ADHESION TECHNIQUES FOR CLIMBING ROBOTS: STATE OF THE ART AND EXPERIMENTAL CONSIDERATIONS

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Climbing robots are now widely accepted as valid options in situations where it is important to move on sloped or vertical structures in order to inspect, paint, clean or perform the required operations. Even if the first applications of climbing robots appeared more than 40 years ago, many new ideas are continuously being proposed in the scientific literature and in the market.

In this work a classification of the different adhesion techniques proposed for climbing robots is proposed and discussed. Adhesion methodologies can be classified as active when they require an external energy supply to support the robot, or passive if no energy is needed (e.g. permanent magnets or suction cups). Another classification can be done on the basis of the nature of the forces required to support the robot: pneumatic, if the adhesion force is generated by a pressure difference; magnetic if the force is magnetic; mechanical if it depends only on mechanical supports, chemical if it is due to some particular glue, or electrostatic. Moreover within each of these categories, different kind of robots have been proposed in the last years, also on the basis of the locomotion architectures: walking with legs, frame walking, with wheels, sliding, jumping, etc.

Recently biologically-inspired gripping methods, trying in many cases to imitate gecko skin, appeared in several research works. However some doubts remain concerning the applicability of such systems in real applications.

Some critical considerations on the different techniques and on their practical advantages and drawbacks will be exposed and an overview of the different climbing robots developed in the last 12 years at University of Catania is also presented.

1. Introduction

The main challenge of a climbing robot is to fight against gravity. Different approaches have been explored in the last years and new adhesion techniques are continuously proposed in the research literature.

A complete survey on the hundreds of climbing robots developed worldwide is beyond the purpose of this paper, where we will mention only some particular examples of climbing robots, in order to better classify each adhesion technique. An interesting history of many of the original climbing robots developed by the University of Portsmouth, during the last decades is reported in [1], while an overview of some applications of climbing robots for nondestructive testing is described in [2]. A summary of some climbing robots developed in Japan and in China is reported in [3] and [4] respectively; while in [5] a survey of commercial applications is reported.

It is interesting to observe that, although the first examples of climbing robots were developed more than 40 years ago, a recent article published in the prestigious IEEE journal Spectrum, was considering "vertical surfaces and climbing as the new frontier for robotic research"! [6]

Climbing robots are usually adopted in all those sectors where it could be dangerous for human to operate directly. Typical applications areas include inspections, cleaning and maintenance, repairing in industrial and civil structures, but many others have been proposed.

An important step toward the dissemination of knowledge of climbing robots has been established in 1998 through the formation of the CLAWAR network, initially funded by the European Commission and then in 2005 converted to an association [7]. The network, through meetings, newsletters and the organisation of the yearly CLAWAR conference, represents a central point for the dissemination of research activities on climbing robots [8] [9]. In particular the proceedings of the CLAWAR conferences are the main source of reference for the last developments in climbing robots. Several special issues in different journals have been also organised by the network [10].

In the following sections a classification of adhesion techniques by the nature of forces will be exposed and then other classifications based on energy or locomotion typology are proposed. Finally an overview of the different climbing robots developed in the last 12 years at University of Catania is also presented with some concluding remarks.

2. Classification of adhesion techniques by nature of forces

Adhesion is fundamental to climb. Adhesion forces must be able to counteract gravity force caused by the weight of the robot, when the robot is moving upside-down on an horizontal surface, or to generate a vinculum reaction, due to the presence of the adhesion and the friction, when moving on a vertical wall.

Adhesion techniques for climbing robots can be classified with respect to different principles.

The first classification that we propose is done on the basis of the nature of the forces needed to remain attached to the wall. The following typologies have been found into the literature, with a few examples of hybrid solutions:

- PNEUMATIC = When the adhesion force is generated from a difference of pressure.
- MAGNETIC = Valid only on ferromagnetic surfaces, when the force is generated by a permanent magnet or an electromagnet.
- MECHANICAL = When the robot is capable through the adoption of mechanical hinges or hooks to remain attached to the surface.
- CHEMICAL = When particular chemical substances are adopted that generate adhesive forces between the robot and the surface. In some cases the real origin of these forces at a microscopic level is mechanical (since the strong friction of the adhesive is the real nature of adhesion), or electrostatic (if Van der Waals forces are exploited), or sometime pneumatic (micro suction). However for the purpose of this classification these forces are considered at a macroscopic level as chemically generated.
- ELECTROSTATIC = When an electrostatic force is generated between the robot and the surface.

In the remaining part of this section these adhesion methodologies will be reviewed individually and some examples and considerations expressed.

2.1. *Pneumatic adhesion*

This is probably the most adopted method for adhesion in climbing robots. One of the first examples of pneumatic adhesion robots are those systems using classical suction cups, usually adopted for picking parts, as robotic feet. The vacuum can be generated by using an electrical vacuum generator, on board or external to the robot and connected by a pipe, or by using a pneumatic (Venturi effect based) vacuum generator. In this last case a strong consumption of pneumatic energy is required, but neither long vacuum pipes nor heavy electrical vacuum generators on board the robot are needed. These robots moves walking or frame walking, are usually slow in motion and needs some redundancy in the feet, to increase reliability in case of the failure of a suction cup. The surface of the wall needs to be flat enough, clean and non-porous to ensure a suitable sealing of the suction cups. Moreover usually the individual suction cups should not be connected simply in parallel to a vacuum generator, to avoid that the loss of negative pressure inside a single suction cup, due to a leak, is propagated to the other cups, causing a sudden loose in adhesion.

On the positive side there is the possibility for such robots to pass over obstacles and the fact that really cheap systems can be built, since most of the robots can adopt COTS components from pneumatic gripping manufacturers.

Particular examples of this category are the ZIG-ZAG, really simple robot built in University of Portsmouth [11], and the ROBUG II, considered as one of the first example of climbing robot capable to make a transition from floor to wall [12].

Many different other configurations have been realised using suction cups. Among these are really interesting some Japanese examples of robots using tracks of suction cups designed in such a way to be automatically connected and detached from the vacuum generator [62].

Another important pneumatic category of robots are those using a large vacuum chamber and wheels for locomotion by sliding the vacuum chamber. In this case the most important factor is related to the particular sealing that must be adopted between the chamber and the surface. In fact the sealing system cannot be completely hermetic, such in the case of classical suction cups of the previous category, otherwise the robot could not move, but not too weak, otherwise air leakage would be too high and a low pressure difference would result in an insufficient adhesion force. In this case an important advantage is the possibility to climb on not perfectly flat or clean walls (Fig. 1) and to climb over small obstacles (usually lower than 1cm).

Several examples have been realised adopting this principle as the BIGFOOT built by Portech Ltd [13], the CROMSCI robot developed by the University of Kaiserslautern with seven vacuum chambers [14], and many other robots developed by the Harbin Institute of Technology in China [4],[15]. The CROMSCI is rather interesting since it adopts separate chambers that can be excluded from the vacuum generator in case of air leakage.

A particular combination of single modules has been also proposed in the ALICIA 3, to permit this robot to pass over obstacles [16].

A big drawback of these systems is caused by the large amount of power needed to generate the vacuum inside the chamber, since the compensation of the unavoidable loss of air in the leakages is needed. In some cases even an internal combustion engine has been adopted as the power source for the aspirator. The pressure difference to be generated is rather low, since the surface of adhesion is large, however the air flow needed is high.

An important improvement in pneumatic adhesion techniques has been established by Duke University with the adoption of the Vortex technology [17]. This category is similar in principle to the previous one; however no sealing is required between the cup and the surface, since a vortex generated inside the cup creates a pressure difference between the inner part and the outer part of the cup that does not require sealing. In this case a smaller power is required to generate the adhesion force and no friction is present between the cup and the surface.

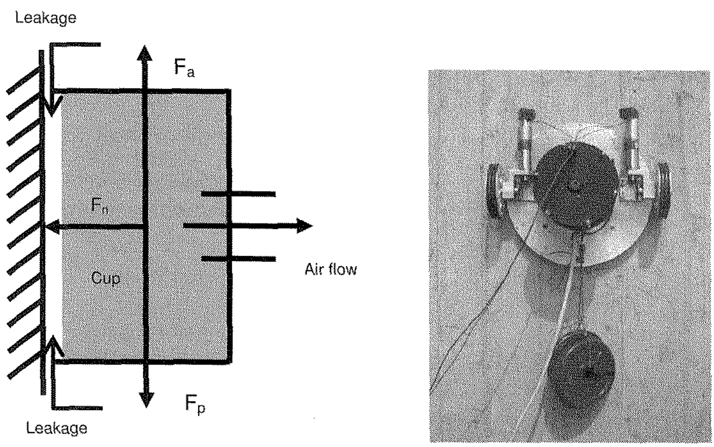


Figure 1. Example of vacuum chamber adhesion. Working principle and test on a not-perfectly-flat wall.

As a consequence faster and completely autonomous robots have been built capable to safely overcome obstacles or leaks in the wall. Moreover these robots are capable to easily transit from the ground to a 90 degrees wall. However at present the physical phenomena is not deeply understood and a precise characterisation of the relations between the power of the vortex generator and the generated adhesion forces has not been done. Only a few examples of small robots exists using vortex adhesion and several doubts concerning the scalability of these systems remain.

Another application of vortex can be done for underwater cleaning robots. In this case the vortex generated by a rotating brush creates an adhesion force that can be exploited to support the robot.

When working underwater it must be considered that the task is simplified by the help of buoyancy forces. An example of this category is the ROBTANK designed for inspecting petrochemical tanks [18].

2.2. *Magnetic adhesion*

Magnetic adhesion is the most reliable form of adhesion that can be adopted when a ferromagnetic surface is available. In fact really strong forces can be generated easily by using rare-earth magnets or strong current electro-magnets. Important applications are the inspection and repairing of ships or surface vessels in general, or storage tanks.

The classification can be done between robots with legs, peeling robots and robots with wheels. Robots with legs have usually electromagnets in the feet that are switched sequentially according to the walking sequence to allow the supporting legs to stay in contact with the surface, while the other legs move. An example of this category is the REST robot designed by IAI-CSIC Spain [19].

In some case to minimise energy, permanent magnets have been proposed connected to magnet circuits mechanically switched. An advantage of this method is the capability to pass over small obstacles but a drawback is the low speed that can be reached and the need to adopt redundant systems to avoid the loss of adhesion of a single foot. Recently another method has been proposed using permanent magnets named as compliant distributed magnetic adhesion [20]. In this case each foot is composed by a matrix of permanent rare-earth magnets connected to a flexible support. An interesting feature of this method is the so-called detachment procedure by peeling.

Magnet robots with wheels can adopt permanent magnetic wheels with the strong advantage to minimise the gap between the magnet and the surface. However, really flat and clean surfaces are needed since the magnets are usually made by hard materials. Otherwise classical mobile robot soft wheels and a permanent magnet at a small distance to the surface can be used.

A serious drawback of the adoption of permanent magnets is caused by the attraction of ferrous dust that little by little is accumulated into the magnets. If long time operations are performed in not really clean surfaces this aspect can determine serious problems to the robot.

Several examples of robots adopting permanent magnets have been realised. An interesting application has been proposed by Cybernetyx with the OCTOPUS robot used to clean surface of ships or by some robots developed by South Bank University London for NDT [21].

2.3. *Mechanical adhesion*

It is the simplest way to remain attached to a surface especially in the case of particularly structured surfaces, or when it is possible to suitably modify the structure.

Many different examples exist and their structure depends from the specific application.

Two examples developed by the Universidad Carlos III de Madrid are the ROMA family of robots, designed to climb on metallic structures using special grippers to move [22], and MATS an assistive personal climbing robot capable to move in three dimensional space [23].

Another interesting category is represented by those robots designed to climb over trees or over or inside cylindrical structures such as pylons, pillars or pipes. An example is the pole climbing robot proposed to climb on palm tree to harvest the palm oil fruit bunch [24].

Recently a bio inspired system has been proposed that uses micro-spines in order to adhere to the micro-irregularities in the surface of the wall. These robots have claws, hard nail-like structures with no compliances that penetrate the climbing substrate, or spines that latch onto small asperities in the surface. Spinybot [25] and RiSE [26] are two examples of this category.

Many other examples of robots adopts ropes to climb on different types of surfaces generating the adhesion force as a resultant of the vinculum reaction caused by the gravity force and the rope traction. For example the ROBOCLIMBER, developed within an European project, is an interesting example of teleoperated climbing robot for slope consolidation and landslide monitoring [27].

2.4. *Chemical adhesion*

In some case simple adhesive tape has been connected to the surface of the feet that are sequentially attached and detached from the surface. However since the adhesive force tend to decrease rapidly after a few sequences, also due to the unavoidable presence of dust, this solution is not really useful in practical applications. It has been also proposed to use automatic tape dispensing systems to replace periodically the adhesive surface, but in any case a limited mobility is present.

Interesting examples are the Mini-Whegs robot [28], the StickyBot [29], and the Waalbot [30].

In the future maybe particular electrically controllable adhesives will be produced, but in any case the accumulation of dust remains a strong obstacle toward their applicability.

2.5. *Electrostatic adhesion*

It is not really completely understood, but it is now well established that the incredible climbing capability of the Gecko lizard over a wide variety of different surfaces and slopes is due also to the presence of van der Waals electrostatic forces [31], [32].

This phenomena has been tried to be reproduced in many robots, however Geckos are biological and have obviously self-cleaning and self-repairing capabilities that are actually far to be reproduced in artificial systems.

In semiconductor industry electrostatic chucks are adopted to produce distributed adhesion to manipulate silicon wafers [33]. However these are adopted in vacuum and with very flat surfaces.

Recently SRI International has proposed an electroadhesion system to control adhesion in climbing robots. This technology involves inducing electrostatic charges on a wall substrate using a power supply connected to compliant pads situated on the robot [34]. A clamping pressure up to $1{,}5 N/cm^2$ to conductive and non-conductive surfaces has been experimented with small power consumption and fast switching capabilities. This is a really promising approach still at a first stage and in the future we will see if this method will outperform all the others.

3. Classification on the basis of the need of energy

Another important classification can be done on the basis of the need of energy to support the robot.

In theory to stay attached to a wall in a fixed position no energy is required. As a consequence several methods can be classified as passive, since do not consume energy to remain fixed. For example robots that adopt permanent magnets, or passive suction cups, or mechanical gripper belongs to this category. These robots can be really useful in all those situations where the system should remain for long periods in a fixed position. Otherwise other robots have been designed that needs a power source to remain attached. For example, robots that use electromagnets, or pneumatic suction cups, or even mechanical grippers connected to electric motors, dissipate energy just to remain in a fixed position. These systems can be classified as adopting *Active adhesion* techniques. It should be observed that we are dealing with the adhesion methods and it does not matter if energy is adopted or not for locomotion. There are also several examples of robots that are active or passive with respect to the locomotion, but in this work we are concentrating on the adhesion methods.

4. Considerations concerning the locomotion methods

Most of the classical locomotion methods proposed for mobile robots have been experimented in climbing robots: Walking, Frame Walking, Sliding, Wheeled, Hybrid, Tracked, Brachiating (arms with grippers) methodologies have been proposed. Some methods are more useful for some typology of forces, some other not.

Another possible classification concerning the locomotion methods of climbing robots regard their level of mobility. In particular there are 1-D mobility robot that move on flat surface or on tracks or ropes, 2-D mobility robot where full motion over a plane is possible and 3-D mobility robots when a full climbing mobility is allowed, for example they are able to perform a transition from a plane to another [10].

Finally it is important to consider a classification in autonomous climbing robots, when the power supply is on-board, and non-autonomous robots when an umbilical cable supplies the power needed. In this last case the capability of movement is limited by the cable, but these robots have greater payload capabilities and there are no limits in the duration of the operations. It must be observed that in many climbing robot applications safety reasons lead in any case to the adoption of a safety rope, to support the robot in case of undesired detachment from the surface. In this last case inserting a power supply cable is not a big problem and considerably increases the capabilities of the system.

5. Experimental considerations

In the Robotic Laboratory of DIEES of University of Catania since 1996 we experimented many different type of robots, here quickly classified and commented in historical order.

5.1. *ROBINSPEC*

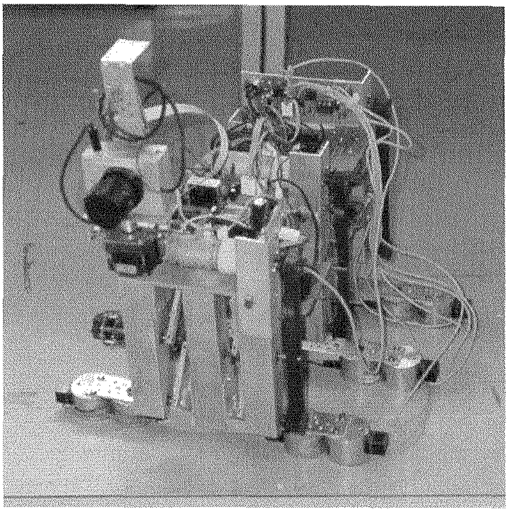
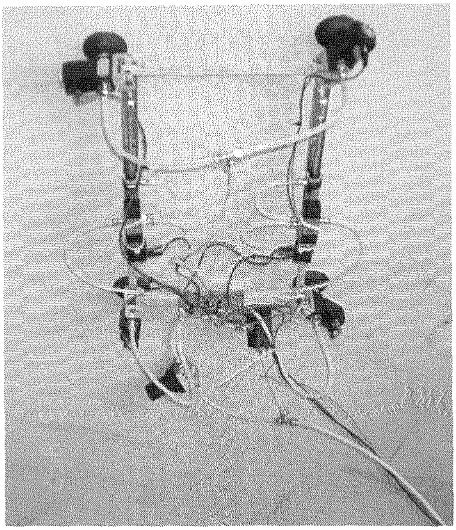


Figure 2. The ROBINSPEC robot with three legs and 12 electromagnets for adhesion.

Magnetic switching, Active, Walking, Autonomous

This robot has been designed for the inspection of petrochemical tanks. An interesting feature was its capability to move by using three legs. During the movement of the legs each motor was responsible for the motion of a single leg, while when the body was moving, all three motors acted concurrently to generate the motion [35], [36], [37].

5.2. *WALLY*



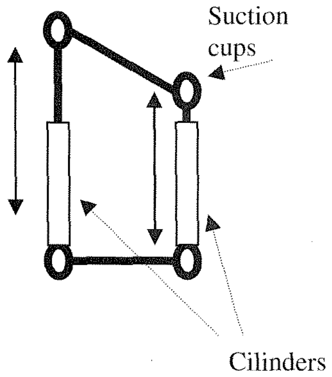


Figure 3. The WALLY robot and its kinematic architecture.

Pneumatic Suction cups, Active, Walking, Non-Autonomous

It represents a very simple and cheap solution for climbing. The main drawbacks were the low speed in movement, the need of an umbilical cable for pressure and vacuum supply and the low reliability in general [38].

5.3. *SURFY*

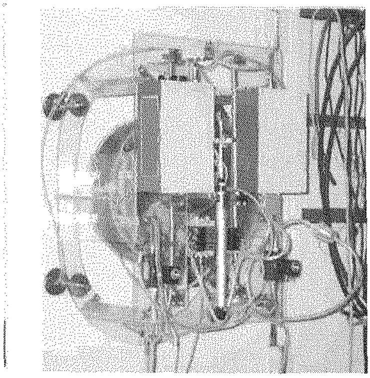
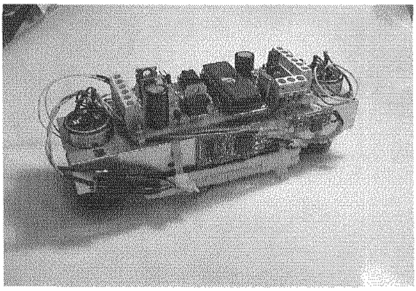


Figure 4. The SURFY robot.

Pneumatic suction cups, Active, Frame Walking, Non-Autonomous

In this classical configuration the chassis was built by using Plexiglas. This fact allowed to reduce cost and weight and also to simplify manufacturing. Accurate design by means of finite element method was performed [39], [40].

5.4. *SCID*



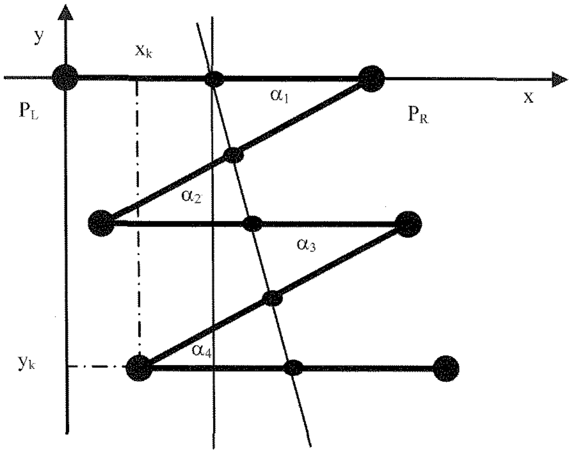


Figure 5. The SCID robot and an example of trajectory.

Magnetic switching, Active, Sliding. Autonomous.

This robot was capable to move passively on a wall. It can go only downwards but no energy is required for the motion. As a consequence it is completely autonomous and very small and lightweight [41], [42].

5.5. *ALICIA 1*

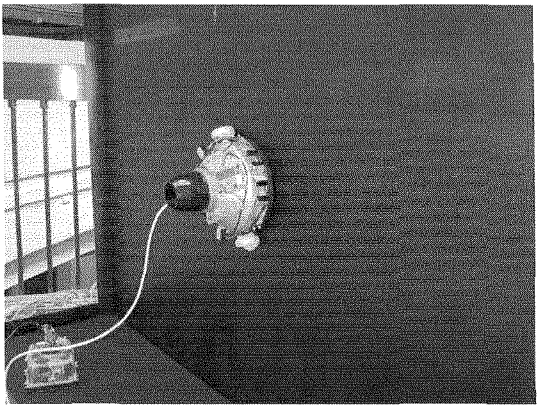


Figure 6. The ALICIA 1 during a climbing robot competition.

Pneumatic Vacuum Chamber, Active, Wheeled, Non-Autonomous

Simple demonstration of climbing robot with a vacuum chamber, designed for the CLAWAR climbing robot competition (Winner in Paris CLAWAR 2002). It has several infrared sensors that permit it to move autonomously avoiding obstacles in the path [60],[61].

5.6. *VENOM*

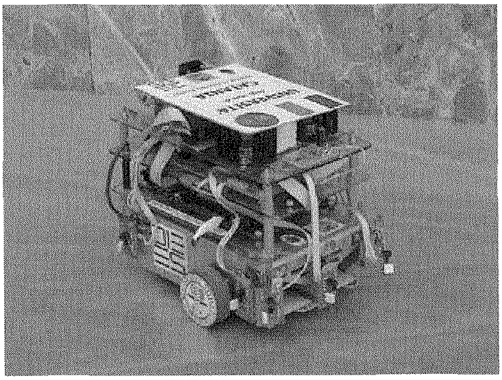
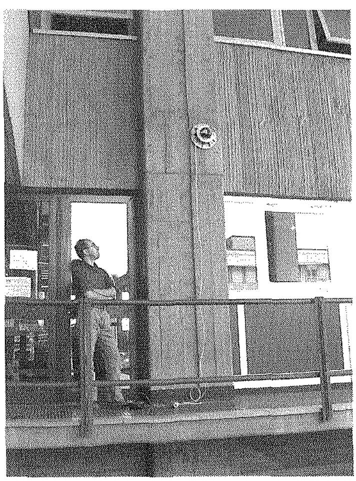


Figure 7. The VENOM robot.

Magnetic Constant Force, Passive, Wheeled, Autonomous.

Another robot designed for the CLAWAR competition (Madrid, 2004). In this case an optical mouse was adopted as odometer in order to localise the robot on the surface. A small rare-earth magnet inserted between the wheels guarantees the needed support force [60], [61].

5.7. *ALICIA 2*



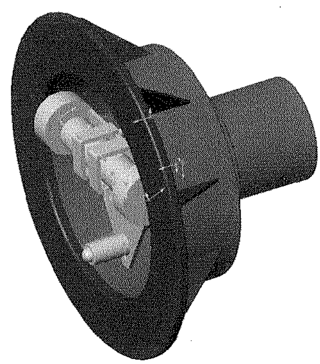


Figure 8. Alicia 2 testing and drawing of an internal view.

Pneumatic Vacuum Chamber, Active, Wheeled, Non-Autonomous.

It is the basic module of vacuum chamber for pneumatic adhesion system. It has been designed as a demonstrator and to perform research activity on the control of the pressure inside the chamber [43], [44], [45], [46], [47], [48].

5.8. *SPIDERBOT 1*

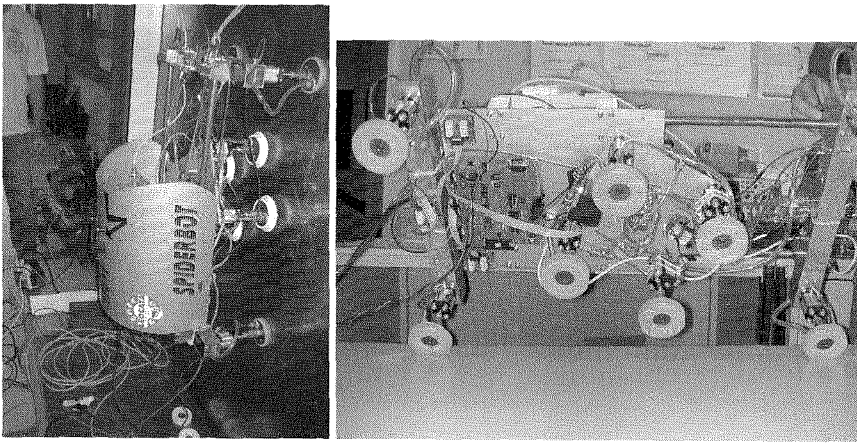


Figure 9. The SPIDERBOT 1 and a view of its eight suction cups.

Pneumatic suction cups, Active, Frame Walking, Non autonomous.

It is an evolution of the SURFY robot with a stronger mechanical chassis and improved control system.

5.9. *ALICIA 3*

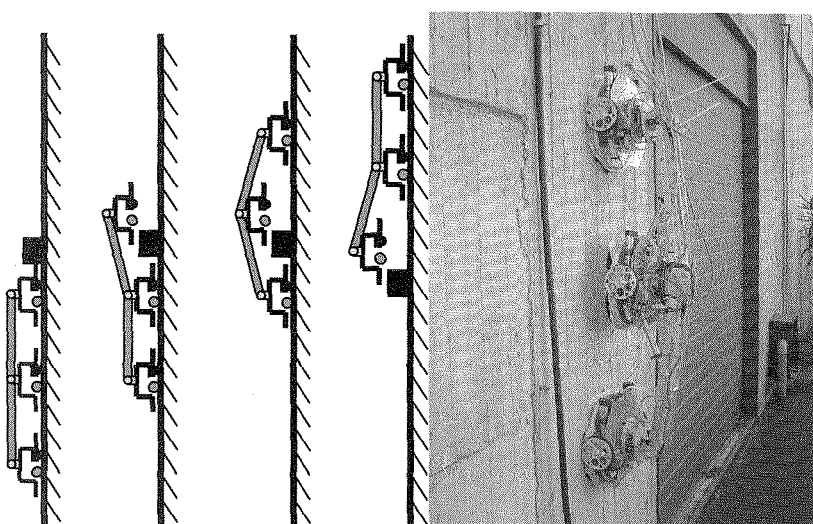


Figure 10. ALICIA 3 working principle and test on a concrete wall.

Pneumatic Vacuum Chamber, Active, Hybrid Wheeled/Walking, Non-autonomous.

Three identical modules connected together by means of two arms. In this way the robot can pass over medium height obstacles [16], [49], [50], [51], [52], [53], [54], [55].

5.10. *SPIDERBOT 2*

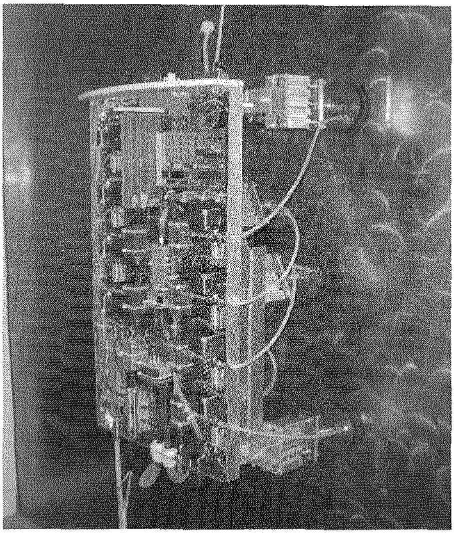


Figure 11. The SPIDERBOT 2 robot is an evolution of SPIDERBOT 1 with a higher payload.

Pneumatic suction cups, Active, Frame Walking, Non-Autonomous

It is an evolution of the SPIDERBOT 1, more reliable with larger payload capabilities and stronger mechanical construction.

5.11. *ALICIA VTX*

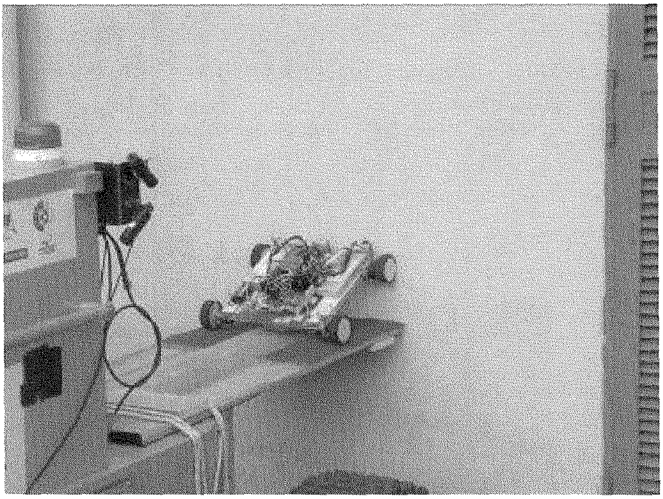


Figure 12. The ALICIA VTX robot during a horizontal/vertical transition in cooperation with a mobile robot.

Pneumatic Vortex, Active, Wheeled, Autonomous.

This robot is capable also to move from the floor to a wall, has been adopted also to show the cooperation between a mobile robot and a climbing robot [56],[57].[58].

6. Conclusion

If we consider a matrix when we put on one axis the nature of the adhesion force and on another the locomotion typology and inside the cells an example of a robot, the following classification can be obtained:

Table 1. Adhesion force type versus locomotion architecture.

	Pneumatic	Magnetic	Mechanical	Chemical	Electrostatic
Wheeled	[43]	[21]	[64]	??	??
Walking	[12]	[19]	[25]	[29]	[34]
Frame Walking	[39]	[37]	[27]	??	??
Tracked	[62]	[66]	??	??	??
Hybrid	[16]	??	??	[28]	??
Sliding	??	[41]	??	??	??
Brachiating	[63]	[65]	[22]	??	??

This table could be furthermore divided into several categories for each force typology and with respect to the active or passive nature of the adhesion force.

Many empty cells exist in this table, some of them are impossible to build, some are useless, some are unknown to the authors, but probably some other if experimented could give innovative solutions or suggestions for new typologies.

From this overview it results that climbing robots are a real interesting topic of research in robotics. At present all commercial applications are based on magnetic and on pneumatic adhesion forces; in the future some new and interesting robots will be discovered.

7. Acknowledgments

The authors would like to acknowledge the contribution given to this research by the many students of the Engineering Faculty of the University of Catania that in the last 12 years helped us with their work and their fantasy to the development of all our robots.

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