Development of Climbing Robots with Different Types of Adhesion

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Abstract- There is enormous potential in industrial inspection tasks for climbing robots than can work in hazardous environments, climb on different types of surfaces and enter into very small spaces that have difficult access. For example when cleaning, painting, repairing and diagnostic inspection of walls of general buildings, or performing non destructive testing inspection and maintenance of oil storage tanks, nuclear power plants, petrochemical factories, medical applications etc.

The paper describes several types of robot adhesion in different environments, some of which have been incorporated into wall climbing robot designs. The adhesion methods discussed generate forces with permanent magnets, vacuum suction cups, propellers, needles or grippers, glue or adhesive tape, and Van der waal's effect.

I. Introduction

The design of a climbing robot must consider some of the engineering requirements (control system, ergonomics, umbilical, stability, simplicity, climbing power), the environment (liquid, air), the physics principles (traction, speed, weight, payload, buoyancy, etc.) and the method of adhesion to surfaces (vacuum, magnetic, propeller thrust force, nanotechnology etc.).

The main subject to consider is the climbing power and/or umbilical, which it has a very close dependence for any climbing robot. To reduce the weight of climbing robots it is necessary to have as few systems on board the robot as possible. However, the size and weight of the umbilical increases as now power, control, signal and data cables are required. A large umbilical can cause problems with the motion of the robot and should ideally be soft, light and very thin to minimize the effect on the robot. Also, the umbilical increases the weight of the robot proportional to the length of the cables and hence decreases its payload carrying capacity [1], [2], [3].

For the purposes of driving a wheeled climbing vehicle, high friction is generally desired. A common approximation of force of friction is $F = \mu F_N$. Where, μ is the coefficient of friction. F_N is the normal reaction force, which acts perpendicularly to the contact surface. In practice, this is an approximation but in many situations other factors, e.g., the area of contact, play a role. In a simple system in equilibrium, the friction force should be at least equal to the force due to gravity acting on the mass of the robot to prevent the robot from sliding down a wall.

A. Adhesion Forces for a climbing robot

Wall climbing robots generally use one of six types of adhesion force to stick the robots on the wall.
The most common forces are:

i. Magnetic force
ii. Vacuum suction force
iii. Propeller attraction force
iv. Needles or gripper forces
v. Glue or adhesive tape forces
vi. Van der waal's forces

i. Adhesion by magnetic force

The performance of a climbing robot depends dramatically on the position, direction and type of the magnetic field. The simplest form of magnetic adhesion is by using permanent magnets to obtain a constant force. The force can be actively controlled by using electromagnets or combinations of permanent magnets and electrical coils. Magnetic adhesion is applicable to ferrous materials like steel, iron, nickel, cobalt, and gadolinium.

The most important magnetic property, specifically for the attachment mechanism, is the magnet power. The factors that determine magnet power are its material composition, arrangement of magnets, environmental temperature, and its mechanical strength. There are different types of permanent magnet materials with different properties for different applications, with the most commercially available types:

Neodymium magnets, made from sintered neodymium, iron and small amounts of boron. These are the most common in climbing robot magnets and have the highest energy product of any permanent magnetic material, but they are very expensive and corrode easily.
Samarium-cobalt magnets, these are the second strongest magnetic materials and high magnetic power; the sintered rare-earth magnetic material made of samarium and cobalt. Samarium Cobalt have excellent corrosion resistance and can be used in high temperatures.
Alnico magnets, these are made with Aluminium, Nickel and Cobalt and have higher temperature resistance, but not as strong as the previous two magnets.
Ceramic magnets, these are made from low cost sintered magnetic materials with iron oxide and barium/strontium carbonate. These are the most fragile, least power and only available in simple forms.
Plastic magnets – these are a non-metallic magnets made from polymer, which are a combination of tetracyanoquinodimethane and emeraldine-based polyaniline. They are lightweight and waterproof but have weak magnetic force.
Other factors like temperature or impact also contribute to the magnet's power, if the maximum temperature limit of the material is exceeded, the performance of the magnet will decrease, or extreme temperatures decrease the magnetic flux density or even demagnetize. Magnets are also impact sensitive, breaking easily if they are physically hammered or dropped.

The Neodymium and Samarium-Cobalt magnets have proved to be most useful in climbing robot applications.

ii. Adhesion by vacuum suction force

The definition of vacuum is not precise but it is commonly taken to mean pressures below and often considerably below atmospheric pressure. Essentially it is a difference-in-pressure, or differential, that can be used to do work. The units of measure for positive pressure and vacuum pressure are the same but a "-" sign or the word "vacuum" signifies a negative pressure relative to atmosphere.

Most wall climbing robots use Nitrile rubber suction cups to be able to move or stay on vertical surfaces. The rubber suction cups are used in the robot feet, and these are pneumatically powered to generate a pulling force on the wall by using vacuum ejectors, pumps or air pressure.
The major advantages of this type of climbing robot are that they can transport on structures of different material composition, for instance, ferrous metal, non-ferrous metal and plastics; they have the best prospects of satisfying intrinsic safety requirements for hazardous environments; they have high a power to weight ratio; and they can provide compliant walking over uneven terrain [1].
On the other hand, one of the disadvantages of pneumatic robots is that the vacuum system of the robot requires a clean and smooth wall surface to prevent ejector or pumps from blocking up. The second disadvantage is that the vacuum adhesion method does not guarantee that the robot will remain attached to a surface in the event of pneumatic supply failure.

Types of materials for suction cup

Nitrile: It is the common material for general purpose use; it has good fatigue characteristic and it is suited for most industrial environments and temperatures.
Silicone: It has a very wide temperature range and is suitable for both sub-freezing applications and for elevated temperatures. Silicone is inherently suppler than other rubbers and it seals better on textured

surfaces. Silicone causes problems with painted or plated parts, which means some plants will not allow it to be used.
Conductive Silicone: It provides a conductive path to dissipate static electrical charges which means that electronic components will not be damaged.
Viton: It provides the highest temperature rating but is also harder, so sealing on textured surfaces is affected.

iii. Propeller attraction force

Different techniques are possible to create a climbing robot by propeller; the most recognized technique uses a vortex of air to create a vacuum system. A vortex is a spinning, often turbulent, flow or any spiral motion with closed streamlines. The shape of air or its mass swirling rapidly around a centre forms a vortex.
The dynamics of vortex can be any circular or rotary flow that possesses vorticity. Vorticity is a mathematical concept used in fluid dynamics. It can be related to the amount of "circulation" or "rotation" in a fluid. In fluid dynamics, vorticity is the circulation per unit area at a point in the flow field. It is a vector quantity, whose direction is (roughly speaking) along the axis of the swirl. Also in fluid dynamics, the movement of a fluid can be said to be vortical if the fluid moves around in a circle, or in a helix, or if it tends to spin around some axis. It motion can also be called solenoidal. In the atmospheric sciences, vorticity is a property that characterizes large-scale rotation of air masses. However the atmospheric circulation is nearly horizontal, the (3 dimensional) vorticity is nearly vertical, and it is common to use the vertical component as a scalar vorticity.

A vortex can be seen in the spiralling motion of air or liquid around a center of rotation. A good example of a vortex is the atmospheric phenomenon of a whirlwind or a tornado.
The performance of a vortex can be measured by some parameters,

Airflow: How much air can circulate per unit of time; in litres per second (l/s) or cubic feet per minute (CFM or ft^3/min).
Air speed: How fast can the air move per unit of time; in metres per second (m/s) or miles per hour (mph).
Suction: Vacuum, conventional unit of pressure in Pascal (Pa).
The suction is the maximum pressure difference that the vacuum can create; suction can be measured in Pascal. For example, a typical domestic vacuum cleaner model has a negative suction of about 20 kPa; this means that it can lower the pressure inside the hose from normal atmospheric pressure (about 100 kPa) by 20 kPa. The higher the suction rating, the more powerful vacuum obtains. Higher air speed usually means more effective vacuum force.

iv. Needles or gripper forces

The adhesive technique force with needles or spines is inspired by mechanisms observed in some climbing insects and spiders, with involves arrays of microspines to catch the surface asperities [4]. The method consists of using arrays of a certain number of spines located on the toes of the robot and articulated with multi-link legs. The suspension legs need to maximize the probability that each spine will find a useable surface irregularity and distribute the climbing weight to many spines or grippers.

v. Glue or adhesive tape force

Traditional adhesive tape can support large normal and tangential forces per area. These forces are normally static and most of the tapes are elastics or deformable wet adhesives. The technique has been used for the development a very light climbing robots on vertical glass surfaces. The tapes have significant orthogonal forces to the substrate [5].
This method of adhesion for climbing robots is not usable in industrial environments for safety reasons and the fact that after couple of practical tests the tape becomes dirty or occasionally bent, creased or torn and has to be replaced frequently.

vi. Van der Waal's forces

The Van der waal forces is a dry adhesion tape, it comes from robot surface to contact forces, which act on all materials in contact. It technique is considerable nano-robotic system, which allows precision interactions with nanoscale objects, or can manipulate with nanoscale resolution.

The inspiration comes from the gecko lizard which can climb on walls and ceilings of almost any surface texture. Rather than using it's claws or sticky substances, the gecko is able to stick to the wall through dry adhesion which requires no energy to hold it to the surface and leaves no residue [6]

The gecko's trick to sticking to surfaces lies in its feet, specifically the very fine hairs on its toes. There are billions of these tiny hairs which make contact with the surface and create a huge 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 gecko's secret lies in the structure of these hairs themselves.

B. Climbing robots design using different types of adhesion technique

Wall climbing robot with hydraulic vacuum adhesion

Figure 1 shows a three wheeled triangular robot was developed to investigate sliding suction cups adhering to the wall with vacuum created hydraulically. The sliding suction cups are constructed with a canvas material and a nylon rim to give low sliding friction but a high adhesion force. Suction in the cups is created by using underwater pumps [7], [8]. The drive DC motors are sealed in watertight containers that are air pressurised for safety. The robot mass in air is 5 kg and it can carry an additional payload of 3 kg in water. Power and control signals are transmitted to the robot via a lightweight umbilical cable.

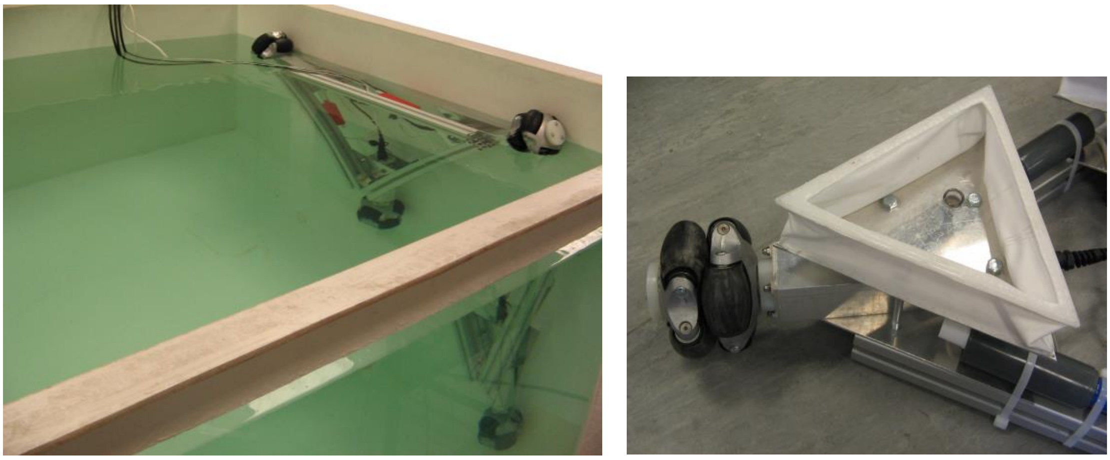


Figure 1 left: Underwater wall climbing robot. Right: sliding suction cup and wheel module.

The robot has very high manoeuvrable with the three independently driven wheels, also provide stable platform with three contact point, which keep a permanent contact with the surface, although changing surface curvature when the robot changes its orientation.

The robot structure is constructed from anodized aluminium links, profiles and brackets. This prototype is modules design that is exactly identical to assemble and disassemble. The objective was to develop a symmetrical robot that can be constructed from the modules in any order thus reducing assembly time. Hence, the full structure of the robot is constructed from identical links, the three motors, three suction cups, three pumps, can be interchangeably placed in the robot and thus will make it very easy to replace and modify the full structure.

Wall climbing robot with permanent magnet adhesion

The robot called WallExplor uses permanent magnet adhesion to climb on ferrous materials. The robot was developed to perform non-destructive testing (NDT) of large vertical steel plates.

It consists of two hinged platforms that enable transfer between horizontal/vertical surfaces and vertical/vertical surfaces (figure 2). During a surface change, one platform crosses over to the new surface while the other platform remains on the old surface (figure 3). Each platform has sufficient magnetic adhesion force to support the robot load at all times. Although this is not necessary when transferring from floor to wall, it is essential when transferring from the corner between two walls. The robot dimensions are 300 x 240 x 200 mm and it weighs 6 kg. Motion is actuated by two 150W DC motors with each motor transmitting drive to all three wheels on one side of the robot with a belt and pulley system.

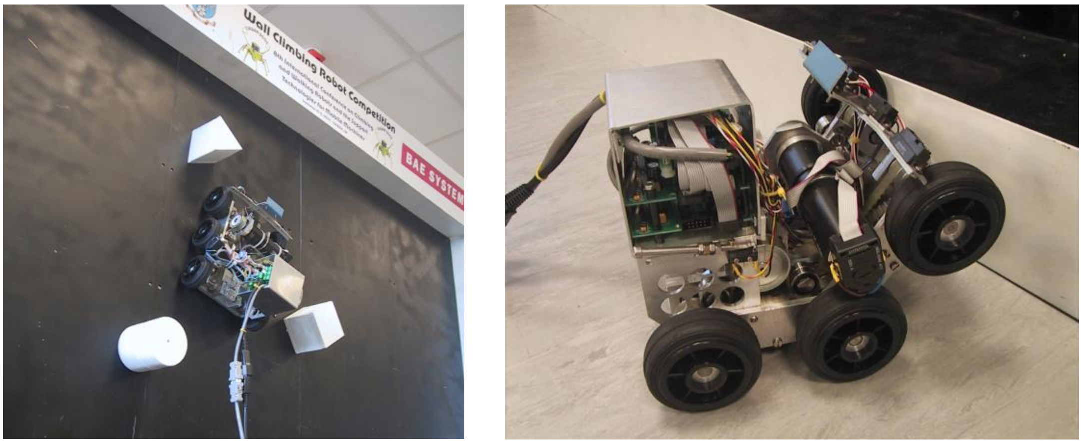
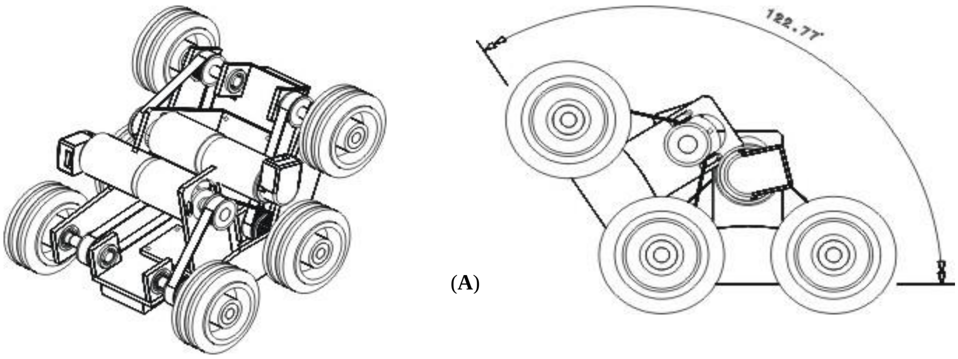


Figure 2. Left: avoiding obstacles by WALLEXPLOR on the competition wall; right: Surface change from floor to wall.

An I/O card and two PIC servo controllers are carried on-board the robot. The robot umbilical is composed of a 24 VDC power supply cable and a twin pair cable for serial RS232/RS485 communications with a PC. The robot can be programmed and tele-operated via this link or it can be switched to a fully autonomous mode. Another twin pair cable remotely sets the parameters and transmits data from an on-board NDT flaw detector back to a PC on the ground for defect imaging.



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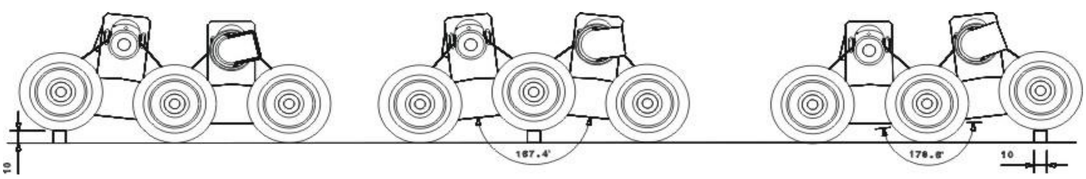

(**B**)

Figure 3. (A) Drawings of Platforms folded during surface transition, (B) Climbing over the one centimetre high and one centimetre wide strip on the wall.

Adhesion to the steel wall is by permanent rare earth disk magnets (Neodymium-Iron-Boron). These are arranged in three rows underneath the three wheel axles. An air gap of one millimetre is maintained between the magnets and the climbing surface. One reason for using the permanent magnets in this

configuration is to develop a magnetic field in the climbing steel plate between each axle. This will enable non-destructive testing of the plate with the magnetic flux leakage method. The other reason for using permanent magnets is that they provide a safe means of adhesion in the event of power loss. Also, while performing the NDT of very large structures such as petrochemical storage tanks, hulls of cargo container ships, steel bridges, etc., it is advantageous to park the robot on the structure and not have to retrieve it during breaks in the inspection.
A gravity sensor indicates when the robot is on the floor or the wall. Two mercury sensors indicate deviation of robot motion from the vertical so that the robot can continue to climb in a vertical straight line after going round obstacles.

Wall climbing robot with vortex-vacuum force

A wall climbing robot with vortex vacuum technique has been developed to provide fast motion on all types of surfaces (e.g. brick, concrete, etc.). The adhesion is by means of a single sliding suction cup with vacuum created with a propeller. A wheeled locomotion system enables fast motion and the robot can climb on nearly any kind of vertical wall surface in an urban environment. A small size and minimal weight enables the robot to easily transfer from the ground to a wall and vice versa. The adhesion mechanism is based on a very small 18.000 rpm motor, which creates a rotating column of air by spinning a rotor with a tiny aluminium propeller. This cylindrical column of air has an interior air pressure that is much lower than the ambient air pressure, and the resultant partial vacuum provides an attraction force generated over the surface.

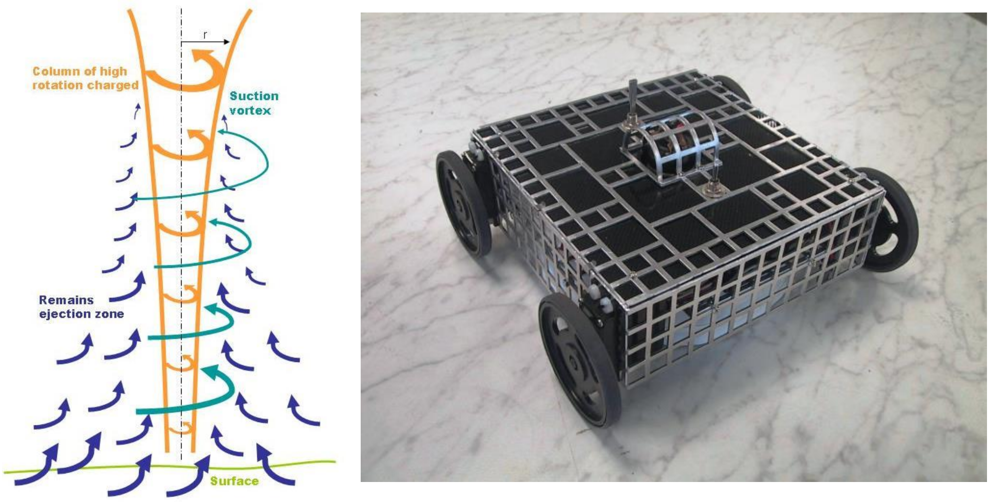

Figure 4. Left: Vortex Phenomenon; right: Wall climbing robot with vortex attraction technique.

The body structure of the robot was made with perforated aluminium (figure 4), to reduce the weight of the robot, and hold the electronics equipments and batteries on board. The drive wheels are four servo motors with 360 degrees of rotation. Each pair of wheels is driven simultaneously to obtain rotation in any direction on its own central spot and move forward and backward. The motors are controlled by a radio control system. The robot can operate for about 30 minutes; it is supplied by two sets of rechargeable batteries.

Climbing robot for wind turbine towers with force gripper adhesion

A portable NDT scanning system is required to detect internal defects in a wind turbine using X-ray tomography technology. In tomography images in the form of spatial X-ray absorption maps of 2 dimensional sections of a test object are produced and three dimension absorption maps are then reconstructed from successive two dimensional tomography images. Such images allow much smaller defects to be detected than are possible with shadow radiography, in which multiple absorption images along successive cross section orthogonal to the X-ray beam are superimposed in the final image, with commensurate loss of contrast. [9]

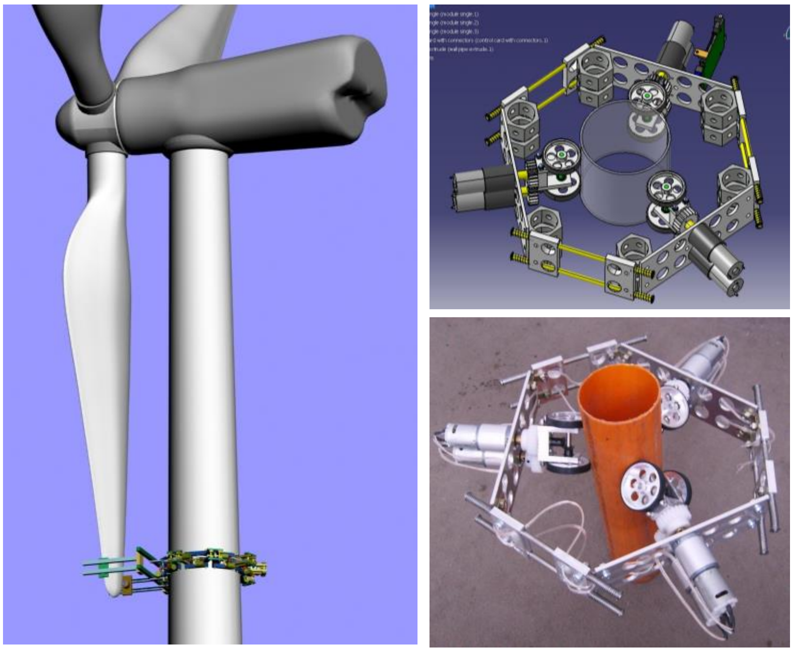

Figure 5. Left: conceptual designs of a wind turbine with a climbing robot. Right: small scale prototype of climbing robot for wind turbine tower with gripper force.

Figure 5 in the left side shows a conceptual design of a wind generator, it is an enormous steel tower with length of about 150 m and about 45 m distance between the hub (centre of rotation) to the end of a wind blade. Moreover, figures 5 in the right side shows a novel ‘crane ring’ climbing robot with a payload capability allowing it to climb around the cylindrical tower and scan the blades in situ with a Cartesian scanning arm.

The principle of this climbing robot uses a gripper force with any number of modules to complete the ring. The main advantage of this design is that all modules will produce the same centripetal force over the tube, which mechanically creates the adhesive force.

A scale prototype to test the gripper force has been built with three modules which are completely identical and can be easily joined together to climb on any circumferential tube. Each module uses two motors, one for the drive motion and the other to turn the angle of the wheel so that the robot climbing trajectory can be spiral, vertically or rotate in its own spot.

The other advantage is that most wind towers have a tapering radius, similar to a conic surface. To prevent slipping, the prototype uses spring forces to grip the tower. Active force control could also be used to adapt to changing radius but this method has not been used here.

C. Conclusions

Developing a climbing robot for remote inspection, non destructive testing or industrial inspection in different environments requires the achievement of several conditions. Some recent climbing robot developments are described that use some of these adhesion technologies to climb vertical structures. The adhesion methods which are suitable for industrial applications are permanent magnets, vortex vacuum, hydraulic vacuum, and force grippers.

D. Acknowledgements

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References

[1] Climbing and Walking Robots' Editors M.O.Tokhi, G.S.Virk and M.A. Hossain, Springer, *Proceedings of the 8thInternational Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines CLAWAR 2005*, Springer Verlag, ISBN -10 3-549-26413-2 ISBN-13 978-3-540-26413-2 99 p.p935-941.

[2] Sattar T.P and Bridge B. (2005) The Centre for Automated and Robotic Non-Destructive Testing, CLAWAR Newsletter, *GROWTH Thematic Network on Climbing and Walking Robotics: Mobile robotic demonstrators and applications*, Issue 14, May 2005, pp 19-24, ISSN 1446-8491

[3] Jizhong Xiao, Ali Sadegh, Matthew Elliott, Angel Calle, Avinash Persad, Ho Ming Chiu, "Design of Mobile Robot with Wall Climbing Capability", *Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Monterey, California, USA, 24-28 July, 2005, pp 438-44

[4] Alan T. Asbeck, Sangbae Kim; William R. Provancher; Michele Lanzetta, "Scaling hard vertical surfaces with compliant microspine arrays", *Robotics Science and System Online Proceedings* http://www.roboticsproceedings.org/, 2007

[5] Kathryn A. Daltorio1, Andrew D. Horchler1, Stanislav Gorb2, Roy E. Ritzmann3, and Roger D. Quinn, "A Small Wall-Walking Robot with Compliant, Adhesive Feet", *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005 p.p 4018-4023

[6] StickyBot robot, Stanford University, http://bdml.stanford.edu/twiki/bin/view/Main/StickyBot, 2007

[7] European CRAFT project RIMINI, "Development of new and novel low cost Robot Inspection Methods for in-service Inspection of Nuclear Installation", Call identifier FP6-2002-SME-1, Co-operative research proposal N°512984

[8] H.E. Leon Rodriguez, T.P. Sattar, J. Shang, A.K. Bouloubasis and Y.P. Markopoulos (2006), "Wall Climbing And Pipe Crawler Robots For Nozzle Weld Inspection Inside Nuclear Pressure Vessels", *Proceedings of the 9th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, September 12 - 14, 2006, Brussels, Belgium, pp 545-551

[9] European CRAFT project CONCEPT-INSPECT, "Computerised Open Environment Portable Tomography", 6th Framework Programme CRAFT COOP-SME: COOP-CT-2006-032949.