qualitative evaluation scale of mechanical complexity (MC) and control complexity (CC) are presented in Table A6. Grades start from low and continue with medium-low, medium, medium-high and high. Finally, cost evaluation grades are presented in Table A7. Grades start from low and continue with medium-low, medium, medium-high and high.

Table A6. Mechanical and Control Complexity values.

Name	Type	Category	MC	CC
Scewo Bro [25]	WT	Track	Medium-low	Medium-low
WT Wheelchair [27,28]	WT	Track	Medium-high	Medium-high
TopChair-S [26]	WT	Track	Medium-low	Medium-low
Tao [29]	WT	Track	Medium-low	Medium-low

Table A6. *Cont.*

Name	Type	Category	MC	CC
B-Free Ranger [30]	WT	Track	Medium-high	Medium-high
ZED Evolution [31]	WT	Track	Medium-high	Medium-high
Caterwil GTS5 Lux [32]	WT	Track	Medium-low	Medium-high
Fortissimo [33]	WT	Track	Medium-low	Medium-high
Hkust [33]	WT	Track	Low	Medium-low
All-Terrain Wheelchair [34]	WT	Track	Medium-high	Medium-high
iBOT 4000 [35,36]	WT	Wheel cluster	Medium-low	Medium-high
Wheelchair.q [37,38]	WT	Wheel cluster	Medium-low	Medium-high
Castillo [39]	WT	Wheel cluster	Low	Low
Wang [40]	WT	Hybrid and Leg	Medium-low	Medium-high
Zero Carrier [41,42]	WT	Hybrid and Leg	Medium-high	High
Lee [47]	WT	Hybrid and Leg	High	High
JWCR-1 [43,44]	WT	Hybrid and Leg	Very-high	Very -high
WL-16 II [45,46]	WT	Hybrid and Leg	Very -high	Very -high
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	High	High
Morales [51]	WT	Articulated Mechanism	High	High
Lawn [52]	WT	Articulated Mechanism	High	High
TBW-I [53]	WT	Articulated Mechanism	High	High
HELIOS-V [54]	WT	Articulated Mechanism	Medium-high	Medium-high
Chen [55]	WT	Articulated Mechanism	High	High
RPWheel [56]	WT	Articulated Mechanism	Medium-high	Medium-high
Zhang [57,58]	CT	Track	Medium-low	Medium-high
Dongsheng [67]	CT	Track	Medium-low	Medium-high
Htoo [65]	CT	Track	Low	Low
Amoeba Go-1 [22]	CT	Track	Medium-low	Medium-high
Yoneda [59]	CT	Track	Low	Low
Riuqin [66]	CT	Track	Low	Low
TAQT Carrier [60]	CT	Track	Medium-low	Medium-high
HELIOS-VI [61]	CT	Track	Medium-low	Medium-low
Haulerbot [62]	CT	Track	Medium-high	Medium-high
iRobt 710 Kobra [63]	CT	Track	Medium-low	Medium-high
Deshmukh [68]	CT	Wheel cluster	Low	Low
Wen [69]	CT	Hybrid and Leg	Medium-high	High
Shihua [72]	CT	Hybrid and Leg	Medium-low	Medium-high

Table A6. *Cont.*

Name	Type	Category	MC	CC
PEOPLER-II [70,71]	CT	Hybrid and Leg	High	Most-high
Yeping [73]	CT	Hybrid and Leg	Very-high	Very-high
Yinhui [74]	CT	Articulated Mechanism	Medium-high	Medium-high

Table A7. Mechanical Complexity, Control Complexity and Cost Scale values.

Name	Type	Category	Cost
Scewo Bro [25]	WT	Track	Medium
WT Wheelchair [27,28]	WT	Track	Medium
TopChair-S [26]	WT	Track	Medium-low
Tao [29]	WT	Track	Medium-low
B-Free Ranger [30]	WT	Track	Medium
ZED Evolution [31]	WT	Track	Medium
Caterwil GTS5 Lux [32]	WT	Track	Medium-low
Fortissimo [33]	WT	Track	Medium
Hkust [33]	WT	Track	Medium-low
All-Terrain Wheelchair [34]	WT	Track	Medium
iBOT 4000 [35,36]	WT	Wheel cluster	Medium-low
Wheelchair.q [37,38]	WT	Wheel cluster	Medium-low
Castillo [39]	WT	Wheel cluster	Medium-low
Wang [40]	WT	Hybrid and Leg	Medium
Zero Carrier [41,42]	WT	Hybrid and Leg	High
Lee [47]	WT	Hybrid and Leg	Medium-high
JWCR-1 [43,44]	WT	Hybrid and Leg	High
WL-16 II [45,46]	WT	Hybrid and Leg	High
RT-Mover PType WA [48–50]	WT	Articulated Mechanism	Medium-high
Morales [51]	WT	Articulated Mechanism	Medium-high
Lawn [52]	WT	Articulated Mechanism	Medium-high
TBW-I [53]	WT	Articulated Mechanism	Medium-high
HELIOS-V [54]	WT	Articulated Mechanism	Medium
Chen [55]	WT	Articulated Mechanism	Medium-high
RPWheel [56]	WT	Articulated Mechanism	Medium
Zhang [57,58]	CT	Track	Medium
Dongsheng [67]	CT	Track	Medium
Htoo [65]	CT	Track	Medium-low
Amoeba Go-1 [22]	CT	Track	Medium

Table A7. *Cont.*

Name	Type	Category	Cost
Yoneda [59]	CT	Track	Medium-low
Riuqin [66]	CT	Track	Medium-low
TAQT Carrier [60]	CT	Track	Medium
HELIOS-VI [61]	CT	Track	Medium-low
Haulerbot [62]	CT	Track	Medium
iRobt 710 Kobra [63]	CT	Track	Medium
Deshmukh [68]	CT	Wheel cluster	Low
Wen [69]	CT	Hybrid and Leg	Medium-high
Shihua [72]	CT	Hybrid and Leg	Medium-low
PEOPLER-II [70,71]	CT	Hybrid and Leg	High
Yeping [73]	CT	Hybrid and Leg	High
Yinhui [74]	CT	Articulated Mechanism	Medium

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