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Climbing robots for maintenance and inspections of vertical structures—A survey of design aspects and technologies

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HIGHLIGHTS

- Comprehensive state-of-the-art in climbing robots for maintenance and inspections.
- Overview on locomotion and attraction principles for climbing robots.
- Discussion and classification of requirements for commercial systems.
- Schematics and design aspects of climbing robots.

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ABSTRACT

The maintenance and inspection of large vertical structures with autonomous systems is still an unsolved problem. A large number of different robots exist which are able to navigate on buildings, ship hulls or other human-made structures. But, most of these systems are limited to special situations or applications. This paper deals with different locomotion and adhesion methods for climbing robots and presents characteristics, challenges and applications for these systems. Based on a given set of requirements these principles are examined and in terms of a comprehensive state-of-the-art more than hundred climbing robots are presented. Finally, this schematics is applied to design aspects of a wall-climbing robot which should be able to inspect large concrete buildings.

1. Introduction

Climbing robots in the field of vertical structures are of increasing importance for technical applications, inspections, maintenance and construction tasks. Researchers all over the world are working on systems which are able to navigate on manifold and vertical human-made structures. Most of these research groups started in the 90s and developed first prototypes which are able to climb on vertical walls. The fields of application reach from welding of ship hulls to the inspection of steal bridges or nuclear power plants. Often-cited systems Rest [1], Robug II [2] or Ninja 1 [3] are applied for such tasks. It can be notified that such climbing systems are mainly adopted in places which cannot be reached by humans, where the direct access of a human technician is too expensive or too dangerous.

In general, climbing robots need to be developed depending on the desired tasks and field of application. These aspects define, which locomotion principles or adhesion systems are suitable and which dimension the robot must have. This paper will present design aspects related to climbing robots suitable for inspection and maintenance applications. It will sum up the state of the art from the 90s up to 2013 and classify the different systems related to their application, locomotion and adhesion technology. The survey is focused on robots which are able to climb up vertical structures and does not include so-called *step-* or *stair-climbing robots* as well as systems which are e.g. able to climb along horizontal electrical power lines for inspections.

Section 2 will give an overview on applications of climbing robots and will present requirements to fulfill the desired task in an optimal way. Section 3 sums up suitable principles for locomotion and discusses advantages and disadvantages of the different methods. Section 4 presents the different adhesion mechanisms including some physical fundamentals and an overview on existing climbing robots. It contains magnetic (Section 4.1) and negative pressure adhesion (Section 4.2), mechanical adhesion (Section 4.3) as well as electrostatic (Section 4.4) and chemical attraction

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(Section 4.5). Afterwards, Section 5 discusses and compares the locomotion and adhesion principles and shows, in which way certain design aspects lead to a highly sophisticated wall-climbing robot which should be able to inspect large concrete buildings. Finally, the conclusion is given in Section 6.

2. Applications and requirements

Over the last two decades climbing robots became more and more important in the scientific society. Starting with simple systems equipped with adhesion mechanisms like electromagnets [1], suction cups [4] or slide-rails [5], the applications of these robots grow with their ability to handle different surfaces and to perform faster or more accurate navigation. At the very beginning of climbing robot research these systems have been designed to fit exactly one application or object like a steel bridge or a nuclear power plant. This limitation has decreased due to new locomotion types and adhesion mechanisms during the last years. At this point of time climbing robots are considered to support inspection, maintenance and construction tasks everywhere. In fact, they are helpful if they are able to perform the desired tasks more effectively, cost efficient and more accurate than existing approaches or those tasks, which are dangerous for human beings. Especially this safety aspect is of importance. Common applications for such systems which are dangerous for humans are inspections of nuclear power stations (e.g. leakage detection, measurement of wall thickness or analysis of welding seams) and inspections of tanks and pipelines in chemical industry. Furthermore, climbing robots are used to paint, coat or clean facades of buildings, to perform welding tasks in ship industry or clean and inspect airplane wings and wind turbines. An investigation of aspects related to cleaning robots for glass facades is given by [6], additional information about application fields and climbing robots can be found in [7,8]. Fig. 1 depicts some of the mentioned areas.

Nearly all of the climbing robots have a practical application. This especially counts for robots using well-known and reliable adhesion techniques like magnets or grips designed for ship industry or for inspections of planes, petrochemical tanks or other steel surfaces. The exceptions are those systems whose adhesion principle (e.g. thermal glue) is still in the focus of research. But, although there exists a wide range of different systems, only few climbing robots have been brought to commercial application, like [11–16].

To execute the desired tasks, climbing robots as well as all other technical systems have to fulfill certain requirements. Of course, the requirements and their importance and focus depend on the individual application. Nevertheless, a general set of requirements can be postulated suitable for nearly all climbing robots in the range of inspection and maintenance:

1. *Velocity and mobility*: The vehicle speed and its ability to move are two main aspects in this field. Depending on the dimension of the vertical structures it might be required to achieve relatively high velocity even in vertical direction or overhead for a sufficient fast navigation between inspection areas or similar points of action. Another requirement is related to the desired manipulation and positioning capabilities of the system. This includes the precision of locomotion as well as its trajectory, since some inspection sensors (e.g. a cover meter) need to be moved in a smooth and continuous way over the surface. It might also be desired that the robot is able to move sidewards or to turn 360° to position sensors or tools. Last, but not least, the system should be able to handle steps or protrude structures to be able to reach all positions at the building.
2. *Payload*: Depending on the application the system must be able to carry a payload of different weights. E.g. for the inspection of concrete surfaces a payload of 10 kg and more is mandatory to carry inspection sensors like impact echo, cover meter or a Wenner probe. This requires a much bigger robot in contrast to a system which should only be equipped with a simple camera with a weight of only several hundred grams. Therefore, the dimension of the robot as well as its adhesion and motion components need to be adapted according to the application.
3. *Reliability and safety*: A further important non-functional aspect is the robustness of the system. If the climbing robot fails often during one inspection task it would not be usable in practice. The requirements reliability and safety include robust hardware, optimal controllers and methods to detect and handle hazardous situations and to recover from them. Finally, it might be prescribed by law to secure the system via a cable or rope to eliminate the danger of a drop-off which could harm persons and destroy the robot. But, nevertheless, the system itself should be safe enough to ensure its adhesion, since even a controlled drop-off might become dangerous.
4. *Usability*: Velocity, maneuverability, and the capability of carrying a certain payload are important, but, they are only the basis of the general operability of the system. To bring a robotic system into application it has to be more powerful, more efficient and less dangerous than common approaches e.g. in terms of inspection devices. This includes also aspects maintainability and a broad range of handable tasks. Therefore, it must be able to carry different payloads (e.g. inspection sensors or tools) depending on the desired task, high mortality parts need to be easily replaceable, and the operation must be faster and less complicated compared to existing approaches. Additionally, also aspects like energy consumption, weight or dimension of the system can be important.

Based on the individual task, a robot developer has to decide which requirements have to be fulfilled and select a suitable locomotion and attraction principle. Next sections will introduce these approaches and discuss pros and cons of each method.

3. Locomotion types

As mentioned before, mobile climbing robots have been in the focus of research the last two decades. In literature various combinations exist combining different types of locomotion with different adhesion principles [7]. During robot development a question has to be considered: What kind of locomotion principle is the optimum for the given task and the environment? In general, one can distinguish four classes of locomotion with their individual assets and drawbacks:

Arms and legs A very common locomotion principle in the range of climbing robots is the use of arms or legs. In many cases nature is the inspiration for the chosen robot setup [17], e.g. in terms of insects or geckos which can climb walls and ceilings. Depending on the individual task, climbing robots have been created with different numbers of limbs of different degrees of freedom. In literature one mainly finds robots with two [18–23], four [24–28,3,2,29,30] and six [1,31–34] legs. Systems equipped with eight or more legs [35] can also be found, but, are less common. The main advantage of legged climbing robots is, that they are highly adaptable to the surface structure, that they can overcome obstacles and steps, or translate from ground to wall. This is possible due to the fact that each foot is equipped with adhesive components which also allows a testing of the foothold for the desired attraction forces. However, the high number of degrees of freedom leads to a complicated mechanical structure and control system in terms of a smooth and harmonic gait control. This also results in a higher weight and larger torques. In general, the velocity of these system is comparably


(a) Motorway bridge.


(b) Cooling towers.


(c) Tanks.


(d) Glass facades [9].


(e) Ship industry [10].

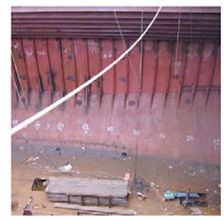

(f) Welding [10].

Fig. 1. Common fields of application like concrete bridges and cooling towers, tanks, glass facades or ship industry.

low with respect to other locomotion principles. This counts especially if – e.g. for safety reasons – only one leg is moved at once leading to a discontinuous and slow movement. That makes it impossible to apply such a system on a large concrete building (e.g. $> 1000\ m^2$), if it takes several hours to reach a desired position for inspection or maintenance.

Wheels and chains For the application on relatively smooth terrain, dozens of climbing robots exist using wheels or chain-driven locomotion. In contrast to the legged systems, the adhesion and locomotion elements are decoupled in many cases as applied in several wheeled [10,36–43] and tracked systems [44,45,15]. The other group of systems combines locomotion and adhesion systems in form of electroadhesive or sticky tracks, tracks equipped with suction cups [46–50] or via magnetic wheels [51,52]. The big advantage of wheeled or tracked locomotion is the fast and continuous movement and the simpler mechanical structure and control elements. But, these robots cannot handle larger steps or obstacles, so they are less flexible related to the surface characteristics and are exposed to slip effects.

Sliding frame Especially in combination with pneumatic [53–57] or magnetic [58] adhesive robots sliding frames are very common. These systems provide a simple mechanical structure via two frames which can be moved in a linear or rotational way against each other. In general, each frame is equipped with a set of attach points like suction cups or magnets and keeps the robot at the wall while the second frame is lifted and moved in the desired direction. This allows easy control of robot motion in combination with safe adhesion since the system can test its foot points before lifting the second frame. The drawbacks of this principle are again a low speed compared to wheeled or tracked vehicles, a discontinuous movement due to the stick-move-stick-move cycle and a comparably large size.

Wires and rails For some fixed applications like the cleaning or maintenance of building facades also rails [5] and wires [59,60,14] are used for robot locomotion. The main advantage of these motion principles is that the system is secured and cannot drop off since the adhesion system only has to position the robot at the building whereas the weight of the robot and additional payload is held by the wires. This allows a much simpler robot mechanics, but, of course demands external guidance and equipment limiting the robot to this unique setup.

Table 1
Comparison of locomotion principles related to the requirements.

Requirements		Legs	Wheels	Tracks	Frame	Wires
1.	Velocity	–	+	+	○	○
	Maneuverability	+	+	○	○	–
	Continuity	–	+	+	–	+
	Adaptability	+	–	○	○	–
	Precision	○	–	–	○	+
2.	Payload	○	○	○	○	+
3.	Wear	○	–	○	○	+
	Safety	+	○	○	+	+
4.	Simplicity	–	+	○	+	+
	Universality	+	+	+	+	–

Beside the four main categories some unique locomotion principles exist which belong neither to the one nor the other class. Examples are the accordion-like locomotion similar to a caterpillar [61] or snail-like locomotion in combination with negative pressure adhesion [62]. But, these systems are rare and only a small niche in climbing robotics. The same counts for systems which perform hybrid locomotion by combining e.g. wheels and kinds of legs [41] or using tracked legs [32] to get the best of two worlds. Nevertheless, these systems of course are more complex and harder to control.

Table 1 sums up the locomotion types and rates different aspects related to the given requirements. Some of the general requirements have been mentioned before while others are explicitly related to locomotion. Continuity for instance means whether a locomotion type is able to perform a smooth motion or not. The term adaptability is linked to the capability to handle different surface geometries and structures. Here, legs are the best solution while wheels and wires are not that variable. It can be seen, that each locomotion principle has its strengths and weaknesses. Depending on the application, these requirements are of different importance, so the locomotion method has to be chosen depending on that.

4. Adhesion principles

Similar to the type of locomotion, also the adhesion principle has to be chosen depending on the given task. This section will present different adhesion principles, starting with magnetic adhesion. An overview about the presented robot prototypes and their locomotion and adhesion principles can be found at the end of this section in Table 3.

4.1. Magnetic adhesion

A common technique for climbing robots is magnetic adhesion. This includes electromagnets as well as permanent magnets, which are either positioned on the surface or kept with a certain distance away from it. Common applications of these systems are inspections, maintenance and construction work e.g. of high power poles, steel tanks or ship hulls. The principle is very reliable on ferromagnetic surfaces and it is able to create strong adhesion forces on a very small area. By using rare-earth magnets it is also possible to create adhesion without energy consumption. In this case the magnets either have to be peeled off or they have to stay within a certain distance from the wall to limit the magnetic forces and the friction.

The adhesion force of a magnet commonly depends on its internal structure, the ferromagnetic characteristics of the surface and of the distance between magnet and surface. In literature, the strength of a simple pole magnet is often given as pull force F_p [63]. According to the Maxwell equation, this force can be calculated via Eq. (1) by the cross section area A of the pole magnet (in square meters, m^2), the magnetic induction (also called magnetic flux density) B of the magnet (in tesla, T) and its permeability μ_0 (in henry per meter, H/m).

$$F_p = \frac{B^2 \cdot A}{2 \cdot \mu_0}. \tag{1}$$

In fact, this force F_p is exerted at the end point of the magnet without considering interaction with a ferromagnetic object or another magnet. Assuming a constant magnetization, Eq. (2) describes the magnetic force F_m, which is exerted on a material. Here, M and V are magnetization (in ampere per meter, A/m) and volume (cubic meters, m^3) of the sample material, H is the magnetic field (in ampere per meter, A/m) induced by the magnet, whose energy varies along the x-axis.

$$F_m = \frac{1}{2} \cdot \mu_0 \cdot M \cdot V \cdot \frac{\delta H}{\delta x}. \tag{2}$$

The influence of the distance between magnet and material and of arrangement of an array of magnets has been investigated by [10]. The authors used a 1×4 magnet array with gaps of 5, 10 and 20 mm between the single magnets. Additionally, a steel back plate has been tested which improves the attraction force. Fig. 2 illustrates the results of [10]. One can see that the steel back plate significantly increases the attraction force (thin lines). Furthermore, there is a reciprocal relationship between the distance (air gap) of magnet and surface and the resulting magnetic attraction force. Also the effect of the distance of the magnets seems interesting, since closer magnets (circles) provide better if the surface is far away, but more distributed magnets (triangles) work much better on a close distance between magnets and surface. Based on these results the authors decided to use smaller block magnets made of neodymium 42 in a close array instead of one large magnet.

The locomotion principles used in combination with magnetic adhesion are e.g. legs, sliding frame mechanism and wheels. The six-legged walking machine Rest [1] in Fig. 3(a) has been designed to perform welding and maintenance tasks in industrial environments and is able to adhere to ferromagnetic surfaces via permanent and electromagnets. Other legged systems are the Rvc (reconfigurable vertical climber) using four legs with permanent magnets on a peeling pad [29], Robinspec by [31], Winspecbot [30] or the climbing machines by [18,64,65], as given in Fig. 3. A common task for these systems are e.g. inspections of gas containers as done by the four-legged robot 4Steel [66].

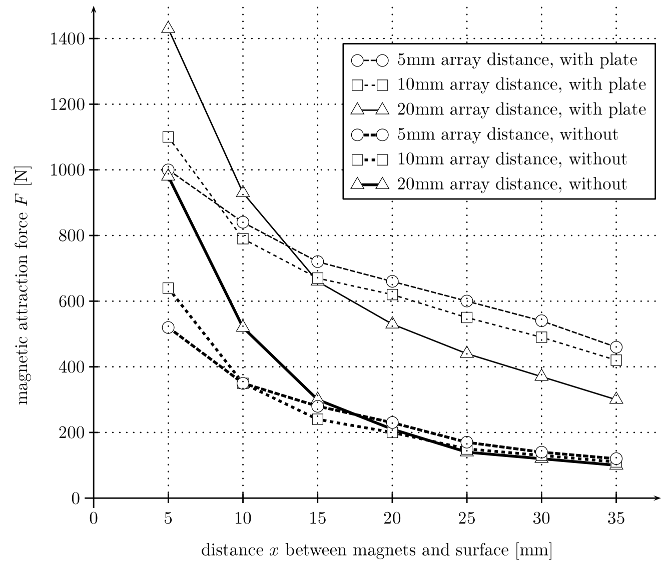


Fig. 2. Attraction forces of an array of magnets with different arrangements and distances to the surface.
Source: Taken from [10].

Another common locomotion type are wheels applied in addition to separate magnets as introduced e.g. by [36] in terms of climbing robots for education or the so-called Ndt robot by [10]. Common application for these systems (compare Fig. 4) are shipbuilding as in the case of wheeled robot by [67] or for inspections of wind turbines as done by the OmniClimber [68]. Another option is to combine magnets into the locomotion system and to use either magnetic tracks or wheels as given by the robots of [69,51,52,70]. This also counts for the large robot Nrec-UltraStrip [71], which has a length of about 1.8 m and a weight of more than 200 kg.

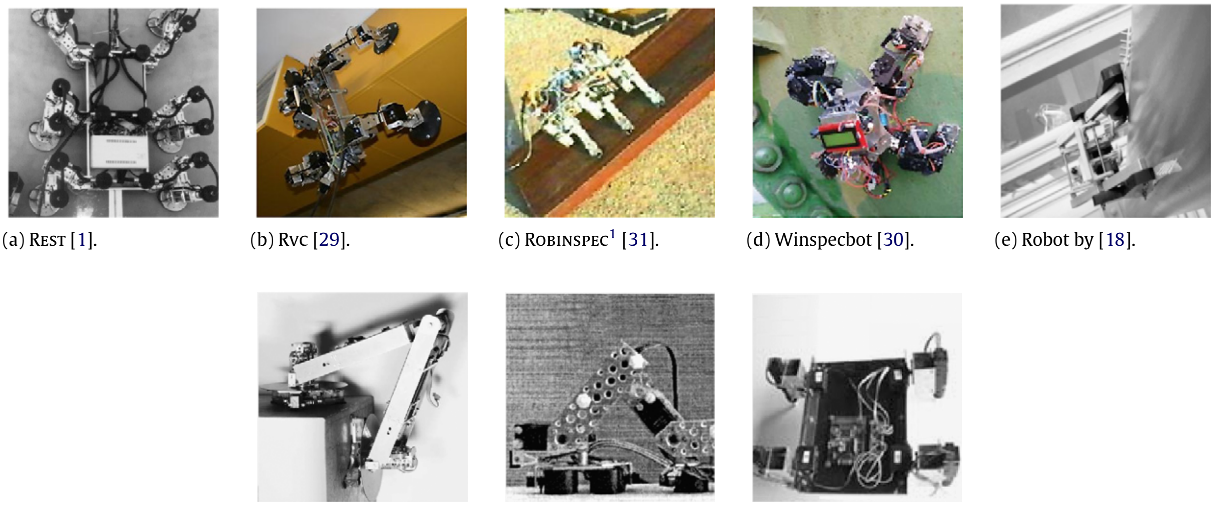
Fig. 5 shows systems which use magnetic tracks for both adhesion and locomotion. Examples are the machines by [72,73] which have been designed to inspect large steel tanks. Also the tracked robot Neptune [11] fits into this categories. In contrast to this, Tripillar [74] is a very tiny robot with a width of less than 10 cm. Combot [75] is larger and uses magnetic tracks for adhesion and locomotion as well as Hydro-Crawler [76]. Also Lazaro I [12] is a tracked climbing robot, but this system uses separate permanent magnets attached to its chassis.

Finally, also sliding frame mechanisms can be found in combination with magnets (see Fig. 6) e.g. for robots, which are designed to climb and inspect electrical towers [58] or steel grid blasting of ship hulls [77]. The robot Sadie [78] has been developed for inspections of nuclear vessels and can be equipped with magnetic as well as with vacuum feet.

Of course, this adhesion principle is not applicable to concrete surface, but for ferromagnetic structures it is the best solution regarding energy efficiency, adhesive power and reliability. Especially walking robots equipped with permanent magnets are very safe, since they can test each foothold for adhesion.

4.2. Pneumatic adhesion

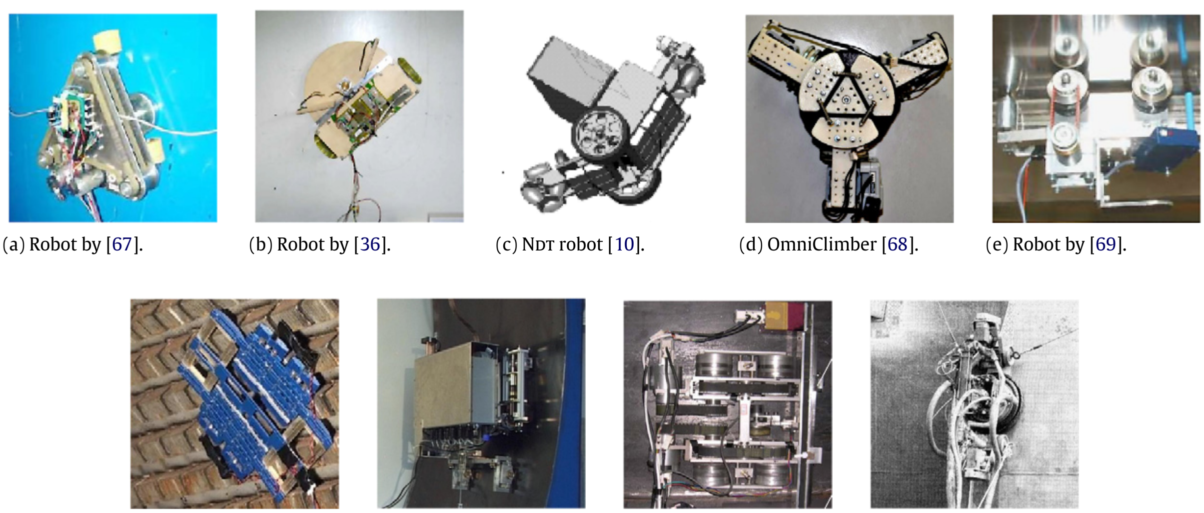
The second technique – probably the most used adhesion method in the field of climbing robots – is pneumatic or negative pressure adhesion. Here it can be distinguished between three different types: Passive suction cups, active suction chambers



(a) Rest [1]. (b) Rvc [29]. (c) Robinspec[1] [31]. (d) Winspecbot [30]. (e) Robot by [18].

(f) Tremo [64]. (g) Robot by [65]. (h) 4Steel [66].

Fig. 3. Climbing robots with magnetic adhesion using legs for locomotion.



(a) Robot by [67]. (b) Robot by [36]. (c) Ndt robot [10]. (d) OmniClimber [68]. (e) Robot by [69].

(f) Thin inspection robot by [51]. (g) Welding robot by [52]. (h) Modular robot by [70]. (i) Nrec-UltraStrip [71].

Fig. 4. Climbing robots using wheels with separate (a–d) or integrated magnets (e–i).

and vortex or thrust systems. These systems are mainly used in applications where no ferromagnetic surface or structural points of contact are given. In the case of suction cups or chambers, the attraction force F can be calculated according Eq. (3) based on the ambient pressure of air p_0, the pressure inside of the suction cup p and the suction area A.

$$F = \Delta p \cdot A = (p_0 - p) \cdot A. \tag{3}$$

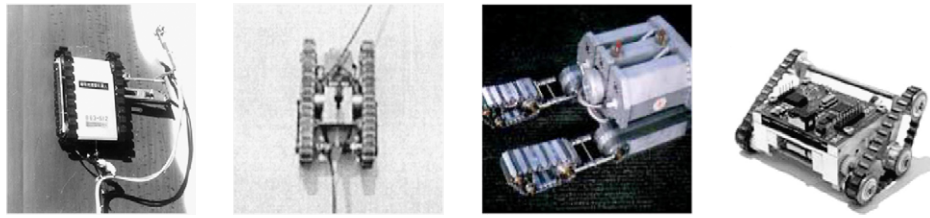
Commonly, robot developers tend to apply larger suction areas to increase the adhesion force or to be able to use more light-weighted vacuum generators producing low pressure differences. This is possible due to the linear relationship between attraction force F and pressure difference Δp and area A.

Other pneumatic adhesion methods are much more complex to analyze. E.g. the Bernoulli principle applied in venturi injectors can be used to create negative pressure via compressed air producing high airflow [39] as well as the so called vortex which has been examined by [79]. Both principles are less common but also applied as it will be presented later on.

Since negative pressure adhesion is used for a large range of climbing robots, a large number of investigations has been done concerning different aspects of this attraction principle. This includes e.g. the analysis of geometry of suction cups [45], of different setups and materials for passive suction cups [80] or friction aspects related to the interaction between suction chamber and surface [81]. But also the setup and geometry of the impeller, e.g. in terms of the angle of the single blades, are in the focus of research [40].

The interaction of the negative pressure system and the environment in general can be described via a thermodynamic model [82]. Basis is the first fundamental theorem of thermodynamics and Bernoulli's equation which describes the steady state flow of an ideal fluid. Here, the mass flow $\dot{m}_{ij}$ between two volumes i and j can be calculated (Eq. (4)) based on current pressure values p_i and p_j inside of both volumes, their connection area (area of airflow) A_{ij} and the density of air ρ_{air}. This counts for a sealing leakage

[1] http://www.robotic.diees.unict.it/robots/robots.htm.



(a) Robot by [72]. (b) Robot by [73]. (c) Neptune [11]. (d) Tripillar [74].

(e) Combot [75]. (f) Hydro-Crawler [76]. (g) Lazaro I [12].

Fig. 5. Climbing robots combining tracks and magnets.

(a) Robot by [58]. (b) Robot by [77]. (c) Sadie [78].

Fig. 6. Sliding frame robots with magnetic adhesion.

between adhesion chamber and ambient air as well as for the opening area of a valve connecting chamber and a vacuum reservoir.

$$\dot{m}_{ij} = \mathrm{sgn}(p_i - p_j) \cdot A_{ij} \cdot \sqrt{2 \cdot \rho_{\mathrm{air}} \cdot \left|p_i - p_j\right|}. \tag{4}$$

Based on this mass flow, the pressure change $\dot{p}_i$ of a volume can be calculated (Eq. (5)). In here, $\kappa_{\mathrm{air}} = 1.402$ is the adiabatic index of air, R_{air} denotes the specific gas constant, T_{air} the temperature and V_i the volume of i. The sum goes over all connected volumes k. In case of a single adhesion chamber with an additional vacuum reservoir the sum contains two mass flows: One from the ambient air into the chamber and one from there to the vacuum reservoir.

$$\dot{p}_i = \frac{\kappa_{\mathrm{air}} \cdot R_{\mathrm{air}} \cdot T_{\mathrm{air}}}{V_i} \sum_k \dot{m}_{ik}. \tag{5}$$

These calculations can be used to both optimize control algorithms as well as for the creation of a realistic simulation of the negative pressure system [83]. In literature, one finds classic Pid controllers [84,59] as well as fuzzy control [85] to adjust the desired attraction force of active adhesion chambers.

4.2.1. Systems using passive suction cups

Passive suction cups are suitable only on very flat surfaces like glass, but can also be combined with different types of locomotion like the tracked Raccoon [86] and the vehicle by [46] or the Dexter robot by [87], which is equipped with two articulated feet. This principle as depicted in Fig. 7 has the big disadvantage that it is not robust against disturbances like dust. Furthermore, the robot must stay in motion since the cups slightly lose negative pressure because of small leakages.

Therefore these systems are not suitable for general maintenance and constructive tasks which also demand the ability of carrying a certain amount of payload. Nevertheless both might be used for simple applications like visual inspections via a camera on even surfaces.

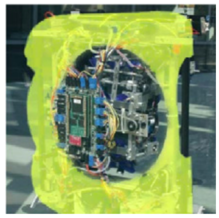
4.2.2. Adhesion chambers in combination with wheels

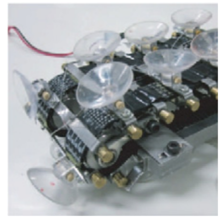
The most common approach related to pneumatic adhesion is the usage of active suction chambers. A combination of suction cups with electrical vacuum generators are mainly applied. In general, these generators either produce a large through flow volume or a high negative pressure—depending on the robot's setup. These active systems have the advantage that they are able to work also on more rough ground compared to passive cups and that they are able to generate high attraction forces. Active suction cups or adhesion chambers can be combined with nearly every locomotion system.

Known wheeled systems are e.g. WallWalker [88], Bit climber [40], Alicia3 [41], Larva [42] or the robot by [89] as depicted in Fig. 8. Most of these systems make use of a simple differential drive—either in combination with a passive support wheel or by using the chamber sealing as support against tilt. This also counts for the commercial system Vacu-Crawler [91] or Bigfoot [92].

Also the robot in [90] combines wheeled locomotion with a vacuum chamber (Fig. 8(f)). But in contrast to the previous systems it uses an omnidirectional drive consisting of four wheels reaching a speed of up to 8 m/min (0.133 m/s). It has a weight of 30 kg and a dimension of 0.29 m × 0.26 m × 0.23 m. The maximal payload is stated to be about 10 kg.

In contrast to that, Cromsci by [43] combines an omnidirectional drive system with a highly sophisticated adhesion system.


(a) Raccoon [86].


(b) Robot by [46].


(c) Dexter [87].

Fig. 7. Climbing robots using negative pressure adhesion via passive suction cups.

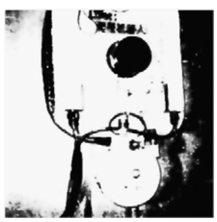

(a) WallWalker [88].

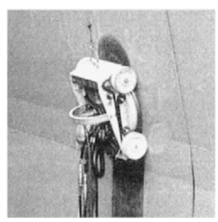

(b) Bit climber [40].


(c) Alicia3 [41].


(d) Larva [42].


(e) Robot by [89].


(f) Robot by [90].


(g) Vacu-Crawler [91].


(h) Bigfoot [92].


(i) Cromsci [43].

Fig. 8. Collection of climbing robots using negative pressure adhesion in combination with wheels.

This robot is equipped with a seven-chamber adhesion system and an adaptable inflatable rubber sealing which makes it suitable for many applications. Further details will be given in Section 5. All in all these systems are suitable for maintenance tasks but have the disadvantage that the surface has to be more or less smooth since they cannot overcome larger steps (except Alicia3 which consists of several connected units).

4.2.3. Climbing robots using a sliding frame mechanism

As mentioned before the sliding frame mechanism allows an easy motion control with the option to test foot points of the adhesion pads for their attraction. Examples for robots using sliding frame mechanism are the different Sky Cleaner systems [93,9,54] shown in Fig. 9(a) and (b). These systems have been designed to clean glass facades of large buildings. Further machines are PlanarWalker [57], the machine by [53], CleanBot 1 [56], Surfy [94] and the RobAir system [55] which is able to inspect wings and fuselage of aircrafts. Also the different Nero robots developed by [95,96] for non-destructive testing of a nuclear reactor use two movable frames for locomotion—each equipped with four vacuum grippers. The robot of [97] consists of two movable triangular plates. Beside the RobAir system also other robots become popular in the late 90s which have been developed for the inspection of aircrafts. Examples for these are the beam-walker Andi [98] using movable arms with suction cups and a spine for locomotion as well as the three generations of Macs [13] using a frame with circular center. A similar frame-walker is Robicen iii [99] which uses only three suction cups for adhesion (Fig. 9).

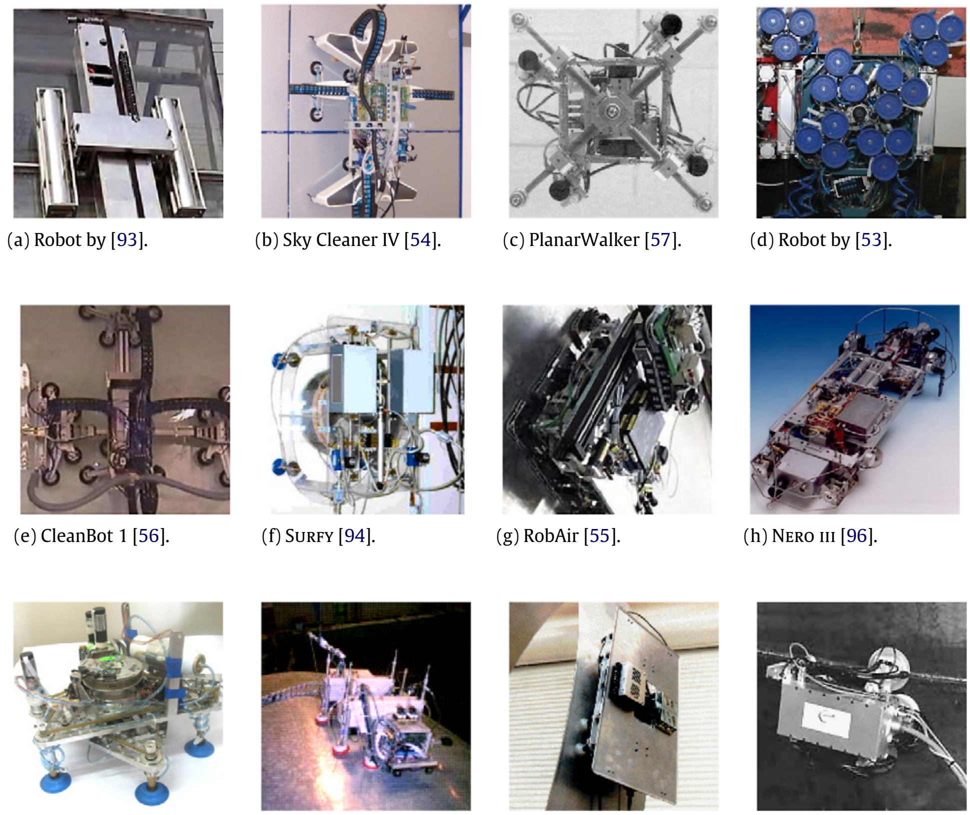
All these systems are mainly used for special applications like stationary operations at one building. Their payload is sufficiently high to carry inspection sensors or tools, but, they cannot be applied to perform maintenance tasks of large vertical structures due to slow navigation velocity.

4.2.4. Legged systems with negative pressure adhesion

Legs are a very popular type of locomotion in the range of climbing robots using negative pressure adhesion. The main advantage of these systems is the adaptability to the building structure which comes with a more complex and slower motion.

In literature one finds a couple of two-legged climbing robots which use active suction cups at its feet for adhesion. Examples are given in Fig. 10 in terms of the biped Ramr [21], the robot called Robin [19] as well as the system developed and analyzed by [20,100]. These systems have in common that they are very light-weighted and can adapt to a large variety of surface geometries, but have only low payload capacity. This does not count for the robot Roma ii [101] which has a maximum length of more than 1.1 m.

Four-legged systems have e.g. been developed by [105,106,102] in terms of the different Robug robots. Robug ii, depicted in Fig. 10(e), has been created to fulfill inspection and maintenance tasks. It can be equipped with vacuum grippers at the feet and with adhesion units at the underside of its body. By this mechanism the system is also able to move like a sliding frame robot and either adhere the main body and move all four legs in parallel or vice versa. This allows a faster movement than moving each leg separately. For adhesion, the suction chambers reach a pressure of

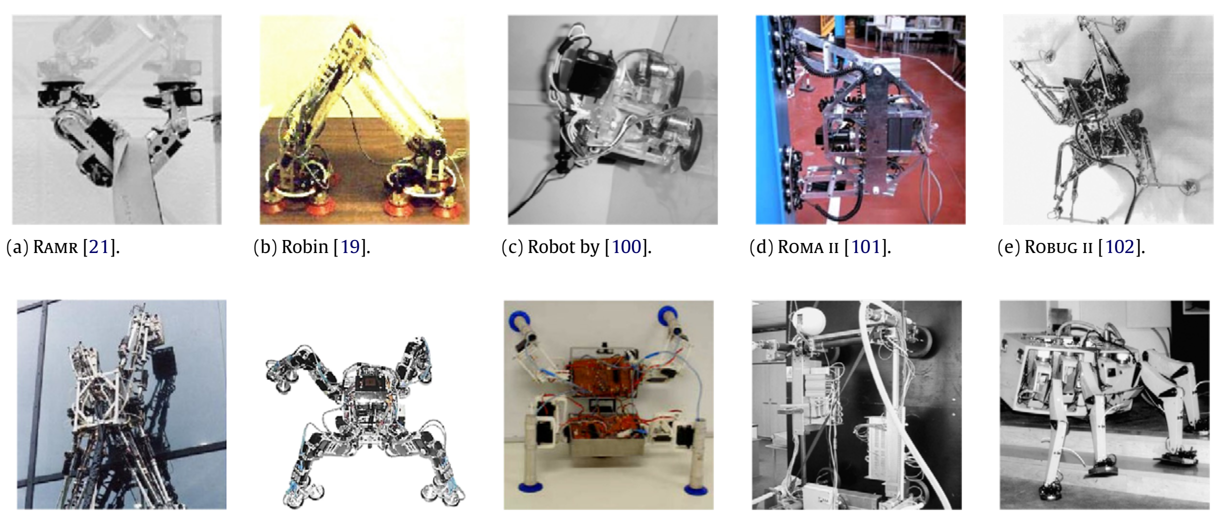


(a) Robot by [93]. (b) Sky Cleaner IV [54]. (c) PlanarWalker [57]. (d) Robot by [53].

(e) CleanBot 1 [56]. (f) SURFY [94]. (g) RobAir [55]. (h) NERO III [96].

(i) Robot by [97]. (j) ANDI [98]. (k) MACS[2] by [13]. (l) ROBICEN III[3] [99].

Fig. 9. Climbing robots with active negative pressure adhesion using sliding frame for locomotion.



(a) RAMR [21]. (b) Robin [19]. (c) Robot by [100]. (d) ROMA II [101]. (e) ROBUG II [102].

(f) NINJA 1 [3]. (g) MRWALLSPET III [28]. (h) Robot by [103]. (i) SAFARI [104]. (j) ROBUG III [35].

Fig. 10. Robots with active negative pressure adhesion using two (a–d), four (e–i) and eight legs (j) for locomotion.

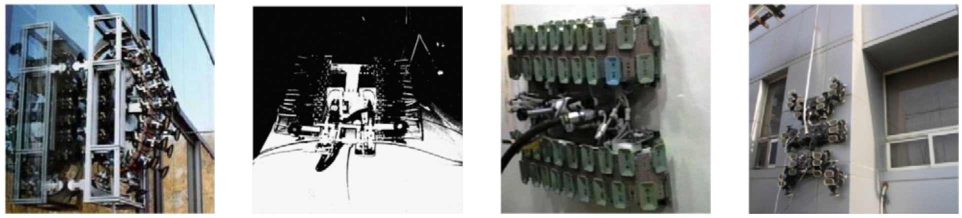
about 80% of the ambient air, which corresponds to an absolute pressure of 80 000 Pa.

Other quadruped walking systems are NINJA 1 [3] – which can use either suction cups or magnets for adhesion – and MRWALLSPECT III [28]. Its similar predecessor MRWALLSPECT IV [107] has been optimized to adjust to nearly all kinds of environments including slopes, vertical walls or ceilings which is the main advantage of legged systems. Other system, like the one by [103] are designed in a modular way and can be used with four legs as shown in Fig. 10(h) or extended to a six-legged robot. The robot SAFARI [104] makes use of four legs which are a mixture of classic legs and sliding frame. With ROBUG III [35] also an eight-legged system was build which is able to move like a spider.

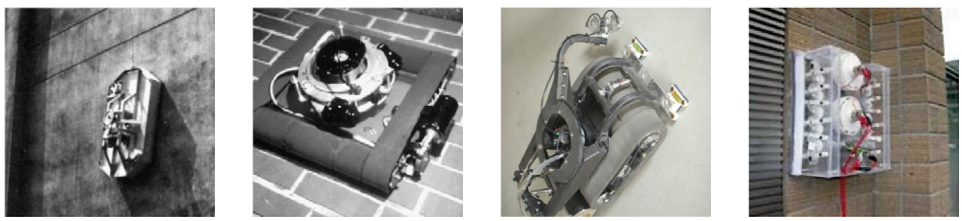
Beside their general adaptability to the surface geometry also payload seems to be satisfying for general inspection and maintenance operations on vertical buildings. Nevertheless, the locomotion speed is comparably low.

2 Image taken from [98].

3 http://zientzia.net/artikuluak/robicen-iii-ingurune-arriskutsuetarako-robot-igoka/.



(a) CleanBot 4 [47]. (b) Rostam [108]. (c) AutoCrawler [98]. (d) Robot by [32].



(e) Robot by [4]. (f) Caterpillar [45]. (g) Icm Climber[4] [15]. (h) Robot by [62].

Fig. 11. Collection of robots using tracks with suction cups (a–d) or separate adhesion components (e–h).

4.2.5. Tracked climbing robots using pneumatic adhesion

The characteristics of tracked systems in general can be denoted as in-between legs and wheels: They are faster and less adaptive than legs, but are able to overcome larger obstacles than wheels. Since they need to be of a certain size for mechanical reasons, their payload is high enough to carry tools and sensors for different maintenance tasks. In general, one can classify tracked systems into two categories: Those which adhere via special tracks and those whose adhesion system is (nearly) decoupled from locomotion.

Fig. 11 shows examples for the two different categories. CleanBot 4 [47] makes use of tracks which are equipped with suction cups on it. The robots Rostam [108] and AutoCrawler[5] [98] have been developed for aircraft inspections and maintenance and use double-tracks with active suction cups. Furthermore, a multi-body robot has been developed by [32] which combines two locomotion principles. The system is equipped with six arm-like components, but each of them consists of tracked elements with suction cups on it. Although it is not as variable as common legged system, it is able to overcome higher steps than common wheeled or tracked vehicles.

Other robots like the machine by [4] consist of an adhesion chamber with internal locomotion units. Beside tracks this system can also be equipped with a wheel drive. In contrast to that the caterpillar system by [45] and the Icm Climber [15] (Fig. 11(g)) use the tracks as sealing. The complete adhesion chamber is sealed by straight elastic bands at the sides and in front and rear of the robot. This allows a good performance in combination with low wear of the sealing components.

A less common locomotion type which is similar to tracks has been used by [62]. Their robot performs a kind of snail-like locomotion via a wave propagation unit as shown in Fig. 11(h). It has dimensions of 0.29 m $\times$ 0.315 m $\times$ 0.15 m and a weight of only 2 kg. The adhesion system consists of a single adhesion chamber with a brush sealing evacuated by fans. Depending on the surface structure the system is able to reach velocities of 0.84 m/min (coarse tiles), 1.38 m/min (smooth surface) up to 2.52 m/min on grooved tiles in vertical direction.

All these systems have been developed for maintenance tasks of vertical buildings and can be used for certain applications.

4.2.6. Tether-supported climbing robots

Beside the presented locomotion types a handful of further robots exist which have been developed for stationary use at high-rise buildings. These systems are moved by a belt or via tether support which allows good performance and high payload capacity. Of course, these systems are limited to the individual structure only, but can be used to clean or maintain large areas like glass facades in a safe and economic way.

Fig. 12 depicts some of these systems in terms of the robot SkyBoy [59], a window cleaner by [60], SiriusC [14] and a robot [109] cleaning the central building of Leipzig Trade Fair in Germany. Although these systems are in operation, their field of application is very limited and specialized to the certain building. In contrast to the previous systems, the adhesion mechanism of these supported systems are mainly used to keep the robot at the wall while the tethers hold most of the weight.

4.2.7. Robots using other pneumatic adhesion principles

Beside classic active and passive suction cups also other principles have been used in the range of climbing robots to generate attraction forces. The vortex system e.g. is a patented adhesion method known as Vram (vortex regenerative air movement), which generates adhesive forces via a vortex inside of the robot. This vortex is created by a high-speed rotor and allows adhesion without additional sealing elements as needed by the cup-based systems. So far, only few systems have been developed using this principle, as e.g. the Clarifying Climber Robot by *Clarifying Technologies*[6] [16], City Climber [38], Alicia Vtx by [37] or the entertainment robot ParaSwift [44], which are all wheel-driven and shown in Fig. 13. Some researchers try to understand this adhesion principle and analyze the aerodynamic of these systems [79].

A similar setup for locomotion has been chosen by [39] for a robot using the venturi effect to generate the needed negative pressure (Fig. 13(e)). It is said that at a positive pressure of 5 bar and an airflow of about 50 l/min one suction pad reaches an attraction force of 6.4 N [113] which is low compared to other adhesion principles. But, also legged systems exist which make use of the venturi principle. The gecko inspired robot by [110] uses fluidic vacuum generators which generate a vacuum via flowing fluids.

4 http://www.icm.cc.

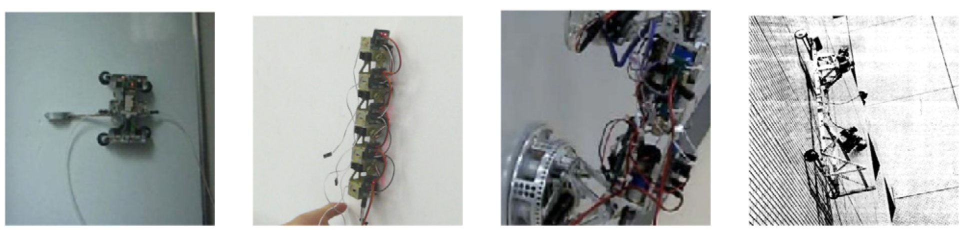
5 Mr. Seemann, AutoCrawler L. L. C., US patent 5487440 A.

6 http://www.clarifyingtech.com/public/robots/robots_public.html.

(a) SkyBoy [59]. (b) Robot by [60]. (c) SiriusC [14]. (d) Robot by [109].

Fig. 12. Climbing robots using wires or tethers for locomotion at high-rise buildings.

(a) Clarifying Climber III [16]. (b) Alicia Vtx [37]. (c) City Climber [38]. (d) ParaSwift [44]. (e) Robot by [39].



(f) Robot by [110]. (g) Robot by [111]. (h) Robot by [22]. (i) Robot by [112].

Fig. 13. Climbing robots using the vortex mechanism (a–d), the venturi principle (e, f), vibrating suction cups (g, h) or thrust force (i).

Another active adhesion principle tries to improve the attraction forces via a vibration method. Examples for this can be found in terms of the inchworm-like system by [111] or the biped robot by [22]. Both are very light-weighted and seem to be less applicable due to low payload. But, nevertheless, they are very interesting because of low energy consumption.

Finally, some researchers started development of propeller type climbing robots. As in the prototype given in Fig. 13(i) by [112] the attraction is generated via thrust force of two propellers, motion is realized via wheels. Unfortunately, the system stability was too low which hindered further research.

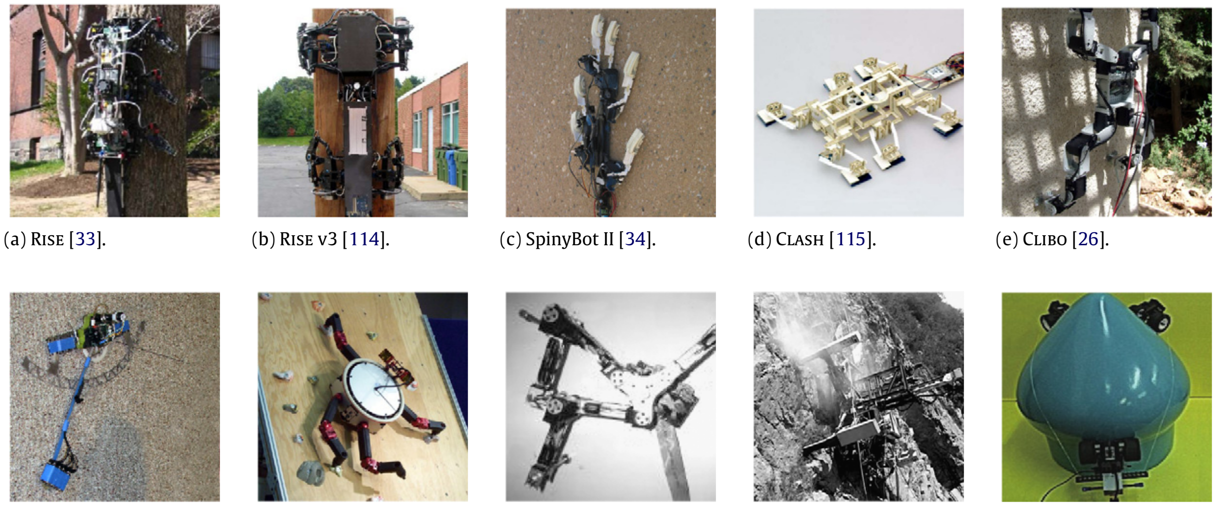
The given examples show that climbing robots using negative pressure adhesion are widely spread and can be used for different tasks in the range of maintenance, inspection or cleaning. The main problems related to pneumatic adhesion in terms of suction chambers are the leak tightness of the vacuum cups especially on rough surfaces and a high power consumption, if classic active vacuum generators are used. Here, legged systems have the advantage that they can test the leak-tightness of each foothold and to test other positions if the adhesion is not ensured. On the other hand, these systems are relatively slow and therefore not applicable for common tasks, which require a sufficient fast navigation speed. All in all it can be stated, that the applicability of these systems is generally given, although there is a large variety of characteristics and pros and cons of the individual locomotion and pneumatic adhesion principles.

4.3. Mechanical adhesion

Another attraction principle is mechanical adhesion based on claws (or spines) or via a gripping or clamping mechanism. These systems can be used for surfaces which are either sufficiently rough so that the spines find enough contact points for attraction, or which provide protrude elements or a structure which can be gripped. The main advantage lies in the energy consumption of the adhesion mechanism, in its applicability for rough or structured surfaces and in its safety. Especially the grip-based adhesion is very safe since even a loss of power does not necessarily lead to a drop-off of the system (if the mechanical setup supports this). On the other hand, such systems are not very fast and are of limited maneuverability. Furthermore their payload is low compared to robots using magnetic or pneumatic attraction.

Fig. 14 gives some examples for climbing robots equipped with (micro-)spines. Here, one mainly finds legged systems as different versions of robot Rise [33,114], SpinyBot II [34], Clash [115] or the quadruped Clibo [26] having spines at their feet. These robots often have a simple mechanical structure and a low weight, which enables them to climb even on concrete walls. For SpinyBot II a maximal force of 1–2 N per contact between spine and surface (asperity) was measured [120]. As mentioned before, they are not suitable to carry a high payload of several kilogram. Another principle of locomotion has been introduced in terms of the robot Rocs [116] sticking to walls coated by a carpet or other net structures. This robot moves up the wall by swinging a mass from left to right shifting the two claws upwards alternately. The main goal of this research was an energy-optimized climbing system, which makes the complete system inapplicable for the desired maintenance tasks since it has very limited motion capabilities and payload and is, so far, restricted to a certain surface structure.

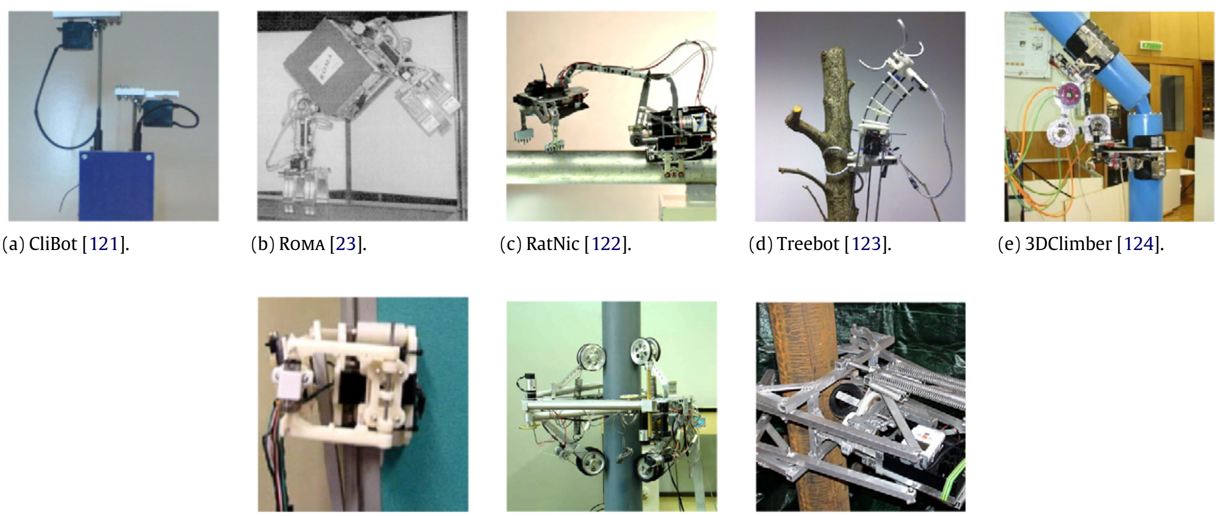
The robot Lemur IIb is also equipped with legs, but it uses existing protrusions for climbing [27] without gripping them. So far, it can climb sloped surfaces but no vertical walls or



(a) Rise [33]. (b) Rise v3 [114]. (c) SpinyBot II [34]. (d) Clash [115]. (e) Clibo [26].

(f) Rocs[7] by [116]. (g) Lemur IIb [27]. (h) Libra [117]. (i) RoboClimber [118]. (j) Robot trio [119].

Fig. 14. Examples for robots using claws and spikes (a–f), articulated climbing feet (g, h) and tether support (i, j).



(a) CliBot [121]. (b) Roma [23]. (c) RatNic [122]. (d) Treebot [123]. (e) 3DClimber [124].

(f) MovGrip [125]. (g) Ut-Pcr [127]. (h) Robot by [126].

Fig. 15. Climbing robots with grippers (a–e) and clamping mechanisms (f–h).

overhead. The same counts for the three-limbed robot Libra [117], which makes use of protrude structures for climbing and for RoboClimber [118] using tethers for moving up. These robots are attracted to their foot points via gravitational forces. Also the inspection device by [119] uses gravity for attraction, but it consists of three wheel-driven robots connected via strings which interact and perform inspections tasks of domes in cooperation mode.

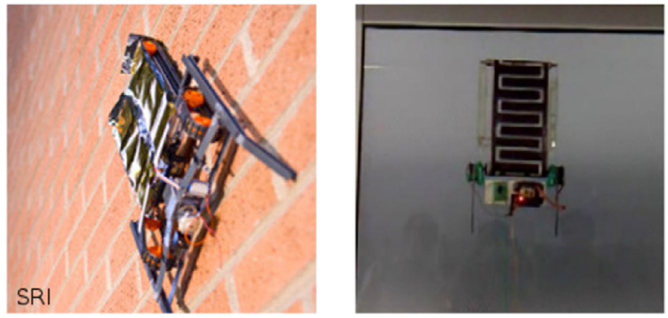
In contrast to that, there exists a couple of robots like CliBot [121] or Roma [23], which use arms with clamping or gripping mechanisms to stick to the surface, as illustrated in Fig. 15. Of course, there must exist a corresponding structure with suitable points of adhesion. Roma e.g. has been designed to climb on a beam-based structure with its two grippers. Besides this, the development of RatNic from the InspiRat project [122] has a biologically inspired background to build up a robot, which is able to climb cables and tubes like a rat. Also Treebot [123] and 3DClimber [124] have been designed to climb trees or poles, which could be helpful also in terms of inspection and maintenance applications of human-made structures. But, there also exist tracked or wheeled systems like MovGrip [125], Ut-Pcr [127] or the robot by [126] pressing their motion units to a pole or a wall by enclosing it.

For climbing on concrete walls some systems are applicable (e.g. Rise robot) whereas others are specialized to certain structures only. Especially the clamping and grasping mechanisms are very safe with respect to robot adhesion, since they can be realized in a way that the grip closes in case of a blackout. In contrast to that, robots using spikes strongly depend on the surface structure, which makes a drop-off possible. They are e.g. not able to climb on smooth surfaces like glass or metal.

4.4. Electrostatic adhesion

Beside the classic attraction principles some new approaches arise which bring more material science e.g. from biology and chemistry into climbing robotics. An increasing discipline in the research field of climbing robots is the *electroadhesion*. Here, electroadhesive pads comprising conductive electrodes and

7 http://unews.utah.edu/news_releases/robot-climbs-walls/.



(a) Robot[8] by [128]. (b) Robot by [129].

Fig. 16. Electroadhesive climbing robots.

Table 2
Estimated adhesion (normal) force via electroadhesive pads as determined by [128].

Material	Force	Material	Force
Shelf wood	1.375 N/cm^2	Drywall	0.525 N/cm^2
Paper	0.52 N/cm^2	Glass	0.84 N/cm^2
Dry concrete	0.3 N/cm^2	Steel	4.24 N/cm^2

insulation substrate are used to generate electrostatic or *Van der Waals forces* between the surface and the robot. So far, there only exist a few of robots using this active adhesion mechanism like the tracked vehicles by [128,129], as shown in Fig. 16.

This technology seems to be a very promising approach since it is safe, energy-efficient and robust concerning different surfaces. Recent experiments by [128] have shown that only about 0.02 mW/N are needed to stay clamped. Table 2 sums up some findings about the applicability of electroadhesive robots to several materials. Unfortunately, this technology is not really completely understood and still at a first stage of development. Furthermore, the payload of existing systems as the one depicted in Fig. 16(a) is low with only 200 g compared to the robot with a total dimension of 50 × 70 cm and a weight of 1000 g [130]. Nevertheless, it is possible that it will outperform the other approaches within the next ten years due to a couple of advantages as mentioned before.

Another kind of electrostatic force is the passive gecko principle – also known as dry adhesion – based on microscopic fibrillae (hairy structures), which adhere to the surface on an atomic level. The generated attraction forces can reach up to 10 N/cm^2 [131]. Here, tracked vehicles [48,49] can be found as well as legged robots. Examples for these are Geckobot [25], Waalbot [132] and StickyBot [24]. Also the Mini-Whegs 7 system [133] makes use of this adhesion principle, but it uses a kind of wheels with polymer tape on it. These systems have a low energy consumption for adhesion and can be used for different surfaces. Nevertheless, the microscopic hairs have a limited lifetime and need a special mechanism for peeling off (see Fig. 17).

In general most of these systems are specialized to certain environmental setups. With regard to the given application, the gecko principle might not be the optimal solution due to a low payload. Only electroadhesive robots seem to be a promising way in the range of maintenance to allow safe adhesion in combination with a high payload.

4.5. Chemical adhesion

Additionally, less common adhesion principles are examined in literature which can be summed up as chemical adhesion (Fig. 18). This includes robots using sticky tapes in combination with a kind of wheels [134] and tracks [50], as well as multi-legged systems [135] equipped with tacky elastomere feet. The general advantage of this adhesion principle lies in its low energy consumption when the system is not moving, while during motion a certain force is needed to peel off or detach the material from the surface. Another chemical principle is thermal glue [136] which changes its characteristics depending on the temperature (Fig. 18(d)). A similar principle is possible via magnetorheological fluids which change their chemical behavior depending on a magnetic field. This mechanism is used by the robot of [137] to create attraction forces to different kinds of surfaces.

The research of these robots comes often from material science to test new approaches of adhesion. Therefore, they often are developed as a proof of concept. With respect to an application in the range of maintenance and inspections these systems will not be able to carry a sufficient payload in a short time. Thus, other systems might be more suitable.

All the introduced systems and principles are without any claim of completeness and correctness.[9] But, this section should give a comprehensive summary on existing approaches and on their manifoldness. Table 4 sums up the introduced attraction methods and rates them related to some important requirements. As in the case of the different types of locomotion, individual pros and cons exist which need to be considered. Magnetic and grip-based adhesion e.g. are highly robust and reliable, but suitable only for very special applications, since they need either ferromagnetic surfaces or protrude structures. But, both have a very good rating concerning high mortality parts as given in the last row. This counts especially in comparison to methods with sliding components which have to be replaced (e.g. sealings) or which work with consumables (e.g. glue).

Additional information on the presented adhesion techniques, locomotion types and robotic systems can be found in some further publications, e.g. [138–140]. The presented systems are summarized and categorized[10] in Table 3. It can be observed that some combinations of locomotion and attraction principle are missing since they are e.g. either not possible or not useful.

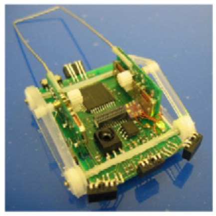
5. Discussion of design aspects for an inspection robot for concrete buildings

The introduced requirements can now be used to analyze and discuss the locomotion and adhesion methods for a practical task. A very interesting field of application for mobile climbing robots

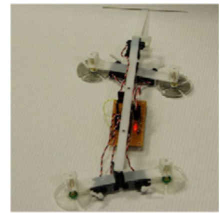
[8] Image by courtesy of SRI International, http://www.sri.com/.

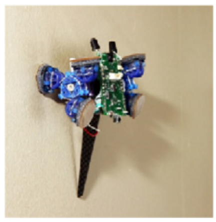
[9] It is for sure hard to classify each robot correctly since some fit more than one category, but a unique decision has to be done. Otherwise one needs a set of 'hybrid' classes (e.g. tracked legs or sliding-frame arms) which would be beyond the scope of this paper.

[10] Due to limitations in space and since not all robots have a name only the reference is given in this table.


(a) Tiny robot [48].


(b) Tracked [49].

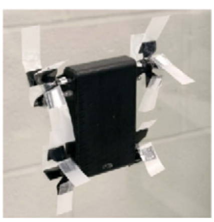

(c) Geckobot [25].


(d) Waalbot [132].

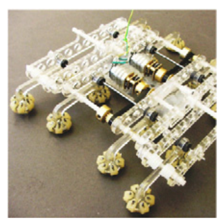

(e) StickyBot [24].


(f) Mini-Whegs [133].

Fig. 17. Gecko principle robots in combination with tracked locomotion (a, b), different types of legs (c–e) and a kind of 'taped' wheels (f).


(a) Sticky robot [134].


(b) Tracked [50].


(c) Multi-legged [135].


(d) Glue robot [136].

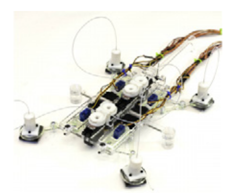

(e) Four-legged [137].

Fig. 18. Climbing robots using different types of chemical attraction like sticky material or glue.

Table 3
Classification of the presented robots depending on their locomotion and adhesion principles. Some systems are mentioned twice if their locomotion or adhesion system can be replaced or extended.

		Magnetic	Negative pressure (pneumatic)			Mechanical	Electrostatic	Chemical
			Cups	Chambers	Others			
Legs/arms	2	[18,64,65]	[19,87,100] [101]	[21]	[22]	[23,116,121] [122–124]	[132]	[136]
	3	–	–	–	–	[117]	–	–
	4	[3,29,30] [66]	[28,103]	[3,102,104]	[110]	[26,27,114]	[24,25]	[137]
	6	[1,31]	[103]	–	–	[33,34,115]	–	–
	≥8	–	–	[35]	–	–	–	[135]
Wheels		[10,36,51] [52,67,68] [69–71]	–	[4,40,41] [42,43,88] [89–91] [92]	[37–39] [44,16,112]	[125,127,126] [119]	[133]	[134]
Frame		[58,77,78]	[53–55] [56,57,93] [94,96,97] [98,13,78]	[99]	–	[118]	–	–
Tracks		[72,73,11] [74–76] [12]	[32,46,47] [86,98,108]	[4,45,15]	–	–	[48,49,128] [129]	[50]
Other		–	[14,109]	[59,60,62]	[111]	–	–	–

are inspection tasks of concrete buildings as given in the first row of introductory Fig. 1. Especially the large number of motorway bridges provides a high potential for climbing robots to maintain their stability, safety of traffic and durability via regular inspections as prescribed by law. So far, inspections of these vertical structures are made by hand by using complex access devices like cranes or gondolas to reach the desired position for inspection, as illustrated in Fig. 19. In some cases, large scaffolds are used to bring the technician to the building, but also professional climbers are involved if the structure cannot be reached otherwise (Fig. 19(c)).

To develop a robot which is able to perform these risky and cost-intensive tasks autonomously, the catalog of requirements needs

Table 4
Comparison of adhesion principles related to the introduced requirements.

Requirements		Magnetic	Suction cups	Chambers	Vortex	Claws	Grips	Electrostatic	Chemical
1.	Materials	–	∘	+	+	+	–	+	∘
	Roughness	+	–	∘	+	+	+	+	∘
2.	Payload	+	–	+	∘	–	∘	∘	–
3.	Reliability	+	–	∘	∘	+	+	+	–
	Forces	+	∘	+	∘	+	+	+	–
4.	Consumables	+	∘	∘	+	∘	∘	+	–

(a) Lifting carriage. (b) Gondola. (c) Industrial climber.

Fig. 19. Inspections of concrete buildings via standard access devices or industrial climbers.

to be examined:

- The vehicle should be able to move horizontally, vertically and over side on slightly bended concrete surfaces.
- It needs to reach a velocity of about 10 m/min for a sufficient fast navigation and move continuously for inspection sensors like a cover meter.
- It might be also desired that such a system is able to move over steps of up to 2 cm, which may result from construction processes like sheething gaps or from damages.
- The desired payload can be set to approximate 10 kg—in the best case it is possible to carry not only one but a set of different inspection sensors.
- For usability, the total weight should not exceed 30 kg and its dimension should stay below 80 cm so that it can be handled by only one technician.
- For safety purposes, the inspection system needs to be secured via a cable which can also be used for energy supply.
- The system should be able to perform some automatical evasion and navigation strategies since the human operator might not be able to foresee critical situations.

The resulting question is, which combinations of locomotion principle and type of attraction are useful in the range of maintenance and inspection of large concrete buildings. Table 5 sums up and identifies knock-out criteria for the given methods and presents those combinations which can be used. One can state, that e.g. legged systems will not be able to go up a high river dam or bridge pylon in a short time as wheeled or tracked robots. The adaptability and step-overcoming ability of legged systems (e.g. ground-to-wall transition, obstacles) might not be that important for nearly flat buildings like the mentioned ones. Magnetic adhesion e.g. is not suitable since it only works in combination with ferromagnetic structures, as well as suction cups which are more or less limited to smooth surfaces.

One can sum up, that for the given task only some combinations of adhesion and locomotion methods are suitable. It can be stated, that the adhesion principles of vortex and electroadhesion are still in development and not completely understood. Furthermore, tracked vehicles are not able to perform free motions in the plane since they only have two degrees of freedom, which speaks for the use of wheels. These decisions would lead to the design of a wheeled robot using negative pressure adhesion (compare Fig. 8).

Fig. 20. Climbing robot CROMSCI driving on a concrete wall.

The wheel-driven robot CROMSCI [141] (Fig. 20) is such a system which has been build up to perform inspection tasks on large concrete buildings like bridge pylons, dams, or cooling towers area-wide and semi-autonomously. It is able to climb on vertical walls via closed-loop controlled negative pressure adhesion, as first introduced in terms of an early prototype [142].

On top of the round chassis lies the vacuum reservoir including pressure sensors and valves for closed-loop pressure control. The adhesion is realized via seven individual vacuum chambers which are supported by the reservoir. A movable manipulator arm [143] can be mounted to carry the sensors for inspection. CROMSCI has to be connected via an umbilical cord to a ground station because of high energy consumption of the suction engines and for communication purposes. Table 6 sums up the key data of CROMSCI, further images and videos can be found on the robot's website.[11]

Regarding Table 5, wheels have been selected for locomotion since they provide the highest velocity and maneuverability.

[11] http://agrosy.cs.uni-kl.de/cromsci/.

Table 5
Applicability of the different principles for navigation tasks on large concrete buildings.

	Legs	Wheels	Tracks	Frame	Wires
Magnetic	No (non-ferromagnetic structures)	No	No	No	No
Suction cups	No (rough surfaces, low payload)	No	No	No	No
Chambers	No (too slow)	Yes	Yes	No (too slow)	No (not univ./adapt.)
Vortex	No (too slow)	Yes	Yes	No (too slow)	No (not univ./adapt.)
Claws	No (too slow)	No (low payload)	No (low payload)	No (too slow)	No (not univ./adapt.)
Grips	No (too slow)	No (no protrusions)	No (no protrusions)	No (too slow)	No (not univ./adapt.)
Electrostatic	No (too slow)	Yes	Yes	No (too slow)	No (not univ./adapt.)
Chemical	No (low payload and reliability)	No	No	No	No

Table 6
Key data of climbing robot CROMSCI.

Parameter	Value
Weight/payload	≈50 kg/ ≈10 kg
Diameter/height	0.8 m/0.4 m
Max. velocity	0.1605 m/s
Adhesion area	0.4 m^2
Chamber pressure	−50 to −100 mBar
Downforce	2000–4000 N
Sealing pressure	1200 mBar

To meet these requirements CROMSCI is equipped with an omnidirectional drive system consisting of three independently driven an steerable standard wheels without suspension [144]. This allows a sufficiently fast navigation even in vertical direction and enables the robot to turn on the spot as well as to drive sidewards. Special closed-loop traction controllers reduce the effects of wheel-slip [145]. The missing ability to overcome larger steps and obstacles has been declared to be of secondary importance since the aimed buildings are nearly even.

Related to the principle of attraction the decision was to use negative pressure adhesion via several vacuum chambers. As mentioned before, this mechanism works on many materials including concrete and is able to create high attraction forces to carry the desired payload. A vortex or electroadhesion has not been considered since they are not sufficiently explored and their payload capacity is not really known. Therefore, CROMSCI uses an active negative pressure system [84] consisting of three suction engines, one large vacuum reservoir, and seven individual working chambers generating the downforce. This allows the system to adhere to vertical or overhead concrete structures while the vacuum chambers are moved over the surface without lifting them during locomotion. Therefore, a flexible, but robust sealing mechanism made of an inflatable rubber tube and a special coating via a synthetic fiber material has been realized to reduce friction and wear [146]. The use of several individual vacuum chambers allows a deactivation of untight chambers [141] by closing the valve to avoid a propagation of ambient pressure to the remaining chambers which could result in a drop-off. Inactive chambers can be tested from time to time whether they can be reintegrated into the negative pressure system or not.

6. Conclusion

This paper presented the current state-of-the-art in climbing robots which could be applied for maintenance, inspection or construction tasks. Applications and requirements are examined and different principles for robot locomotion as well as for attraction to the vertical structures are discussed.

As a conclusion it can be said, that no system exists which meets the given requirements. So far, only some special solutions in terms of robotic prototypes exist which are limited to a specific setup or certain environments. The challenge for a universal robot are contradictive requirements demanding a light-weighted, small and fast robot which is able to navigate on a vertical wall safely, to overcome steps and obstacles and to carry a high payload.

Further research on adhesion and locomotion is necessary to bring these systems to commercial application. But it can be stated that some are on a very promising way, as e.g. the presented prototype CROMSCI which combines negative pressure chambers with wheels.

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