CLIMBING ROBOTS FOR NDT APPLICATIONS[[1]](#footnote-1)

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A variety of automated solutions for non-destructive testing have been developed to facilitate in-situ sensing for inspection requirements to ensure safety and effective operation in a variety of hazardous application scenarios. The paper focuses on climbing robot technologies which have been developed to monitor the condition of assets such as concrete pillars, highway bridges, tunnels, wind turbine blades and towers, hull ships, pipelines, nuclear installations, etc. A review of the robot technologies is presented together with a number of climbing robots being developed via magnetic and vacuum adhesion.

Keywords: Climbing robots, adhesion and locomotion, magnetic adhesion, vacuum suction adhesion.

# Introduction

Robotics is a relatively recent technology with the appearance of fixed base industrial manipulators in the 1960s for manufacturing applications where the work piece was brought to the robot for carrying out intended tasks. In the 1980s mobility became important for applications which required in-situ operations and a variety of locomotion techniques have been developed based on mechanisms comprising wheels, tracks, legs, crawlers, etc. As part of developing the needed mobility, the need for climbing robots has become important where the mobility aspects include adhesion as well as locomotion. The EC Network of Excellence on Climbing and walking robots (CLAWAR, www.clawar.org) was set up in 1996 to coordinate efforts to widen the application base for such robots and CLAWAR Association charity continues the work via its mission to advance robotics for the public benefit. The paper focuses on climbing robots which has been central within CLAWAR from the start as climber robots for inspection have been important from the early 1990s. Notable early examples are shown in Figure 1.

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| Fig92_Ninja | Fig2-%20Robug%202s%20transfer |  | Fig132_Robin |  |  |  |
| Ninja | Robug 2 | Bigfoot | Robin | LSBU Robair | Bigsucker | Alicia |
| Fig9a%20-%20Nero3 | Fig12%20-%20Sadie |  |  | Fig62_Heli-pipe | Fig41_Siemans_Pipe |  |
| UoP Nero3 | UoP Sadie | Disk Rover | LSBU Crocells | Heli-pipe | Siemens | Inchworm |

Figure 1 – Examples of climbing robots developed; from left to right; Top row are vacuum suction robots: Hirose’s Ninja, UoP’s Robug 2, Bigfoot, Univ Vanderbilt’s Robin, London South Bank’s Robair, Nishi’s Big sucker, Univ Catania’s Alicia; Bottom row: Magnetic climbing robots: UoP’s Nero3 and Sadie, Hirose’s Disk Rover, LSBU’s Crocells; Pipe climbing robots, ULB’s Heli-pipe robot, Siemens pipe climber, Univ Kosice’s Inchworm.

Climbing robot technology has developed considerably since those early days and a short review is presented in section 2 with some examples developed. Example climbers developed by the authors for NDT applications are presented in section 3 and the paper ends with conclusions and future trends.

# Adhesion Methods

As already stated climbing robots rely on an adhesion methodology to ensure the robot stays attached to the travel surface which can vary in a variety of ways, eg., material, surface texture, environment topology, etc. Applications scenarios can range from climbing on a steep slope, a vertical wall, a ceiling or in/on pipes and some exemplars are shown in Figure 2. Obviously the operational surfaces can be simple and uncluttered to complex and cluttered with static/dynamic obstacles. The operational environments require due consideration so that appropriate climbing solutions can be designed for the adhesion and locomotion requirements.

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| Ramps | Walls | Ceilings | Pipes |

Figure 2 - Example of climbing surfaces/environments for climbing robots

A summary review of the adhesion methods is provided here but it should be noted that these methods need to be coupled with suitable mechanisms to ensure the needed locomotion is also possible. For example, the use of sliding based locomotion is acceptable in flat(ish) operational environments but legged designs with foot-based adhesion may be more suitable for environments with steps and ledges as well as for performing plane transitions.

## Magnetic adhesion

Magnetic based adhesion methods are applicable for ferromagnetic materials where it provides an energy efficient, reliable, adhesive force that can be adopted and utilised in many robotic climbing platforms.

The strength of the adhesion force can be calculated by examining the magnetic characteristics of the climbing surface, the magnetic mechanism used and the distance between the two. The calculated adhesion force must be capable of counteracting the weight of the robot and payload. By studying the magnetic circuit comprising the robot, air gap and the surface being climbed, it is possible to design the needed strength of the magnetic flux in the air gap for the adhesion. Materials are evolving rapidly to provide magnets of great strength.

There are a number of different types of implementation approaches which can be used to employ this adhesion technique for practical applications; these include, magnets plus wheels, magnetic wheels, magnets on caterpillar tracks, magnets on sliding mechanisms or on feet of legged designs, etc. Example designs are presented in Figure 3.

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| Wheeled: Hunter | Tracks. Majic | Sliding: Nero3 | Legged: Wininspec |

Figure 3 - Example of magnetic climbing robots. InnotecUK’s Hunter and Majic for inspection in petrochemical industries, UoP’s Nero3 for nuclear applications, Kamagaluh & Virk’s Winspecbot

## Vacuum suction

Vacuum suction is a widely used method for climbing on non-ferrous surfaces by creating a negative pressure for adhering to the surface being climbed via vacuum chamber mechanism/suction cups mounted on suitable positions such as in wheels, caterpillar tracks, or on feet of legs or on the underside of the robot body. The main design issue is to ensure that the adhesion force is sufficient to hold the robot and its payload onto the travel surface as it moves about. To explain the issues we consider a robot of weight *W* attached to a vertical wall via a vacuum cup as shown in Figure 4 and dimensions as shown. The adhesion force *F* is calculated as the product of the negative pressure in the vacuum cup with the cup area and assume there is a coefficient of friction *µ* between the cup and the wall surface. To prevent the robot slipping down the wall we must have , and to stop it from tipping off the wall we must have . This leads to the important relation  which gives a useful geometric relation to design wall hugging robots which will stay stuck to the climbing wall surface. Such an approach was used by UoP and Portech for designing a large Bigfoot-type robot shown in Figure 4 able to provide a stable anchoring point able to support over 500kg for working on high-rise buildings.

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| Vacuum gripper design | Large Bigfoot for anchoring support |

Figure 4: Designing vacuum adhesion climbing robots

The negative pressure can be generated via a variety of methods such as vacuum pumps, centrifugal impellers or venturi pumps, etc. This concept of designing adhesion vacuum cups can be used with different locomotion methods and some examples are presented in Figure 5.

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|  |  | Image result for vacuum climbing robot omni directional |  |  |
| X-Y sliding | Omni-sliding | Vectored | Tracked (Kim, 2008) | Legged (T. Kang, 2003) |

Figure 5: Exemplar vacuum suction methods and locomotion strategies for climber robots; from left to right; the X-Y sliding robot developed by Zhang, 2006 is used for cleaning the glass walls of the National Grand Theatre in China. It uses vacuum suction to grip onto the glass wall surface via two frames which leads to XY motions when used in sequence; Omni robot developed by Shang, 2007 scales aircraft wings and fuselages via motions in any direction; Vector thrust robot developed by Xiao, 2005 uses aerodynamics to produce a low pressure zone in the enclosed chamber allowing it to cling to the surface and motion is facilitated via motor; the tracked robot developed by Kim, 2008 employs tracks to move it with several suction pads installed on the outer surface of the tracks to allow adhesion onto the climbing surface; the legged robot developed by Kang, 2003 has suction cups installed on legs to allow it to adhere and move on walls with more maneuverability and the ability to traverse obstacles.

# Climbing robots in the literature

Many climbing robots have been developed over the years and reported in CLAWAR conferences over the years; examples are presented in Figure 6. Some have even been commercialized.

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| Plane transitions | Tree/pole climbing | | Serpentine robot | Offshore |

Figure 6: Examples of climbing robots developed; from left to right; Michigan’s Flipper robot able to perform plane transitions like Robin and Robob2 robots; Pennsylvania’s tree/pole climbing robots RISE 2 and 3; Virgina Tech’s serpentine Hydras robot; Tandemech Engineering’s award winning climber for windfarm applications (http://robohub.org/meet-the-winners-of-robot-launch-2014).

# Climbers for NDT applications developed by InnotecUK

Current NDT services require personnel to reach all surfaces of critical infrastructure structures for regular inspection to ensure operational conditions are within design parameters and likelihood of accidents is minimized. The inspection procedures are often cumbersome, dangerous, tedious and expensive. Climbing NDT robots provide an efficient, accurate and better alternatives to the manual techniques presently used within industry. InnotecUK is a company focused on developing robotized inspection solutions and climbing robots form a significant section of the current activities. We present next a few example projects which are underway or have been recently completed to develop innovative climbing robots for NDT applications where the robot must carry the sensing system to in-situ locations to carry out the needed inspections.

## Hunter

Hunter uses magnetic adherence for climbing and operating on ferrous surfaces in inaccessible or hazardous environments such as storage tanks, pressure vessels, pipelines, ship hulls and wind turbine structures. A major design requirement was the ability to carry payloads of around 25kg which covers most commercial NDT equipment so user specified tests could be carried out. Hunter’s ability to climb vertical walls and ceilings while carrying over 25kg has been achieved through the clever and precise engineering of its magnetic wheels. Through extensive research, it was found that the most appropriate and commonly used industrial magnetic material was Samarium Cobalt (SmCo). The wheel diameter and width was calculated to provide 300N adhesion force required to hold the 30kg weight of the robot and its payload. The wheels were engineered to ensure precise arrangement of the permanent magnets separated by copper block spacers around the inner rim. Using this design methodology and a magnetic yoke, the flux strength at the wheels is able to provide the necessary adhesion force required to counteract gravity. High accuracy and high torque Dynamixel motors were employed to control the differential drive system of the robot which allows Hunter to accurately move around and, using suitable localization and NDT equipment, pin point and confirm locations of defects. Figure 7 shows some images of Hunter climbing on various ferrous surfaces for performing NDT inspection tasks and its control unit.

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| F:\paper_photos\hunter.JPG |  |  |  |

Figure 7: Hunter robot climbing on ferrous surfaces for inspection tasks and its control station

## Vortex

Vortex is a vacuum suction based climbing robot developed for inspection of non-ferrous surfaces such as concrete dams, cooling towers, bridges, composites and other construction materials. The suction is created based on a patent by Illingworth and Reinfeld [12] which uses the tornado in a cup principle. For this an impeller is mounted inside a casing so that as it is rotated, the whole fluid swept by the impeller moves as a solid body generating vortical fluid flow in the form of a helical or spiral shaped flow. The fluid flow creates a low pressure region extending from the impeller end of the device which is used to provide adherence. Computational fluid dynamical modelling and simulation studies have been carried out via ANSYS and are presented in Hussain [13]. Vortex uses air suction through a nozzle of specific geometry to provide the vacuum needed to adhere to the surface being climbed. Wheels are added to provide locomotion for the robot as desired. The final design has been optimized via extensive experimental testing and Figure 8 shows the robot moving on various surfaces as well as the control console.

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Figure 8: Vortex climbing on non-ferrous surfaces for inspection tasks and its control system

## RiserSure

RiserSure is a recently started EC funded project focusing on inspection of riser pipelines in oil and gas installations involving operations in deep waters. For the extraction of natural resources at depths greater than 200-300m, a static structure with rigid pipes cannot be used and a surface vessel and flexible riser pipes that connect the sea bed to the production unit and other facilities are needed. Flexible risers are complex structures operating under severe conditions under significant strain so failures need to be prevented and hence the need for inspection. Examples of riser pipelines are presented in Figure 9. A novel subsea digital radiography detector technology has been proposed and a deployment system able to move along riser pipelines is being developed.

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Figure 9: Different riser pipelines considered in Risersure

# Conclusions

Since the early days of climbing robot experimentation and development good advances have been made. The developments need to continue as industry seeks to reduce and limit human involvement in hazardous environments. Magnetic and vacuum suction adhesion technologies are commonly used to give robots the ability to scale a variety of surfaces and locomotion is accomplished using mechanisms such as wheels, tracks, and legs. Currently there are a number of platforms that are commercially available designed to climb surfaces and two such systems, namely Hunter and Vortex have been introduced. The detection of the early stages of critical failure cracks is paramount to avoid the loss of human life, damage of property and the environment. Reliable, efficient and cost effective climbing robots are therefore vitally important within the NDT industry.

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