New Technologies for Climbing Robots Adhesion to Surfaces [⋆]

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Abstract: The interest in the development of climbing robots is growing steadily. 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. Climbing robots have already been developed for applications ranging from cleaning to inspection of constructions difficult to reach. These robots should be capable of travelling over different types of surfaces, with different inclinations, such as floors, walls, ceilings, and to walk between such surfaces. Furthermore, they should be able of adapting and reconfiguring for different environment conditions and to be self-contained. Regarding the adhesion to the surface, the robots should be able to produce a secure gripping force using a light-weight mechanism. This paper presents a survey of different technologies proposed and adopted for climbing robots adhesion to surfaces, focusing on the new technologies that are recently being developed to fulfill these objectives.

Keywords: Robot, climbing, adhesion, suction, magnetic.

1. INTRODUCTION

Climbing robots are useful devices that can be adopted in a variety of applications like maintenance, building, inspection and safety 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.

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.

Up to now a lot of research has been devoted to wall climbing robots and various types of experimental models were already proposed. The major two issues in the design of wall climbing robots is their locomotion and adhesion methods.

With respect to the locomotion type, three types are often considered: the crawler type, the wheeled type and the legged type. 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.

According to the adhesion method, these robots are generally classified into three groups: magnetic, vacuum or suction cups and gripping to the surface. Recently, new methods for assuring the adhesion, based in biological findings, have been proposed. The magnetic type principle implies heavy actuators and is used only for ferromagnetic surfaces. 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.

Bearing these ideas in mind, the paper is organized as follows. Section two presents several climbing robots applications. Sections three and four present the locomotion principles, and the conventional technologies for adhering to surfaces that these robots adopt, respectively. Section five introduces some new, biological inspired, technologies for climbing robots adhesion to surfaces and, finally, section six 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 technical inspection, maintenance and failure, or breakdown diagnosis in dangerous environments. These tasks are necessary in the outside of tall buildings, bridges (Robert T. Pack and Kawamura (1997); Balaguer et al. (2005)), nuclear power plants (Savall et al. (1999)) or pipelines (Park et al. (2003)), wind turbines (Rodriguez et al. (2008)) and solar power plants (Azaiz (2008)), for scanning the external surfaces of gas or oil tanks (Park et al. (2003); Longo and Muscato (2004b)) and offshore platforms (Balaguer et al. (2005)), for performing non-destructive tests in industrial structures (Choi et al. (2000); Kang et al. (2003)), and also in planes (Backes et al. (1997); Robert

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T. Pack and Kawamura (1997); Chen et al. (2005)) and ships (Robert T. Pack and Kawamura (1997); Armada et al. (2005); Sánchez et al. (2006)). Furthermore, they have been applied in civil construction repair and maintenance (Balaguer et al. (2005)), in the prevention and fire fighting actions, in anti-terrorist actions (Li et al. (2007)), in cleaning operations in sky-scrapers (Elkmann et al. (2002); Zhu et al. (2003); Gao and Kikuchi (2004); Zhang et al. (2004)), for cleaning the walls and ceilings of restaurants, community kitchens and food preparation industrial environments (Cepolina et al. (2004)), in the transport of loads inside buildings (Minor et al. (2000)) and for reconnaissance in urban environments (Tummala et al. (2002)). Finally, their application has also been proposed in the education (Berns et al. (2005); Bell and Balkcom (2006)) and human care (Balaguer et al. (2005)) areas.

3. PRINCIPLES OF LOCOMOTION

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

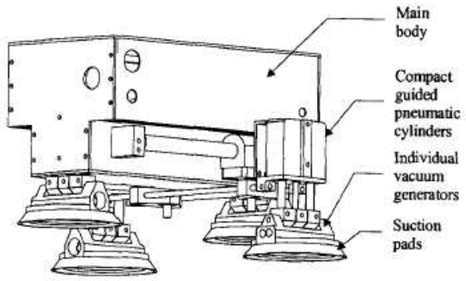

Fig. 1. ROBICEN III climbing robot

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

A final alternative for implementing the locomotion is 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 where they are moving (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 weight and complexity is more adequate. For these reasons the biped structure is an excellent candidate (Figure 3, left). Presently there are many biped robots with the ability to climb in surfaces with different slopes (Robert T. Pack and Kawamura (1997); Tummala et al. (2002); Krosuri and Minor (2003); Xiao et al. (2003, 2004); Shores and Minor (2005); Armada et al. (2005); Balaguer et al. (2005); Brockmann (2006); Resino et al. (2006)). When there is the need for increased safety or payload capability are adopted quadrupeds (Hirose et al. (1991); Hirose and Arikawa (2000); Kang et al. (2003); Armada et al. (2005); Daltorio et al. (2005); Kennedy et al. (2006)) (Figure 3, right) and robots with a larger number of legs (Armada et al. (2005); Inoue et al. (2006); Li et al. (2007)).

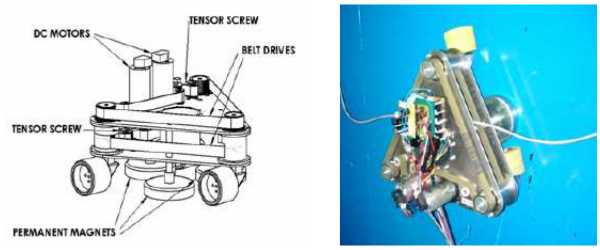

Fig. 2. CAD representation on an wheeled climbing robot (left) and its real aspect (right) (Sánchez et al. (2006))

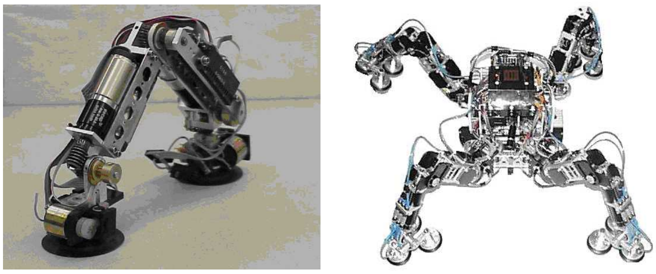

Fig. 3. RAMR1 climbing robot (left) and MRWALL-SPECT III quadruped climbing robot (right)

4. TECHNOLOGIES FOR ADHERING TO SURFACES

In this section are reviewed the main aspects of the three adhesion methods usually adopted in climbing robots: vacuum or suction cups, magnetic and gripping to the surface.

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 is light and easy to control. This operating principle allows to climb 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 irregularities (Hirose et al. (1991)).

This type of attachment has some major drawbacks associated with it. 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. Lastly, 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 drawback is the problem of supplying compressed air. The vacuum can be generated through the Venturi Principle (Savall et al. (1999); Choi et al. (2000); Elkmann et al. (2002); Zhang et al. (2004); Balaguer et al. (2005)) or through a vacuum pump, either on-board the robot (Tummala et al. (2002); Kang et al. (2003); Gao and Kikuchi (2004); Cepolina et al. (2004); Li et al. (2007)), or external to the robot (Zhu et al. (2003)).

RAMR1 is an example of a biped climbing robot, adopting suctions cups for the adhesion to the surface being the vacuum generated through an on-board vacuum pump (Figure 3, left).

When the vacuum is generated through the Venturi Principle or through vacuum pumps, it makes climbing robots noisy (a solution for this 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 equipment. This solution also causes some level of steady, not negligible, energy consumption. Vacuum pumps external to the robot imply the need to a tether cable. Hence, it is desirable to avoid an active vacuum generation and a separate installation for vacuum transportation.

Bearing these ideas in mind, Brockmann proposes the use of passive suction cups (see Figure 4) because they are low cost, simple and robust and allow a light-weight construction of climbing robots. However, although being a promising approach, several aspects related to the behavior of passive suction cups have to be better understood (Brockmann (2006)).

Fig. 4. Passive suction cups without (left) and with (right) a strap (Brockmann (2006))

Another 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)).

Recently, another technology, named Vortex Regenerative Air Movement (VRAM), has been patented. This adhesion system adopts vortex to generate high adhesion forces with a low power.

4.2 Magnetic Force

Another principle adopted for creating the adhesion force, in specific cases where the surface allows it, is the magnetic adhesion. Magnetic attachment can be highly desirable due to its inherent reliability; furthermore, the method is fast but it 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 is an unsuitable choice (Menon et al. (2004)).

The most frequent solution is the use of electromagnets (Shores and Minor (2005); Armada et al. (2005)). Another possibility is the use of permanent magnets to adhere to the surface, combined with wheels or tracks to move along it (Sánchez et al. (2006)). The advantage of this last solution is that there is not the need to spend energy for the adhesion process (Berns et al. (2005)). 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)).

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 and 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 over. These robots typically exhibit grippers (Balaguer et al. (2005)) (Figure 5), or other special designed gripping systems (Linder et al. (2005); Balaguer et al. (2005); Kennedy et al. (2006); Bell and Balkcom (2006); Inoue et al. (2006)), in the extremity of their limbs.

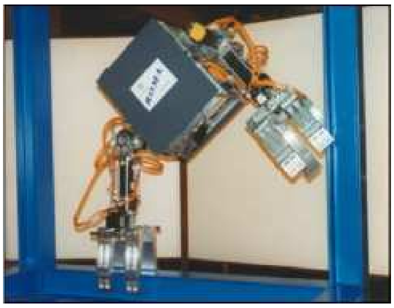

Fig. 5. ROMA1 robot climbing a beam-based structure

5. NEW ADHESION PRINCIPLES

In spite of all the developments made up to this point, the technologies presented are still being improved and no definite and stable solution has yet been found. Therefore, developments continue in this research area.

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

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.

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 geckos ability to stick to surfaces lies in its feet, specifically the very fine hairs (which 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) on its toes. 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.

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 allows for no delay in locomotion, thus very fast locomotion speeds. Furthermore, it is not necessary to time the attachment as critically as with the electromagnetic attachment. Only a force is required, so the attachment is passive in nature, and therefore simple to control.

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

Much like the real gecko material, the synthetic adhesive will be super-hydrophobic and therefore 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, so 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 first of these machines was latter improved by Murphy et al. (2006), giving rise to a small-scale agile wall climbing robot, named Waalbot, able to navigate on smooth surfaces of any orientation, including vertical and inverted surfaces, and using adhesive elastomer materials for attachment (Figure 6, left). Using two actuated legs with rotary motion and two passive revolute joints at each foot this robot can climb and steer in any orientation. The presented prototype can climb 90^o slopes at a speed of 6 cm/s and steer to any angle.

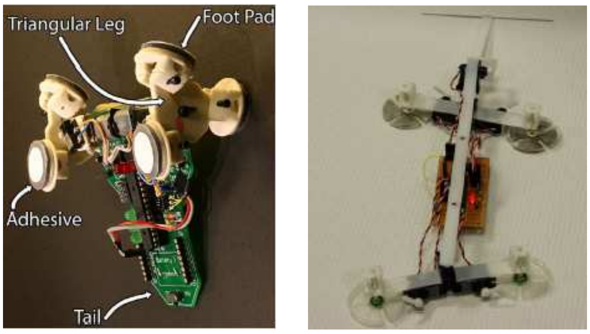

Fig. 6. Photographs of prototype Tri-Foot Waalbot climbing a 90^o vertical surface (left) (Murphy et al. (2006)) and of Geckobot (right) (Unver et al. (2006))

After, Menon and Sitti (2005) developed two other different climbing robots concepts. The first robot, called the Rigid Gecko Robot (RGR), has been designed for operating both in Earth and space environments. Reliability and robustness are the most important requirements for the RGR. It is a relatively large robot actuated by conventional motors. The second robot, called the Compliant Gecko Robot (CGR), has been designed using unconventional technologies which will allow its miniaturization to few centimeters scale and is designed for terrestrial applications. The CGR prototype has a composite structure and its Gecko mimicking locomotion relies on shape memory alloy wire actuators. Latter, Unver et al. (2006) develop another climbing robot, based on these ones, with 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), and named Geckobot (Figure 6, right). Geckobot can climb up to 85^o stably on Plexiglas surfaces. However, beyond this angle stability diminishes abruptly.

The fibrillar adhesive presented by Menon et al. (2004), however, is still under development and does not yet achieve as high performances as other soft and dry adhesives. Synthetic gecko adhesive was tested and compared to soft adhesives such as Silly Putty and flat polydimethyl siloxane (PDMS). It was experimentally verified that Silly Putty exerts the highest normal adhesive force and it was therefore chosen for testing their robotic application (Menon and Sitti (2005)). For testing the Geckobot, PDMS adhesive was used (Unver et al. (2006)). Although PDMS is a stable material, it is degraded and contaminated by dust and dirt within the time. Therefore, after sometime it looses its adhesive characteristics and some properties. This problem would be improved using micro-patterned PDMS to have self-cleaning characteristic 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-Whegs (Figure 7, 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 authors report that this robot 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.

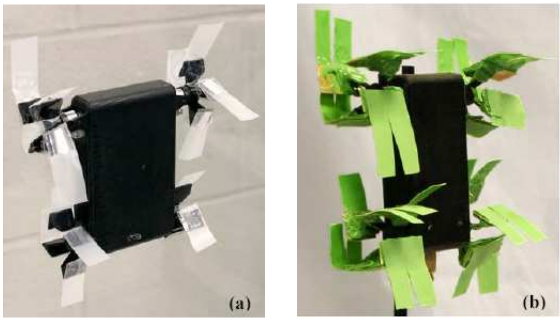

Fig. 7. Mini-Whegs 7 on vertical glass (a) with office tape feet and (b) with micro-structured polymer feet and 25 cm long tail (tail not shown) (Daltorio et al. (2006))

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 7, 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 less 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 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 each have 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. It 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 (i) that as many spines as possible will independently attach to the asperities, and (ii) that 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 compliances, 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 8, 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, to maximize the probability that multiple spines on each foot will find asperities and share the load.

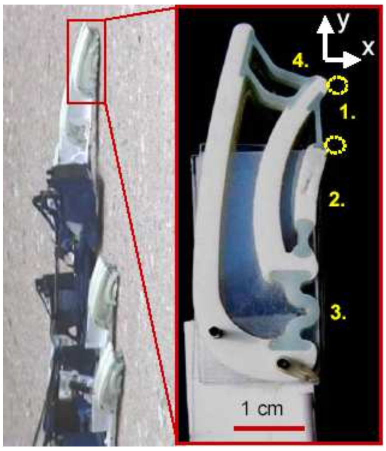

Fig. 8. View of upper section of Spinybot on concrete wall and detailed view of a toe on the foot (Asbeck et al. (2006))

6. CONCLUSIONS

During the two last decades, the interest in climbing robotic systems has grown steadily. Their main intended applications range from cleaning to inspection of difficult to reach constructions. This paper presented a survey of different technologies proposed and adopted for climbing robots adhesion to surfaces, focusing on the new technologies (mainly biological inspired) that are presently being developed to fulfill these objectives.

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