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A Survey of Technologies and Applications for Climbing Robots Locomotion and Adhesion

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1. Introduction

The interest in the development of climbing robots has grown rapidly in the last years. Climbing robots are useful devices that can be adopted in a variety of applications, such as maintenance and inspection in the process and construction industries. These systems are mainly adopted in places where direct access by a human operator is very expensive, because of the need for scaffolding, or very dangerous, due to the presence of an hostile environment. The main motivations are to increase the operation efficiency, by eliminating the costly assembly of scaffolding, or to protect human health and safety in hazardous tasks. Several climbing robots have already been developed, and other are under development, for applications ranging from cleaning to inspection of difficult to reach constructions.

A wall climbing robot should not only be light, but also have large payload, so that it may reduce excessive adhesion forces and carry instrumentations during navigation. These machines should be capable of travelling over different types of surfaces, with different inclinations, such as floors, walls, or ceilings, and to walk between such surfaces (Elliot et al. (2006); Sattar et al. (2002)). Furthermore, they should be able of adapting and reconfiguring for various environment conditions and to be self-contained.

Up to now, considerable research was devoted to these machines and various types of experimental models were already proposed (according to Chen et al. (2006), over 200 prototypes aimed at such applications had been developed in the world by the year 2006). However, we have to notice that the application of climbing robots is still limited. Apart from a couple successful industrialized products, most are only prototypes and few of them can be found in common use due to unsatisfactory performance in on-site tests (regarding aspects such as their speed, cost and reliability). Chen et al. (2006) present the main design problems affecting the system performance of climbing robots and also suggest solutions to these problems.

The major two issues in the design of wall climbing robots are their locomotion and adhesion methods.

With respect to the locomotion type, four types are often considered: the crawler, the wheeled, the legged and the propulsion robots. Although the crawler type is able to move relatively faster, it is not adequate to be applied in rough environments. On the other hand, the legged type easily copes with obstacles found in the environment, whereas generally its speed is lower and requires complex control systems.

Regarding the adhesion to the surface, the robots should be able to produce a secure gripping force using a light-weight mechanism. The adhesion method is generally classified into four

groups: suction force, magnetic, gripping to the surface and thrust force type. Nevertheless, recently new methods for assuring the adhesion, based in biological findings, were proposed. The vacuum type principle is light and easy to control though it presents the problem of supplying compressed air. An alternative, with costs in terms of weight, is the adoption of a vacuum pump. The magnetic type principle implies heavy actuators and is used only for ferromagnetic surfaces. The thrust force type robots make use of the forces developed by thrusters to adhere to the surfaces, but are used in very restricted and specific applications.
Bearing these facts in mind, this chapter presents a survey of different applications and technologies adopted for the implementation of climbing robots locomotion and adhesion to surfaces, focusing on the new technologies that are recently being developed to fulfill these objectives. The chapter is organized as follows. Section two presents several applications of climbing robots. Sections three and four present the main locomotion principles, and the main "conventional" technologies for adhering to surfaces, respectively. Section five describes recent biological inspired technologies for robot adhesion to surfaces. Section six introduces several new architectures for climbing robots. Finally, section seven outlines the main conclusions.

2. Climbing Robots Applications

Climbing robots are mainly adopted in places where direct access by a human operator is very expensive, because of the need for scaffolding, or very dangerous, due to the presence of an hostile environment.
In the last decades different applications have been envisioned for these robots, mainly in the areas of cleaning, technical inspection, maintenance or breakdown diagnosis in dangerous environments, or in the outside of tall buildings and human made constructions.
Several climbing robots have already been developed for the following application areas:

- **Inspection:** bridges (Balaguer et al. (2005); Robert T. Pack and Kawamura (1997)), nuclear power plants (Savall et al. (1999); Yan et al. (1999)), pipelines (Park et al. (2003)), wind turbines (Rodriguez et al. (2008)), solar power plants (Azaiz (2008)), for scanning the external and internal surfaces of gas or oil tanks (Longo and Muscato (2004b); Park et al. (2003); Sattar et al. (2002); Yan et al. (1999)), offshore platforms (Balaguer et al. (2005)), and container ships (Mondal et al. (2002));
- **Testing:** performing non-destructive tests in industrial structures (Choi et al. (2000); Kang et al. (2003)), floating production storage oil tanks (Sattar et al. (2008; 2006)), planes (Backes et al. (1997); Chen et al. (2005); Robert T. Pack and Kawamura (1997)) and ships (Armada et al. (2005); Robert T. Pack and Kawamura (1997); Sánchez et al. (2006));
- **Civil construction:** civil construction repair and maintenance (Balaguer et al. (2005));
- **Cleaning:** cleaning operations in sky-scrapers (Derriche and Kouiss (2002); Elkmann et al. (2002); Gao and Kikuchi (2004); Yan et al. (1999); Zhang et al. (2004); Zhu et al. (2003)), for cleaning the walls and ceilings of restaurants, community kitchens and food preparation industrial environments (Cepolina et al. (2004)) and cleaning ship hulls (Fernández et al. (2002));
- **Transport:** for the transport of loads inside buildings (Minor et al. (2000));
- **Security:** for reconnaissance in urban environments (Elliot et al. (2006); Tummala et al. (2002)) and in anti-terrorist activities (Li et al. (2007)).

Finally, their application has also been proposed in the education (Bell and Balkcom (2006); Berns et al. (2005)) and human care (Balaguer et al. (2005)) areas and in the prevention and fire fighting actions (Chen et al. (2006); Nishi (1991)).

3. Principles of Locomotion

In this section are analyzed the characteristics of the four main locomotion technologies implemented in climbing robots, namely the crawler, wheeled, legged and propulsion types.

3.1 Locomotion using Sliding Segments (Crawling)

With respect to the locomotion type, the simpler alternatives often make use of sliding segments, with suction cups (Backes et al. (1997); Cepolina et al. (2004); Choi et al. (2000); Elkmann et al. (2002); Savall et al. (1999); Zhang et al. (2004); Zhu et al. (2003)) or permanent magnets (Yan et al. (1999)) that grab to surfaces, in order to move (Figure 1). The main disadvantage of this solution is the difficulty in crossing cracks and obstacles.

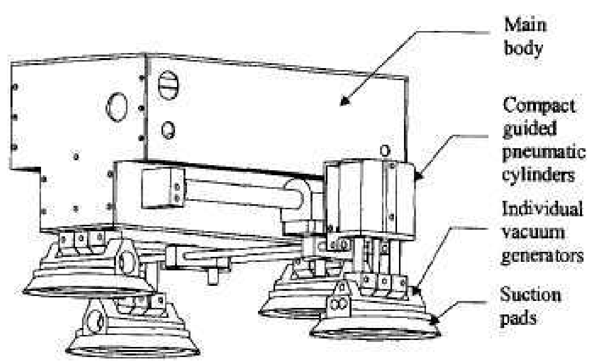

Fig. 1. ROBICEN III climbing robot (Savall et al. (1999))

3.2 Locomotion using Wheels

A second form of locomotion is to adopt wheels (Gao and Kikuchi (2004); Longo and Muscato (2004b); Park et al. (2003); Sánchez et al. (2006); Yan et al. (1999)) (Figure 2). These robots can achieve high velocities. However, some of the wheeled robots that use the suction force for adhesion to the surface, need to maintain an air gap between the surface where they are moving over and the robot base. This technique may create problems either with the loss of pressure, or with the friction with the surface, namely if the air gap is too small, or if some material is used to prevent the air leak (Hirose et al. (1991)).

3.3 Locomotion using Legs

A third form of locomotion consists in the adoption of legs. Legged climbing robots, equipped with suction cups, or magnetic devices on the feet, have the disadvantage of low speed and require complex control systems, but allow the creation of a strong and stable adhesion force to the surface. These machines also have the advantage of easily coping with obstacles or cracks found in the environment (Hirose et al. (1991)). Structures having from two up to eight legs are predominant for the development of these tasks. The adoption of a larger number of limbs supplies redundant support and, frequently, raises the payload capacity and safety. These advantages are achieved at the cost of increased control complexity (regarding leg coordination), size and weight. Therefore, when size and efficiency are critical, a structure with minimum

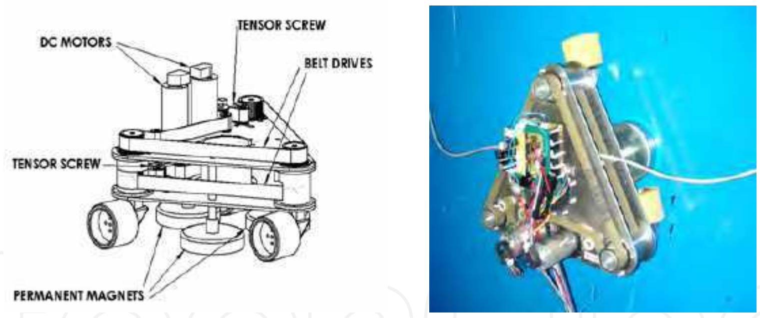

Fig. 2. CAD representation of an wheeled climbing robot (left) and its real aspect (right) (Sánchez et al. (2006))

weight and complexity is more adequate. For these reasons the biped structure is an excellent candidate (Figure 3). Presently there are many biped robots with the ability of climbing over surfaces with different slopes (Armada et al. (2005); Balaguer et al. (2005); Brockmann (2006); Krosuri and Minor (2003); Resino et al. (2006); Robert T. Pack and Kawamura (1997); Shores and Minor (2005); Tummala et al. (2002); Xiao et al. (2003; 2004)).

Fig. 3. RAMR1 biped climbing robot (Tummala et al. (2002))

When is needed an increased safety or payload capability are adopted quadrupeds (Armada et al. (2005); Daltorio et al. (2005); Hirose and Arikawa (2000); Hirose et al. (1991); Kang et al. (2003); Kennedy et al. (2006)) (such as MRWALLSPECT III, presented in Figure 4), or robots with a larger number of legs (Armada et al. (2005); Inoue et al. (2006); Li et al. (2007)). The control and leg coordination of these larger robots is, however, more complicated.

3.4 Locomotion through Propulsion

The propulsion type robots make use of the forces developed by propellers to move and to adhere to the surfaces (Nishi (1991)), but are used in very restricted and specific applications. Nishi (1991) developed a climbing robot using the thrust force of propellers to locomote (Figure 5). The contact between the robot and the surface is maintained though a large number of non-actuated wheels. The thrust force is inclined to the wall side to produce the frictional force between the wheels and the surface. Since strong wind is predicted on the wall surfaces

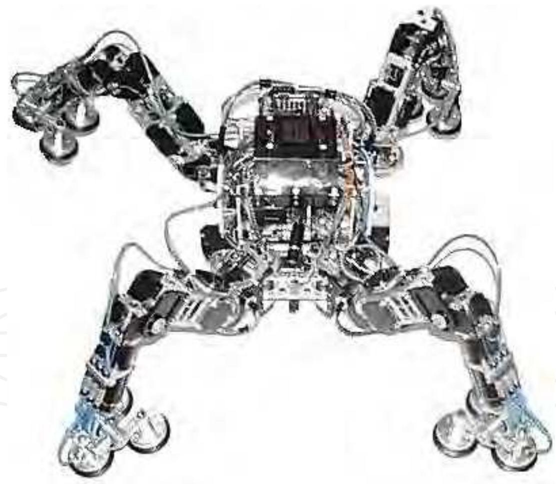

Fig. 4. MRWALLSPECT III quadruped climbing robot (Kang et al. (2003))

of high buildings, the direction of thrust force is controlled to compensate the wind force acting on the robot. A frictional force augmentor is also considered, which is an airfoil to produce the lift force directed to the wall side by the cross wind. Nevertheless, is has been shown that slipping of this robot occurs for abrupt changes in the wind direction or speed.

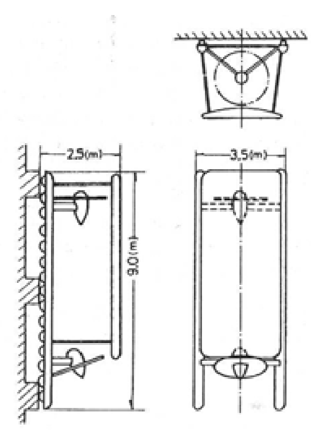

Fig. 5. A conceptual model of a propeller based wall climbing robot (Nishi (1991))

4. Technologies for Adhering to Surfaces

The most important work in developing a climbing robot project is to design a proper adhesion mechanism to ensure that the robot sticks to various wall surfaces reliably without sacrificing mobility (Elliot et al. (2006)).
In this section are reviewed the main aspects of the four adhesion methods usually adopted in climbing robots: suction force, magnetic, gripping to the surface and thrust force type. The next section will review in some depth the new methods for assuring the adhesion, based in biological findings.

4.1 Suction Force

The most frequent approach to guarantee the robot adhesion to a surface is to use the suction force. The vacuum type principle requires light mechanisms and is easy to control. This oper-

ating principle allows climbing over arbitrarily surfaces, made of distinct types of materials, and can be implemented by using different strategies. Usually, more than one vacuum cup is used in each feet in order to prevent loss of pressure (and adhesion force) due to surface curvature or irregularities (Chen et al. (2006); Hirose et al. (1991)). Nevertheless, this type of attachment has some associated drawbacks. The suction adhesion mechanism requires time to develop enough vacuum to generate sufficient adhesion force. This delay may reduce the speed at which the robot can locomote. Another issue associated with suction adhesion is that any gap in the seal can cause the robot to fall. This drawback limits the suction cup adhesion mechanism to relatively smooth, nonporous and non-cracked surfaces. Finally, the suction adhesion mechanism relies on the ambient pressure to stick to a wall and, therefore, is not useful in space applications, because the ambient pressure in space is essentially zero (Menon et al. (2004)). Another problem is the supply of compressed air. The vacuum can be generated through the Venturi Principle (Balaguer et al. (2005); Choi et al. (2000); Elkmann et al. (2002); Savall et al. (1999); Zhang et al. (2004)), or through a vacuum pump, either on-board the robot (Cepolina et al. (2004); Gao and Kikuchi (2004); Kang et al. (2003); Li et al. (2007); Tummala et al. (2002); Yan et al. (1999)), or external to it (Zhu et al. (2003)).
The RAMR1 is an example of a biped climbing robot, adopting suction cups for the adhesion to the surface, being the vacuum generated through an on-board vacuum pump (Figure 3).
When the vacuum is generated through the Venturi Principle, or through vacuum pumps, it makes climbing robots noisy. A solution for this noise problem has been proposed (Li et al. (2007)). Vacuum pumps on-board the robot increase the weight and the costs of a robot, also due to additional vacuum tubes, muffles, valves, and other necessary equipment. This solution causes some level of steady, not negligible, energy consumption. Vacuum pumps external to the robot imply the need for a tether cable, with the inherent problems of the interference of the umbilical cord for the robot with its mobility and dynamics (Chen et al. (2006)). Hence, it is desirable to avoid an active vacuum generation and a separate installation for vacuum transportation.
Bearing these ideas in mind, Brockmann proposed the use of passive suction cups (see Figure 6) because they are low cost, simple and robust and allow a light-weight construction of climbing robots. However, although being a promising approach, in order to construct a proper system, several aspects related to the behavior of passive suction cups have to be better understood (Brockmann (2006)).

Fig. 6. Passive suction cups with (left) and without (right) a strap (Brockmann (2006))

An alternative way to create the adhesion is to adopt air aspiration on a sliding chamber and then to move the robot through wheels (Longo and Muscato (2004a;b)). A variation of this adhesion method is presented by Elliot et al. (2006) and implemented in the City-Climber robot. These researchers designed a device based on the aerodynamic attraction produced by a vacuum rotor package which generates a low pressure zone enclosed by a chamber. The vacuum rotor package consists of a vacuum motor with impeller and exhaust cowling to direct air flow, as shown in Figure 6, left. It is essentially a radial flow device which combines two types of air flow. The high speed rotation of the impeller causes the air to be accelerated toward the outer perimeter of the rotor, away from the center radially. Air is then pulled along the spin axis toward the device creating a low-pressure region, or partial vacuum region if sealed adequately, in front of the device. With the exhaust cowling, the resultant exhaust of air is directed toward the rear of the device, actually helping to increase the adhesion force by thrusting the device forward.

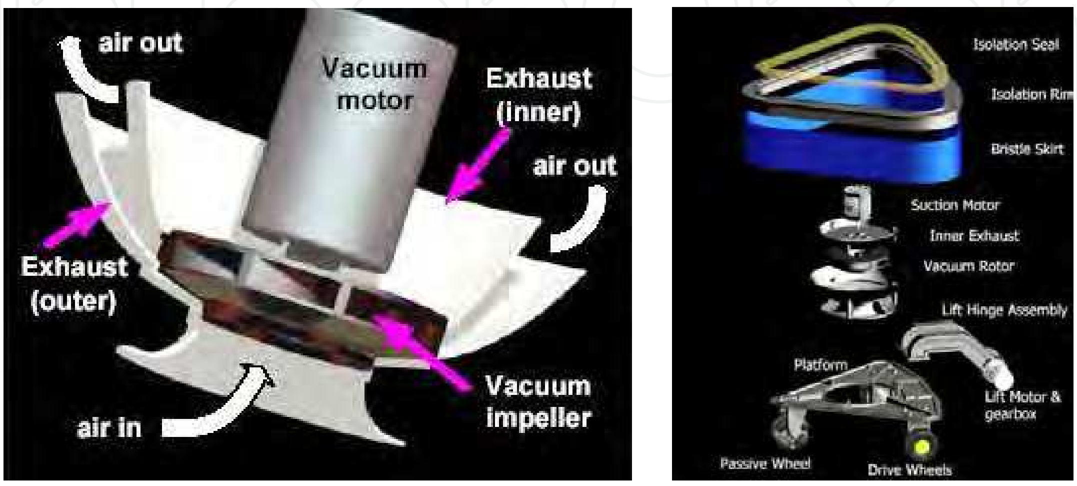

Fig. 7. Vacuum rotor package to generate aerodynamic attraction (left) and exploded view of the City-Climber prototype-II (right) (Elliot et al. (2006))

The experimental test demonstrated that the City-Climber with the module weight of 1 kg (Figure 6, right), can handle 4.0 kg additional payload when moving on brick walls.
Recently, a new technology, named Vortex Regenerative Air Movement (VRAM), was patented (Reinfeld and Illingworth (2002)). This adhesion system adopts vortex to generate high adhesion forces with a low power consumption, and allows the robot to travel on both smooth and rough surfaces. However, the adhesion force generated by the vortex technology is not enough to support large payload (Elliot et al. (2006)) and it is difficult for the robot to make wall-to-wall, and wall-to-ceiling transitions.

4.2 Magnetic Force

The magnetic adhesion is an alternative principle adopted for creating the adhesion force, in specific cases where the surface allows it. Magnetic attachment can be highly desirable due to its inherent reliability. This method is fast, but implies the adoption of heavy actuators. Despite that, magnetic attachment is useful only in specific environments where the surface is ferromagnetic and, therefore, for most applications it represents an unsuitable option (Menon et al. (2004)).
The most frequent solution is the use of electromagnets (Armada et al. (2005); Shores and Minor (2005)). Another possibility is the use of permanent magnets to adhere to the surface, combined with wheels or tracks to move along it (Mondal et al. (2002); Sánchez et al. (2006); Yan et al. (1999)). The main advantages of this last solution are the fact that there is not the need to spend energy for the adhesion process, it will not occur any loss of adhesion in the event of a power failure and permanent magnets are suitable for application in hazardous environments (Berns et al. (2005); Mondal et al. (2002)). A third solution is to use magnetic

wheels that allow to implement the locomotion and the adhesion at the same time (Park et al. (2003)).
The adoption of permanent magnets makes the robot more reliable and safer but there is a drawback: it is more difficult to control the adhesion and release of the robot to the surfaces in which it must work (Yan et al. (1999).

4.3 Gripping to the Surface

The previous adhesion techniques make the robots suitable for moving on flat walls and ceilings. However, it is difficult for them to move on irregular surfaces or surfaces like wire meshes.
In order to surpass this difficulty, some robots climb through man made structures or through natural environments, by gripping themselves to the surface where they are moving. These robots typically exhibit grippers (Balaguer et al. (2005)) (Figure 8), or other special designed gripping systems (Balaguer et al. (2005); Bell and Balkcom (2006); Inoue et al. (2006); Kennedy et al. (2006); Linder et al. (2005)), at the extremity of their limbs.
Examples of this kind of robots, are the ROMA 1 robot (Figure 8), that has two legs with grippers at their ends, for travelling in complex metallic-based environment (Balaguer et al. (2005)).

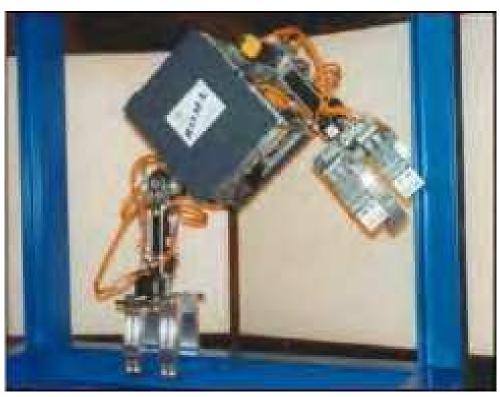

Fig. 8. ROMA1 robot climbing a beam-based structure (Balaguer et al. (2005))

Another example, is the ASIBOT robot (Figure 9), able to move between different points (Docking Stations) of the rooms through an innovative grasping method based on special connectors and a bayonet fitting (Balaguer et al. (2005)).
The Lemur IIb quadruped (Figure 10), intended for free climbing in steep terrain found in space exploration (Kennedy et al. (2006)), climbs over irregular surfaces just like if it was escalating a rock wall.
Finally, the ASTERISK robot (Inoue et al. (2006)) (Figure 11) is equipped with a special mechanism at the extremities of its limbs in order to grab and move on surfaces like wire meshes.
It is also worth mentioning, the toy climbing robot developed at the University of Dartmouth (Figure 12). A major design goal was to keep the project as simple as possible, making feasible for the general public to buy an inexpensive kit for building the robot. Based on these ideas, the robot was built of hobby servo-motors and LEGO pieces, and is capable of climbing a wall of pegs (Bell and Balkcom (2006); Linder et al. (2005)).

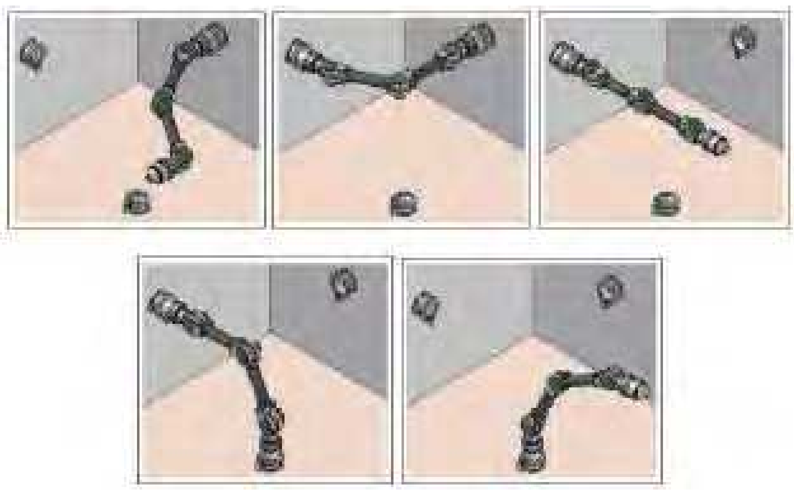
Fig. 9. ASIBOT climbing robot locomotion principle (Balaguer et al. (2005))


Fig. 10. LEMUR IIb robot climbing a test wall (Kennedy et al. (2006))


Fig. 11. ASTERISK robot hanging from a grid-like structure (Inoue et al. (2006))

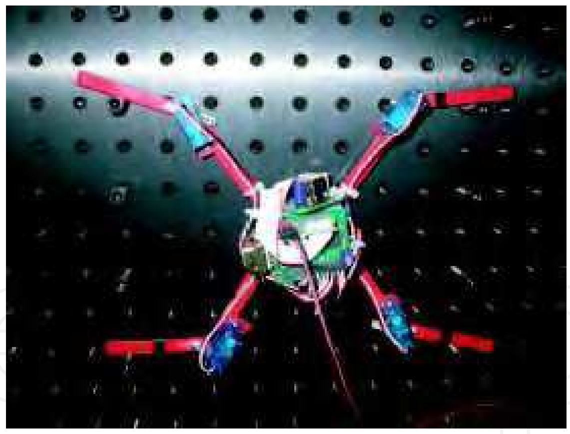

Fig. 12. The robot on the climbing wall (Bell and Balkcom (2006))

4.4 Thrust Force Adhesion

The prototypes that make use of this adhesion principle have been developed for working in submerged applications. These machines mainly allow to perform in-service inspection of the floor and walls of oil, petroleum and chemical storage tanks while submerged in the liquid, thereby saving the cost of emptying, cleaning and manually inspecting the tank (Sattar et al. (2002)).

The RobTank climbing robot, developed by Sattar et al. (2002), can enter oil and chemical storage tanks through 300 mm, or more, diameter openings in their roof, travel on the floor, rotate through any angle within the full 360^o, and change surfaces from the floor to the wall and back to the floor. Regarding the locomotion, two servomotors provide the drive for the wheels of the vehicle while one propeller, mounted on top of the vehicle, provides the thrust force for adhesion to the wall. This way, this vehicle is able to climb on all types of surfaces.

Latter, Sattar et al. (2006) developed a climbing robot for Non-Destructive Testing of the internal tank wall and floor surfaces on Floating Production Storage Oil (FPSO) (see Figure 13, left).

This robot is equipped with two independent, speed controlled, thrusters that move the robot in a horizontal plane in the forward and reverse direction or rotate it to face in any direction. After contact with a wall, thrust forces generated by these two thrusters guarantee the adhesion to the wall, while actuated wheels move the robot on the wall. The robot manoeuvres freely on the wall and can be driven down from a wall to the floor of the tank and back on to it (see Figure 13, right).

A variable buoyancy tank was latter developed to change buoyancy around neutral by obtaining volume change (Sattar et al. (2008)). The tank enables the robot to swim to a given depth and to be parked on the floor with negative buoyancy when inspecting the floor.

5. Biological Inspired Adhesion Principles

In spite of all the developments made up to now, the proposed technologies still need to be improved and no definite and stable solution has yet been found. Therefore, developments continue in this research area.

In the last years a considerable inspiration has been gathered from climbing animals (Daltorio et al. (2005); Menon et al. (2004)). Insects, beetles, skinks, anoles, frogs and geckos have been studied for their sticking abilities (Figure 14). Beetles and Tokay geckos adhere to surfaces

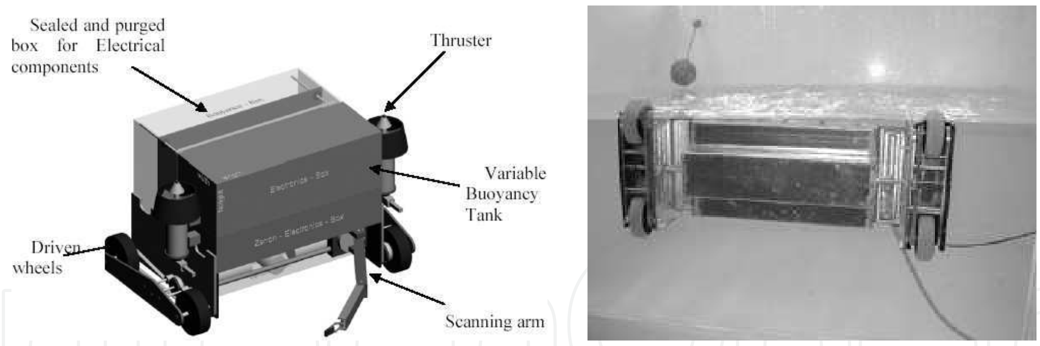

Fig. 13. Conceptual design of FPSO swimming and wall climbing robot (left) and wall-climbing robot climbing a tank glass wall without buoyancy tank (Sattar et al. (2006))

using patches of microscopic hairs that provide a mechanism for dry adhesion by van der Waals forces. Cockroaches climb a wide variety of substrates using their active claws, passive spines, and smooth adhesive pads. Inspired by these animals mechanisms, new methods for assuring the adhesion, based in biological findings, have recently been proposed.

Fig. 14. Gecko foot while climbing a glass surface (Tørrissen (Last Acessed: October 1, 2009))

Using bio-inspired adhesive technology, robots could potentially be developed to traverse a wide variety of surfaces, regardless of the presence of air pressure or the specific material properties of the substrate. Robots using such adhesives might some day be able to climb uneven, wet surfaces.
Bearing these ideas in mind, this section is organized as follows. The next subsection presents some climbing robots that use gecko inspired synthetic dry adhesives. The following subsection introduces climbing robots using micro-structured polymer feet in order to adhere to the surfaces. Lastly, the third subsection, describes some climbing robots using microspines.

5.1 Climbing Robots Using Gecko Inspired Synthetic Dry Adhesives

The ability of Geckos to climb surfaces, whether wet or dry, smooth or rough, has attracted people attention for decades. According to Menon et al. (2004), by means of compliant micro/nano-scale high aspect ratio beta-keratin structures at their feet, geckos manage to adhere to almost any surface with a controlled contact area. It has been shown that adhesion is mainly due to molecular forces such as van der Waals forces. The geckot's ability to stick to surfaces lies in their feet, specifically the very fine hairs on its toes, as can be seen if Figure 15. Those hairs are roughly 5 microns in diameter, and atop each of these micro-fibers sit hundreds of nano-fibers (spatulae) which are 200 nanometers in diameter. There are billions of these tiny fibers which make contact with the surface and create a significant collective surface area of contact. The hairs have physical properties which let them bend and conform to a wide variety of surface roughness, meaning that the adhesion arises from the structure of these hairs themselves. Also, because of their hydrophobic nature, the gecko fibers are self-cleaning.

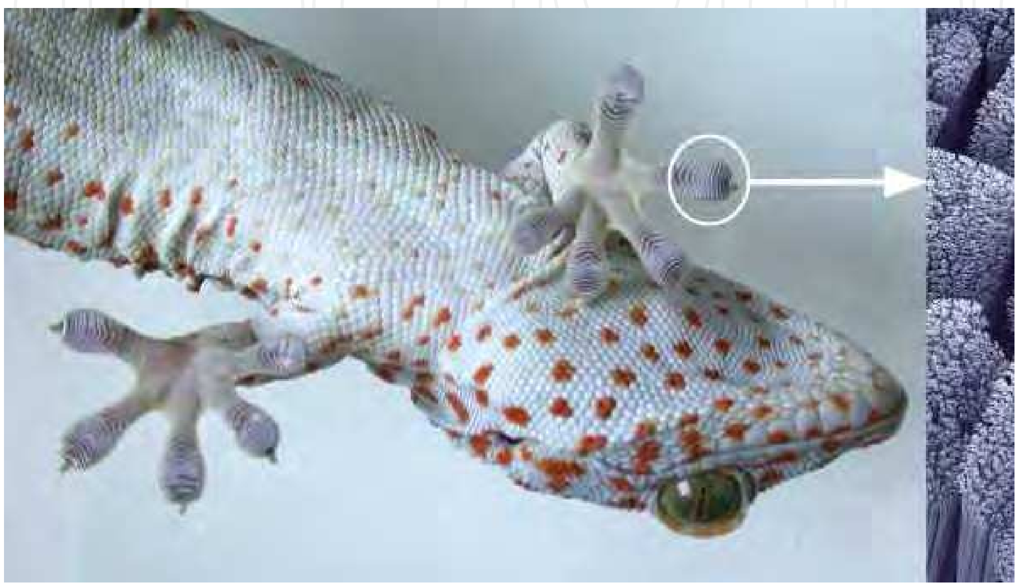

Fig. 15. Detail of the gecko foot (Wikipedia (Last Acessed: October 1, 2009))

Since dry adhesion is caused by van der Waals forces, surface chemistry is not of great importance. This means that dry adhesion will work on almost any surface.

Dry adhesion is more robust than the suction adhesion mechanism. If the dry adhesion pad encounters a crack or gap, there will still be adhesion on the parts of the pad that have made contact. This behavior allows a robot, using dry adhesion, to climb on a wider variety of surfaces. Also, since dry adhesion does not rely heavily on the surface material or the atmosphere, it is suitable for use in the vacuum of space as well as inside liquid environments

Another benefit of dry adhesion is the speed at which attachment and detachment is possible. The attachment is nearly instantaneous as is the detachment, and they both only depend on the force applied. This leads to almost no delay in the locomotion, thus allowing very fast locomotion speeds. Furthermore, it is not necessary to control the timing of the attachment as critically as with the electromagnetic attachment. There is only the need to exert a pressure against the surface, so the attachment is passive in nature and, therefore, simple to control.

Inspired by these ideas, Menon et al. (2004) presented two alternative methods to replicate the structure of the micro-hairs present at the geckos feet.

The first one is based on the development of a synthetic adhesive. Much like the real gecko material it is expected that, in the future, the synthetic adhesive will be super-hydrophobic and, therefore, will be self-cleaning allowing for long lifetime robots. The nature of the adhesion force is such that no energy is required to maintain attachment after it has been initiated. Therefore, a robot using dry adhesion could hang on a wall indefinitely with no power consumption.

In order to test these synthetic dry fibrillar adhesives inspired in the geckos feet, Menon et al. (2004) developed two different vehicles to show the feasibility of the climbing mechanisms: the first one using legged wheels and the second robot consisting in a tread vehicle with customized tire. The legged-wheeled machine was latter improved by Murphy et al. (2006), giving rise to a small-scale agile wall climbing robot, named Waalbot. The Waalbot is able to navigate over smooth surfaces of any orientation, including vertical and inverted surfaces, taking advantage of adhesive elastomer materials for attachment (Figure 16, left). This robot can climb and steer in any orientation using two actuated legs with rotary motion and two passive revolute joints at each foot. The presented prototype can climb 90^o slopes at a speed of 6 cm/s and steer to any angle.

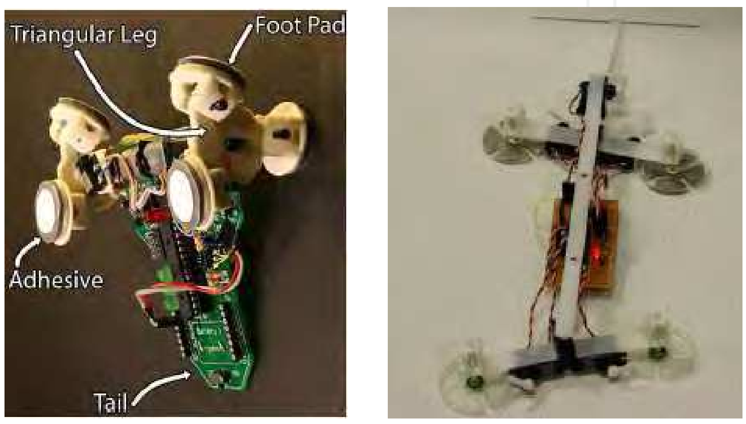

Fig. 16. Photographs of prototype Tri-Foot Waalbot climbing a 90^o vertical surface (left) (Murphy et al. (2006)) and of Geckobot (right) (Unver et al. (2006))

More recently, Menon and Sitti (2005) developed two other climbing robots with different concepts. The first robot, called the Rigid Gecko Robot (RGR), was designed for operating both in Earth and space environments. Reliability and robustness were the most important requirements for the RGR. It was a relatively large robot actuated by conventional motors. The second robot, called the Compliant Gecko Robot (CGR), was designed using unconventional technologies, allowing its miniaturization up to a few centimeters scale and was designed for terrestrial applications. The CGR prototype had a composite structure and its Gecko mimicking locomotion relies on shape memory alloy wire actuators. Unver et al. (2006) developed the climbing robot Geckobot (Figure 16, right) based on these two. The robot has an overall weight of 100 grams (including the electronic board) and featuring a peeling mechanism for the robot feet, since this aspect is very crucial for climbing robots power-efficient detachment (as seen in geckos). Geckobot can climb up to 85^o stably on Plexiglas surfaces. However, it was verified that beyond this angle stability diminishes abruptly.
The fibrillar adhesive presented by Menon et al. (2004) is still under development and does not achieve yet as high performances as other soft and dry adhesives. Synthetic gecko adhesive was tested and compared to soft adhesives such as Silly Puttyï£¡ and flat polydimethyl siloxane (PDMS). It was experimentally verified that Silly Puttyï£¡ exerts the highest normal adhesive force and, therefore, it was chosen for testing their robotic application (Menon and Sitti (2005)). For testing the Geckobot it was used the PDMS adhesive (Unver et al. (2006)). Although PDMS is a stable material, it is degraded and contaminated by dust and dirt. Therefore, after some time it looses its adhesive characteristics. This problem would be improved by using micro-patterned PDMS, in order to have self-cleaning characteristics like geckos (Unver

et al. (2006)). For testing the Waalbot, Murphy et al. (2006) equiped the robot feet with polymer adhesive material (Smooth-On Vytaflex 10), which shares many performance characteristics with the envisioned dry adhesive material. As the adhesives used on the feet of the robot gather dust and other contaminants their performance degrades quickly. Therefore, these adhesives are not suitable for dirty outdoor environments, walking across indoor floors, or for long term tasks.

5.2 Climbing Robots Using Micro-structured Polymer Feet

Daltorio et al. (2005) converted Mini-Whegsï£¡ (Figure 17, left), a small robot that uses four wheel-legs for locomotion, to a wall-walking robot with compliant, conventional-adhesive feet (5.4 cm by 8.9 cm, 87 grams). The feet are bonded to contact areas on the ends of the spokes and the flexibility of the feet acts as a hinge between the feet and spokes. The feet contact the substrate, bend as the hub turns, peel off the substrate gradually, and spring back to their initial position for the next contact. These researchers report that the Mini-Whegsï£¡ 7 can climb glass walls and walk on ceilings, and perform transitions between orthogonal surfaces, using standard pressure sensitive adhesives. The main problem with this approach (although some tests were made to find the best foot design and adhesive tape contact area (Daltorio et al. (2007))) is that after some runs, the robot falls with increasing frequency as the tape becomes dirty or damaged.

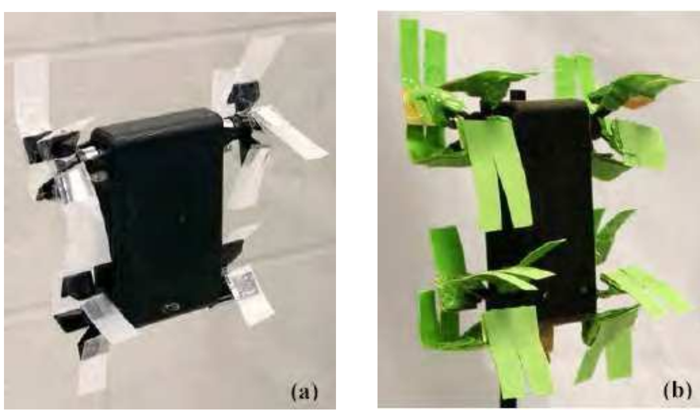

Fig. 17. Mini-Whegsï£¡ 7 on vertical glass (a) with office tape feet and (b) with micro-structured polymer feet and 25 cm long tail (tail not shown) (Daltorio et al. (2006))

Further developments of this robot, reported by Daltorio et al. (2006), lead to the replacement of the feet with a novel, reusable insect-inspired adhesive (Figure 17, right). Two polymer samples were tested: a smooth one and an insect-inspired surface-structured one. The reusable structured polymer adhesive presents less tenacity than the previous adhesive, resulting in an inferior climbing capability. However, after the addition of a tail, changing to off-board power, and widening the feet, the robot was capable of ascending vertical surfaces using the novel adhesive. Comparing with the previous approach, the polymer feet retained their traction/adhesive properties for several hours of testing and could be renewed by washing with soap and water.
While the current robot only walks on clean smooth glass, a practical climbing robot should be able to traverse rougher surfaces as well. This requires adhesives to be resistant to dust and to oils. Additionally, alternative attachment mechanisms, such as insect-like claws or spines, could be added to take advantage of surface roughness.

Based on these ideas, Wei et al. (2006) added claws, spines, and compliant ankles to Mini-Whegs, which allowed the machine to climb on soft or porous surfaces. The new front wheel-legs have each three spokes, with a foot (tarsus) connected at the end of each spoke.

5.3 Climbing Robots Using Microspines

According to what has been described, none of the above approaches is suitable for porous, and typically dusty, building surfaces such as brick, concrete, stucco or stone.
Inspired by the mechanisms observed in some climbing insects and spiders, Asbeck et al. (2006) developed a technology that enables robots to scale flat, hard vertical surfaces, including concrete, brick, stucco and masonry, without using suction or adhesives. The scheme employs arrays of miniature spines that catch on surface asperities. Unlike the claws of a cat, small spines do not need to penetrate surfaces. Instead, they exploit small asperities (bumps or pits) on the surface.
According to these authors, as spines become smaller it is possible to ascend smoother surfaces because the density of useable spine/asperity contacts increases rapidly. However, it is needed a large number of spines because each contact sustains only a limited force. Therefore, the key design principles behind climbing with microspines are to ensure that (i) as many spines as possible will independently attach to the asperities, and that (ii) the total load is distributed among the spines as uniformly as possible.
The above principles have been demonstrated in a 0.4 kg climbing robot, named Spinybot, that readily climbs hard surfaces such as concrete, brick, stucco and sandstone walls (Asbeck et al. (2006)). The robot has six limbs, and each one is an under-actuated mechanism powered using a single actuator in combination with passive compliance, which is responsible for engaging and disengaging the spines. A seventh actuator produces a ratcheting motion that alternately advances the legs in each of two tripods up the wall. Each feet of the Spinybot consists of ten planar toe mechanisms with two spines per toe. The mechanisms are created using a rapid prototyping process that permits hard and soft materials to be combined into a single structure. As shown in Figure 18, each toe includes several hard members, connected by soft links, with the spines embedded in the hard plastic. Each toe mechanism can deflect and stretch independently of its neighbors. This maximizes the probability that multiple spines, on each foot, will find asperities where they can "grab" and share the robot load.

6. New Architectures for Climbing Robots

New architectures have also been proposed for climbing robots in order to allow them to surpass different specific problems and applications.
In most cases, large, clumsy gantries are necessary to guarantee access for cleaning staff, or climbers are hired at great cost, to clean the glass of the inner side of atriums and glass roofs. Therefore, this is an application suited to the use of climbing robots. However, the main problem is finding a means to safeguard the robot against falling. Moreover, it is extremely difficult for technical personnel to reach the robot and repair it, in the event of malfunctioning. With these ideas on mind, Elkmann et al. (2002) proposed a balloon-based robot for cleaning the inner side of atriums and glass roofs (Figure 19). The solution proposed by the researchers for automating this particular task, consists of a two-legged walking mechanism, with suction cups in contact with the glass, being the balloon guided by the walking mechanism along the roof.
This system consists of a cigar-formed, helium-filled balloon with a walking mechanism and a cleaning tool located at the front end of the balloon. At the other end of the balloon are

Fig. 18. View of upper section of Spinybot on concrete wall and detailed view of a toe on the foot (Asbeck et al. (2006))

Fig. 19. Balloon-based robot consisting of a walking mechanism and a cleaning tool (Elkmann et al. (2002))

modules like the control box, a water tank, and other systems for weight compensation. The balloon serves to lift the walking mechanism and the cleaning tool up to the glass surface. The robot cannot fall down and, if it is somehow damaged, the robot can be recovered by personnel by simply pulling the cables to the balloon down.
Shores and Minor (2005) presented a morphic bipedal robot with hybrid locomotion, combining the benefits of rolling, walking, and climbing locomotion (Figure 20).

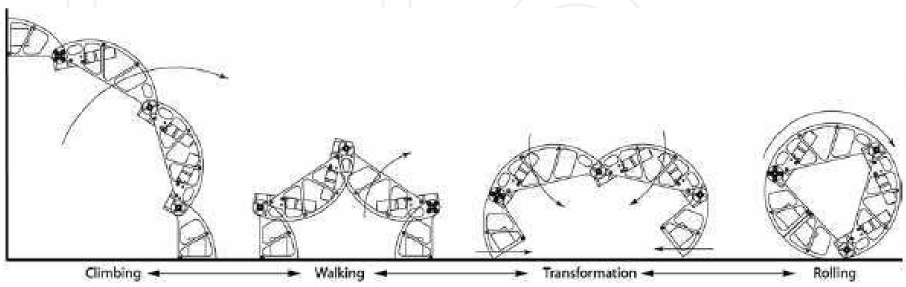

Fig. 20. A hybridized robot transitioning between climbing, walking, and rolling (Shores and Minor (2005))

The design provides these locomotion primitives without the addition of actuators, beyond those required for climbing through the use of a disklike exoskeleton that provides a rolling surface. The feet are equipped with electromagnets that allow the robot to anchor each foot to a ferrous climbing surface. These magnetic feet are centered in the footprint of the exoskeleton to distribute the force of the magnet over a larger area and enable the magnets to support larger moments than they could normally.
Degani et al. (2007) introduced a climbing robot mechanism, which uses dynamic movements to climb between two parallel vertical walls (Figure 21). This robot relies on its own internal dynamic motions to gain height. One benefit of this mechanism is that it allows climbing with only a single actuated degree of freedom.

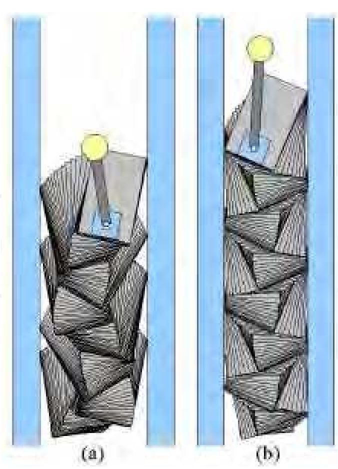

Fig. 21. Two typical motions of the dynamic climbing robot (the main body is traced over time) (a) Purely dynamic (single support) and (b) Double support. (Degani et al. (2007))

7. Conclusions

Considering the severity of many environments where there is the need for human labor, the exploitation of wall-climbing robots has undoubtedly a broad prospect. The main intended applications of these machines ranges from cleaning to inspection of difficult to reach constructions.
Up to now, considerable research was devoted to these machines and over 200 prototypes aimed at such applications had been developed in the world by the year 2006. Nonetheless, the application of climbing robots is still limited. Apart from a couple successful industrialized products, most are only prototypes and few of them can be found in common use due to unsatisfactory performance in on-site tests.
To make wall-climbing robots a popular replacement of manual work, indispensable prerequisites are an high reliability and high efficiency, and, on the other hand, affordable prices. The fulfilment of these requirements is still far, which indicates that there is yet a long way of development and improvement.
Given these considerations, this chapter presented a survey of several climbing robots, adopting different technologies for locomotion and for the adhesion to surfaces. Several possible applications of the presented robots have also been discussed. A special emphasis has been given on the new technologies (mainly biological inspired) that are presently being developed for the robots adhesion to surfaces.

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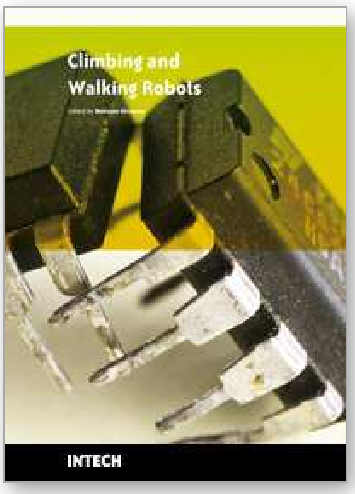

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Nowadays robotics is one of the most dynamic fields of scientific researches. The shift of robotics researches from manufacturing to services applications is clear. During the last decades interest in studying climbing and walking robots has been increased. This increasing interest has been in many areas that most important ones of them are: mechanics, electronics, medical engineering, cybernetics, controls, and computers. Today's climbing and walking robots are a combination of manipulative, perceptive, communicative, and cognitive abilities and they are capable of performing many tasks in industrial and non- industrial environments. Surveillance, planetary exploration, emergence rescue operations, reconnaissance, petrochemical applications, construction, entertainment, personal services, intervention in severe environments, transportation, medical and etc are some applications from a very diverse application fields of climbing and walking robots. By great progress in this area of robotics it is anticipated that next generation climbing and walking robots will enhance lives and will change the way the human works, thinks and makes decisions. This book presents the state of the art achievments, recent developments, applications and future challenges of climbing and walking robots. These are presented in 24 chapters by authors throughtot the world The book serves as a reference especially for the researchers who are interested in mobile robots. It also is useful for industrial engineers and graduate students in advanced study.

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