AUTOMATED NDT ROBOTIC SYSTEM FOR STORAGE OIL TANKS AND NUCLEAR PRESSURE VESSEL

by

Hernando Efrain Leon Rodriguez

A thesis submitted to London South Bank University for the degree of Doctor of Philosophy in Electrical, Computer and Communication Engineering

1st Supervisor:

Dr. Tariq P. Sattar.

2nd Supervisor:

Professor Bryan Bridge

London South Bank University

Centre of Automated, Robotics and Non Destructive Testing

London, UK

August - 2008

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ABSTRACT

This work provides a body of knowledge on climbing and swimming robots and novel application of robots to difficult inspection tasks.

The development of a number of robots is described for industrial non-destructive testing (NDT) tasks where human access is difficult because of large vertical structures, hazardous environments, and location under toxic liquids such as oil and chemicals. These are mobile and wheeled robots that are capable of climbing on large vertical structures such as walls and cylindrical pipes, vessels, chimneys and towers (both on the outside or inside surfaces), on the floors of petrochemical storage tanks and other large horizontal surfaces, operating either in air or while submerged in liquids.

Teleoperated robots deploy NDT probes for the detection of cracks, corrosion, and weld defects using the techniques of ultrasonic phased arrays, ultrasonic plate and creep waves, and alternating current field measurement (ACFM).

The main body of the thesis describes the detailed design, construction, testing and NDT performance of two European funded robotic NDT systems for two different applications but with similar system requirements of buoyancy control, control of thrusters, motion in constrained space to follow weld trajectories, obstacle recognition and avoidance and survival in oil and radiation environments.

The first robot is an amphibious and mobile robotic inspection system that has been developed to test welds located inside a floating production storage oil tank (FPSO tank). The robot has been designed to operate both in air and while submerged in oil to test welds on structural strengthening plates and tank walls. It operates in air when the tank has been emptied with only a few inches of product remaining on the floor. In this case the robot moves on the floor of the tank and inspects welds on the bottom of the strengthening plates and the floor. The robot operates in a liquid by swimming down from a manhole in the roof of the tank and settling on the floor in the vicinity of a test area. In both air and liquid, ultrasonic sensors profile the surrounding strengthening plates and tank walls and guide the robot autonomously along the welds. A Cartesian scanning arm mounted on the robot scans the welds with an ACFM probe and performs NDT inspections (Non Destructive Testing) after the robot has been positioned correctly.

The robot trajectory involves to follow the welds precisely in a constrained space requires motion that is straight-line along the welds, 90º rotations of the robot to follow the weld and present the scanner arm correctly when going from a strengthening plate to a side-wall and back onto the next plate. To achieve this motion, special mechanisms have been designed to rotate all four wheels through turning angles between ± 180º and to independently control all four wheels.

Features of the design that will enable further development for operation in oil and explosive environments are emphasised.

The second robot is called RIMINI (Robot Inspection Method for In-service Inspecting of Nuclear Installation) is an underwater wall climbing robotic inspection system that has been developed for a radiation environment to test circumferential welds located inside pipe nozzles at a distance of 700mm from the inside walls of nuclear pressure vessels. These welds are currently inspected using very large robot arms that are taken into the containment area and assembled. This is a time consuming operation that exposes operators to radiation. A preferred solution is to develop a light weight and compact robot that can be carried into the containment area and inserted into a pressure vessel using an overhead crane. The crane is then removed and used for other tasks. The robot must then be operated to accomplish the weld inspection task in all the pipe nozzles located in the pressure vessel.

PUBLICATIONS RESULTING FROM THIS WORK

11.	Hernando E. Leon Rodriguez, Tariq Sattar, Jianzhong Shang, Underwater wall climbing robot for nuclear pressure vessel inspection, Proceedings of the 11th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2008), September 08 - 10, 2008, Coimbra, Portugal, pages 12, To appear.
10.	Tariq p. Sattar, Hernando E. Leon Rodriguez, Jianzhong Shang, Amphibious Inspection Robot, Proceedings of the 11th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2008), September 08 - 10, 2008, Coimbra, Portugal, pages 8, To appear.
9.	Hernando Leon Rodriguez, Bryan Bridge and Tariq p. Sattar, Climbing ring robot for inspection of offshore wind turbines, Proceedings of the 11th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2008), September 08 - 10, 2008, Coimbra, Portugal, pages 10, To appear.
8.	Hernando Efrain Leon Rodriguez, Tariq P. Sattar, Development of Climbing Robots with Different Types of Adhesion, 24th International Conference, CAD/CAM Robotics and Factories of the Future (CARS & FOF 2008), 29-31 July 2008, Koriyama, Japan, pages 8, To appear.
7.	Tariq P. Sattar, Hernando Efrain Leon Rodriguez, Jianzhong Shang, Shyamal Mondal, Shuwo Chen, Bryan Bridge and Zhangfang Zhao, Mobile wall climbing and swimming robots to inspect aircraft, storage tanks, pressure vessels and large infrastructure, 24th International Conference, CAD/CAM Robotics and Factories of the Future (CARS & FOF 2008), 29-31 July 2008, Koriyama, Japan, pages 12, To appear.
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4.	T.P. Sattar, H.E. Leon Rodriguez, J. Shang, T. Gan and A. Lagonikas (2006), Amphibious Robot For Weld Inspection Inside Floating Production Oil Storage Tanks, Proceedings of the 9th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2006), September 12 - 14, 2006, Brussels, Belgium, pp 533-540
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1.	Sattar T.P., Rodriguez Leon H., Shang J. (2005) Automated NDT Of Floating Production Storage Oil Tanks With A Swimming And Climbing Robot, Proceedings of the 8th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2005), Editors Tokhi, Virk and Hossain, ISBN-10 3-540-26413-2, Springer, ISBN-13 978-3-540-26413-2, pp. 935-942

ACKNOWLEDGMENTS

The author wishes to express his thanks to:

Dr. Tariq P. Sattar, for his great friendly supervision and for giving me the opportunity to be part of the projects (FPSO and RIMINI) that led to the topics in this thesis.

Professor Bryan Bridge, for his advice during the development of the projects and for letting me to be part of the CONCEPT project.

Doctor Jianzhong Shang, for designing the FPSO software and help me with his experience in development of climbing robots.

Doctor Ener Salinas for his enormous friendship and kindly revising and giving corrections to this thesis.

The Nueva Granada Military University in Colombia for sponsoring my Ph.D. studies.

ZENON Company (Greece), for their technical information in both scanning inspection arms.

Mr. Graham R. Edwards, FPSO project manager (TWI), for his information on FPSO NDT results.

Mr. Alan Day, RIMINI, project manager (TWI), for his information on RIMINI NDT results.

My colleges, friends and my family in Colombia, who gave me great support during these years away.

Thanks also go to:

The European Community through the CRAFT project FPSO INSPECT (COOP-2004-508599) with the following partnership: NDT Consultant (UK), TSC Inspection Systems (UK), Isotest Engineering (Italy), Tecnitest Ingenieros (Spain), Spree Engineering Ltd (UK), Miltech Hellas S.A. (Greece), ZENON (Greece), Kingston Computer Consultancy (UK), BP (UK), Petrobras (Brazil) and London South Bank University (UK). The Project was coordinated and managed by TWI (UK).

The European Community through the CRAFT project RIMINI INSPECT (COOP-2004-512984) [4]with the following partnership: Peak-NDT (UK), Vermon (France), TSC Inspection Systems (UK), Trueflaw (Finland), ATG (Czech Rep), Tecnitest Ingenieros (Spain), Mitsui Babcock (UK), NNC (UK), Ignalina (Lithuania), TVO (Finland), Reaktor (Slovakia), CEZ (Czech Rep), ZENON (Greece), London South Bank University (UK). The Project was coordinated and managed by TWI (UK).

ABBREVIATIONS

ACFM	Alternating Current Field Measurement
API Gravity	American Petroleum Institute
BASEEFA	British certification body for equipment intended for use in potentially explosive atmospheres
CARS & FOF	International Conference, CAD/CAM Robotics and Factories of the Future
CCD	Charge Coupled Device
CLAWAR	International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines
COW	Crude oil washes
EC	European Commission - framework 6
ECA	Eddy Current Array
FEM	Finite elements method
FPSO	Floating Production Storage Offloading
FSO	Floating Storage Offloading
GBP	Great British pounds
GUI	Graphic User Interface
ICs	Integrated circuits
HAZ	Heat Affected Zone
IP68	Rated enclosure protection
ITTC	International towing tank conference procedure for resistance, propulsion and propeller open water test
LPS	Local Position System
LSBU	London South Bank University
MAG	Metal Active Gas
MIG	Metal Inert Gas
MSAW	Shielded Metal Arc Welding
NDT	Non Destructive Testing
OCS	Outer Continental Shelf
ORNL	Oak Ridge National Laboratory
PC	Personal computer
PD	Proportional Derivative control
PDA	Proportional Derivative and Adaptive control

PIC	Programmable Intelligent Computer
PID	Proportional Integrate Derivative control
PWM	Pulse Width Modulation control
PWR	Pressurised Water Reactor
RIMINI	Robot Inspection Method for In-service Inspecting of Nuclear Installation
RobTank	In-service Inspection of Oil and Petrochemical Storage Tank
ROV	Remote Operate Vehicle
RPV	Reactor Pressure Vessel
SAW	Submerged Arc Welding
TRLPA	Transmit Receive Longitudinal Phased Array
TWI	The Welding Institution, UK
USB	Universal serial bus
UT	Ultrasonic Testing inspection

SYMBOLS

A_d	Propeller blade area
A/D	Analogue / Digital
β	Pitch angle
B_x	Ultrasonic signal parallel to the metal surface
B_y	Ultrasonic signal perpendicular to the metal surface
β_{tra}	Angle of translation
CFM	Cubic feet per minute
d	Number of blades
D	Propeller diameters
DC	Direct current
e	Thrust efficiency
E_r	Error
g	Gravity
ICs	Integrated circuits
I/O	Input / Output
K_a	Adaptive coefficient
K_d	Derivative coefficient
kg	Kilograms
K_p	Proportional coefficient
l/s	Litres per second
m	Metres
mm	Millimetres
N	Newton
N	Revolution
ρ	Density water
P	Propeller pitch
P/D	Propeller pitch ratio
PP	Polypropylene
PVC	Polyvinyl chloride
PTFE	Polytetrafluoroethylene
Q	Torque

r	radial distance
$rads$	Radiation resistance units
rpm	Revolution per minute
SHP	Propeller’s shaft Horse power
T	thrust
T^o	Water temperature
μ	Coefficient of friction
V	Volts
V_a	Velocity of expelled fluid
V_{rot}	Rotational velocity
V_v	Velocity vehicle
V_{tra}	Translational velocity
W	Watts
z	Number of propellers

Chapter 1: Climbing Robots for Non-Destruction Testing and Inspection

This work has been directed at developing mobile wall-climbing, swimming and amphibious robotic inspection systems to non-destructively test large vertical structures, wind turbine towers and blades, welds located on strengthening plates inside floating production storage oil tanks (FPSO tanks) and inside nozzles emerging from nuclear pressure vessels. In total six prototype robots have been developed.

Performing the inspection of safety critical infrastructure usually requires gaining access to very large structures by erecting scaffolding, abseiling down to test sites, etc., and carrying out special procedures for safe access to structures located in hazardous environments. The time required to carry out the inspection is slowed down as a result and the cost of gaining access is normally much higher than the cost of performing the actual NDT. The inspection can be speeded up and its cost reduced significantly by using compact and versatile climbing robots to gain access to a test site and to perform the NDT [1, 2, 3, 4, 5].

This chapter describes the rationale for wall climbing NDT robotic systems, reports some recent developments to progress such systems, gives a brief history of climbing robots, and discusses issues relevant to the design of climbing robots. To gain further knowledge of climbing robots, the author has developed four prototypes climbing robots, reported in this chapter, that use magnetic force, vortex vacuum, hydraulic vacuum adhesion and gripping forces to adhere the robot to a vertical surface. Two robots that operate underwater are described in chapters 2 to 8. One is an amphibious robot that is designed to swim in liquids or operate in air while the other climbs on the walls of nuclear pressure vessels while submerged in water.

1.1 Wall Climbing NDT Robotic Systems

The rationale for developing wall climbing inspection robots that use NDT techniques for inspection is:

- Bring automation to the NDT task to eliminate errors caused by human operators due to fatigue on jobs that require a great deal of inspection in difficult environmental conditions.
- Improve defect detection by using the ability of robotics to improve sensor probe positioning accuracy and repeatability and use the programmable flexibility of robots to optimally deploy a wide variety of sensor probes and inspection techniques.
- Reduce the cost of performing the inspection by using wall climbing and mobile robots that provide access to test sites that are remotely located on large structures and/or in hazardous environments and hence not easily accessible to humans.
- Reduce costs substantially by performing in-service NDT with robotic deployment of sensor probes thereby eliminating outage costs and production losses.

- Reduce capital equipment costs by developing compact multi-function inspection robots that can flexibly perform a variety of different NDT tasks on different sites. Thus the robots should be readily transportable between different sites, be able to move over floors, change surfaces and climb walls, ceilings and other structures of variable curvature whilst carrying a payload of NDT sensors that can scan test surfaces by deployment with multi-axis arms.

Application areas for automated and robotic NDT are in the inspection of critical infrastructure on offshore oil platforms, nuclear power plant, shipyards, petrochemical and other storage tanks, aircraft, buildings, bridges and railways.

The Centre for Automated and Robotic NDT, London South Bank University has made progress in applying robots to four of these application areas. It has focused on developing wall climbing robots to provide access to large structures in hazardous environments and to deploy NDT sensors for the purposes of defect detection.

Figure 1.1 shows an NDT wall climbing robot that climbs on flat steel walls while carrying a 13.5 *kg* PUMA 260 6-*axis* scanning arm that deploys a 2.5 *MHz* dry contact ultrasonic wheel probe named “RobSbu2” [6]. Depth measurements suitable for the detection of corrosion thinning are performed. A PC based flaw detector displays C-scan images of the scanned material.

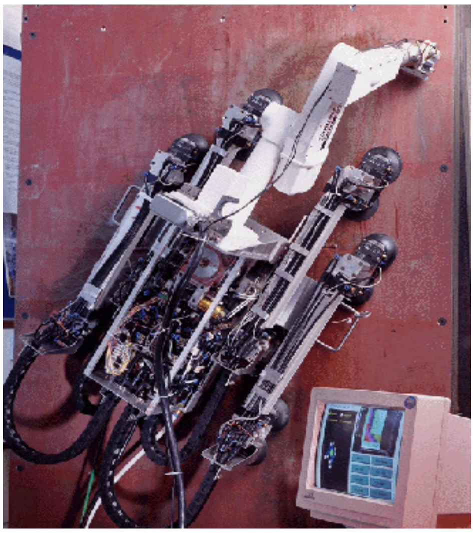

Figure 1.1 Wall climbing NDT inspection robot, RobSbu2.

The climber’s mass is 45 *kg*, dimensions 740 × 700 ×150 mm^3. It can carry a maximum payload of 35 *kg*. It uses vacuum suction cups for adhesion and pneumatic actuators for translation and rotation motion. The umbilical consists of one air tube, a twisted pair for controller communications, one twisted pair for DC supply, and a set of cables for the arm. The total umbilical mass is 0.5 *kg/metre*. Hence, the surplus payload carrying capability of the robot decreases when the robot climbs unless the umbilical is supported in some other way.

Figure 1.2 shows a climbing robot developed by the Centre to inspect nozzle welds on 860 *mm* diameter pipes in the primary circuit of nuclear power plant call “RobNuclear” [7, 8]. The robot can travel all the way round 45 degree nozzle welds while performing contact force ultrasonic NDT with a 23 *kg* 7-*axis* scanning arm. Adhesion to the surface is with vacuum suction cups. The climber’s motion is obtained with pneumatic actuators while the 7-*axis* arm is actuated with electric motors. The robot’s feet are rotated to adapt to surface curvature after each linear step. The seven-axis Robot arm is designed specifically for NDT scanning capability [9]. It is designed to be robust when performing contact NDT and scanning on rigid surfaces that are not known precisely and are located remotely. Couplant tubes for the ultrasonic probes and NDT sensor cables are routed internally through the arm.

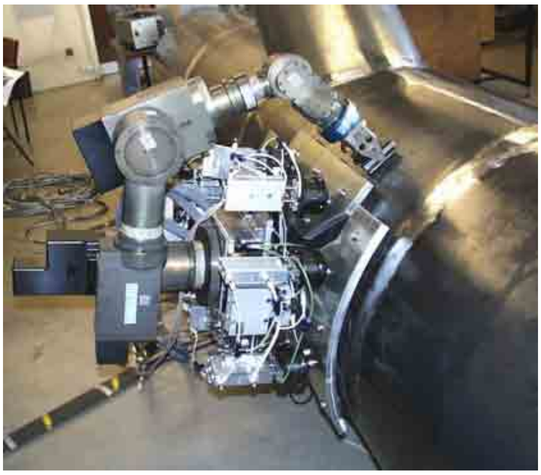

Figure 1.2 Climbing robot to inspect nozzle welds on 860 mm diameter pipes in nuclear power plant, RobNuclear.

Figure 1.3 shows a prototype wall-climbing robot developed by the Centre to inspect welds on the hull of cargo container ships during their fabrication in the dry dock call “RobHull” [10]. The climbing robot uses permanent magnetic adhesion to climb on the hulls of cargo container ships to inspect welds up to heights of 30 *metres* and along 200 *metre* lengths of horizontal weld. The robot is designed to carry payloads of 100 *kg*. A seven axis arm mounted on the robot deploys an ultrasonic sensor.

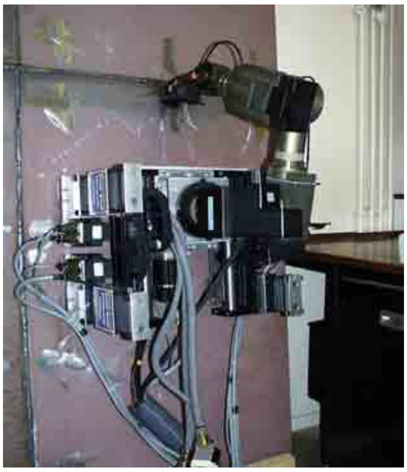

Figure 1.3 Robot for NDT of welds on ship hulls, RobHull.

Figure 1.4 shows a robot developed by the Centre to perform in-service inspection of oil and petrochemical storage tanks while submerged in the product call “RobTank” [11, 12]. The robot can be inserted through 300 *mm* diameter manholes and operates under liquid to inspect storage tank floors and walls. It can make a transition from tank floor to wall and back to the floor. Its mass is 20 *kg*. The payload consists of an infrared camera, four ultrasonic immersion probes, four ultrasonic wheel probes, and two rotating bulkwave probes to give one metre diameter look-ahead capability through the floor plate.

These bulk wave probes are lowered onto the surface and rotated to build a radar map of the floor. This robot was awarded the “Industrial Robot” journal prize for industrial innovation in 2004.

The robot has been tested successfully performing NDT in water on the floor and walls of two storage tanks owned by Petrogal at their refinery in Sines, Portugal.

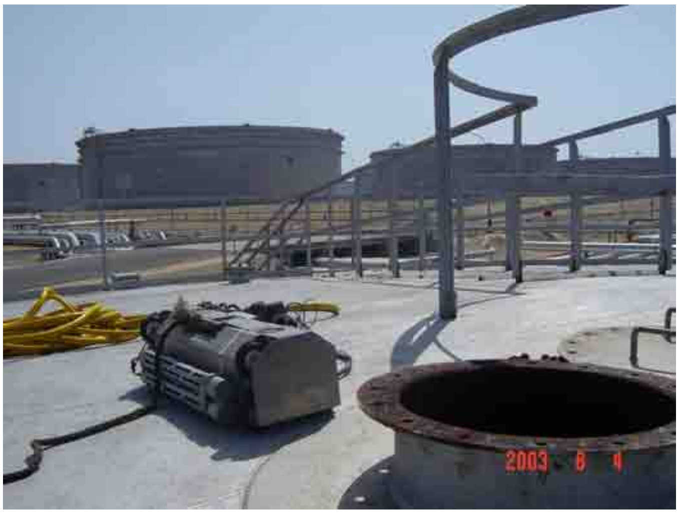

Figure 1.4 Floor and wall climbing robot for the inspection of petrochemical storage tanks, ROBTANK.

For the final tests, the NDT sensors alone were submerged in crude oil to perform NDT of test samples. The next phase of this development will be to obtain intrinsic safety certification for the system.

A robot called RobAir has been developed for the inspection of aircraft fuselage and wings. It uses a hierarchy of universal joints and a flexible structure to enable the robot to adapt to varying surface curvatures. The design consists of two pairs of rodless pneumatic cylinders that can drive the robot motion in two directions. One pair of cylinders, parallel to each other, move together to drive the robot motion along X axis; the other pair drives the robot motion along Y axis.[13]

Two X cylinders are mounted on both sides of a platform called X-platform, while the two Y cylinders are connected by the Y-platform. These two platforms are normal to each other when they are in the neutral position. Between of the two platforms, there is a rotating mechanism driven by a motor. This mechanism adjusts the angle between the two platforms by ±5 *degrees* to correct for off-course deviations.

On the two ends of each cylinder, there are two "*leg*" cylinders to drive the feet up and down, these feet are mounted on the ends of the *X* cylinders and they are located at the four corners; the feet that are mounted on the ends of the *Y* cylinders, they are extended to the edges of the robot to increase the capability of anti-overturning moment. Each foot is constructed of a plate with four small suction cups (figure 1.5).

This robot climbs by stepping gait with two groups of feet working alternatively. When outer group adhere the robot to the surface, the *X* or *Y* cylinders drive the inner group moving one cylinder stoke distance in *X* or *Y* direction respectively, and them they change to the inner group to adhere the robot and left the other group of foot move. The two groups of feet work alternatively in such a way that the robot moves step by step.

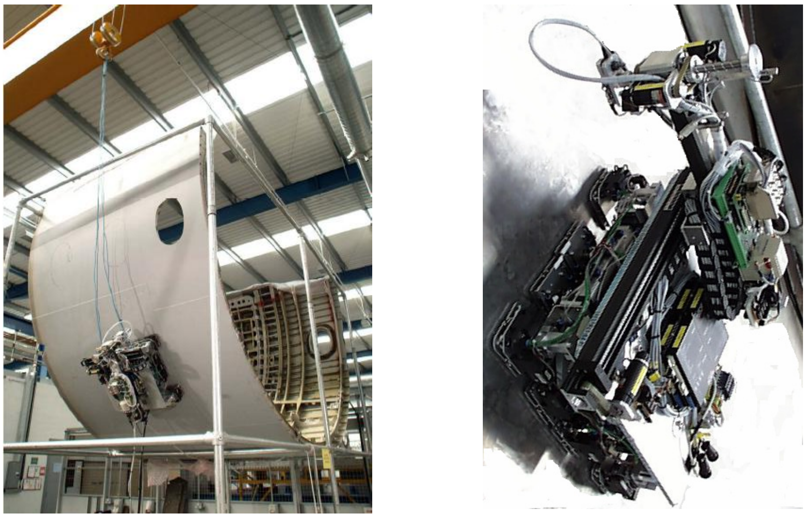

Figure 1.5 Robot works on a D10 aircraft fuselage section (left); overall structure of the robot designs (right).

1.2 Brief History of Climbing Robots

Early 1980's: The first development of wall climbing robots was mainly for children's toys. During that time, vehicle-type wall climbing devices with a variety of attachment mechanisms and a number of wheels were used. Magnets were first used to climb up walls made of ferrous materials, followed by self-suction devices; *1986:* The University of Gakuen-Kibanadai in Japan designed the first robot with capability to move on a vertical wall, this used an inverse thrust force provided by two propellers and adhere the robot in irregular vertical walls [14]; *1987:* Professor Hirose Tokyo Institute of Technology built the first Wall Climbing Vehicle Using Internally Balanced Magnetic Unit [14]; *1990:* The first Wall Climbing inspection robot for nuclear environment was designed by B.L. Luk, A.A. Collie and J. Billingsley from Portsmouth Polytechnic University and could be the first European wall climbing robot; *1991:* The Tokyo Institute of Technology created the first machine That Can Walk and Climb on Floors, Walls and Ceilings [14]; Japanese researchers K.IKEDA and T.YANO developed a wall climbing robot with scanning type suction cups; *1992:* Professor A. Nishi of the University of Gakuen-Kibanadai created a biped walking robot capable of moving on a vertical wall [14]; *1997:* Vanderbilt University develops a climbing robot with rubbertuator, this actuator is like a muscle and produces very strong force [15]; *2000:* The University of Southern in China, develops a wall cleaning robot for a building's glass walls[16]; *2003:* University of California develops biologically inspired dry adhesives using nanofabrication techniques for future wall climbing and surgical robots, and general dry adhesive applications [17]; Lewis Illingtorth, David Reinfeld, develop and patent a wall climbing robot with vortex attraction for planar and non-planar surfaces, the technique turns a propeller at high speed to create negative pressure over surfaces [18]; *2006:* Stanford University and University of Pisa have developed a climbing robot with compliant micro-spine arrays inspired by the mechanisms of insects and spiders for hard vertical surfaces, it allows a robot to scale concrete, stucco, brick and masonry walls without using suction or adhesives [19].

1.3 Techniques for Developing a Climbing Robot

To create the types of climbing robot that are the subject of this work, we have to consider 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,* etc.). Figure 1.6 shows the conceptual diagram for design and development a climbing robot.

1.3.1 Climbing power - umbilical

The climbing power and umbilical have 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.

1.3.2 Environment

NDT inspection systems are normally operated in an industrial environment which is a key factor in the design of any robot. The application areas for robotic NDT or automated systems are in the inspection of critical infrastructure on nuclear power plant, bridges, aircraft, offshore oil platforms, railways, tanks, shipyards, buildings, petrochemical tanks and other storage. They may have to operate in corrosive, highly flammable, explosive, and high radiation environments. Hence, it is essential to design them with high resistance materials and with intrinsic safety in mind.

1.3.3 Traction system

Traction refers to the friction between a drive member and the surface it moves on, where the friction is used to provide motion.

For the purposes of driving a wheeled climbing vehicle, high friction is generally desired.

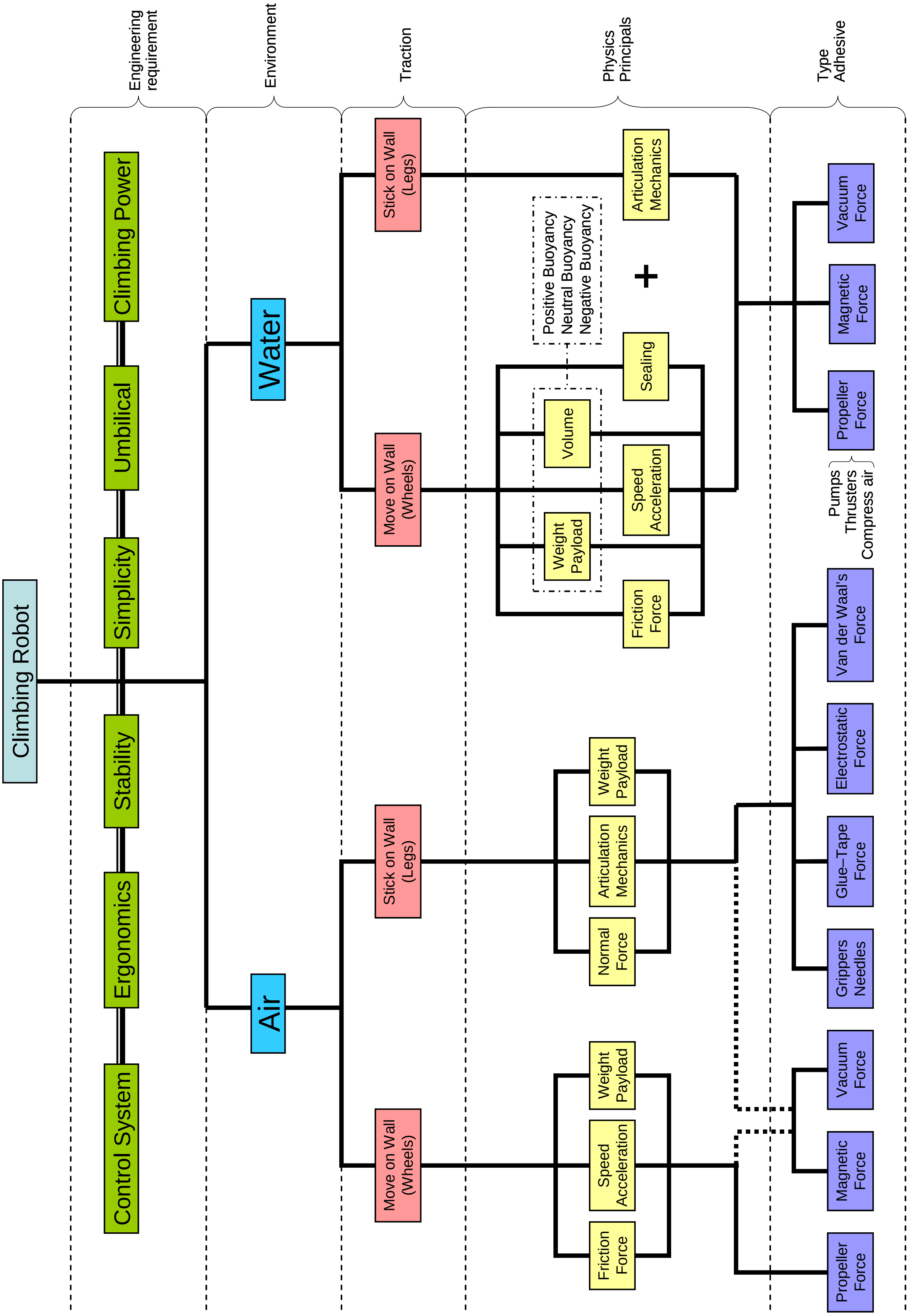
Climbing Robot
Engineering requirement
Control System
Ergonomics
Stability
Simplicity
Umbilical
Climbing Power
Environment
Air
Water
Traction
Move on Wall (Wheels)
Stick on Wall (Legs)
Move on Wall (Wheels)
Stick on Wall (Legs)
Physics Principals
Friction Force
Speed Acceleration
Weight Payload
Normal Force
Articulation Mechanics
Weight Payload
Friction Force
Weight Payload
Speed Acceleration
Volume
Sealing
Positive Buoyancy
Neutral Buoyancy
Negative Buoyancy
+
Articulation Mechanics
Type Adhesive
Propeller Force
Magnetic Force
Vacuum Force
Grippers Needles
Glue–Tape Force
Electrostatic Force
Van der Waal's Force
Pumps
Thrusters
Compress air
Propeller Force
Magnetic Force
Vacuum Force

Figure 1.6 Conceptual illustration for design and development of a climbing robot.

1.3.4 Physics principles – static analysis

The adhesion force (F_a), is the critical part of any climbing robot. It is generated by the selected method of adhesion (magnetic, vacuum, etc.).

Figure 1.7 shows a conceptual climbing robot with static forces acting on it.

If the robot is in static equilibrium, it obeys,

$$\overset{+}{\longrightarrow} \sum Fx = 0$$

$$Fx_1 + Fx_2 - F_a = 0$$

$$\overset{+}{\uparrow} \sum Fy = 0$$

$$Fy_1 + Fy_2 - W_T = 0$$

At equilibrium, the sum of the moments at point 2 in figure 1.7 is M_2,

$$\overset{+}{\hookleftarrow} \sum M_2 = 0$$

$$-F_a \cdot \frac{y_1 + y_2}{2} + Fx_1 \cdot (y_1 + y_2) + W_a \cdot x_1 + W_S \cdot x_2 + ... + W_m \cdot x_m + W_b \cdot x_b = 0$$

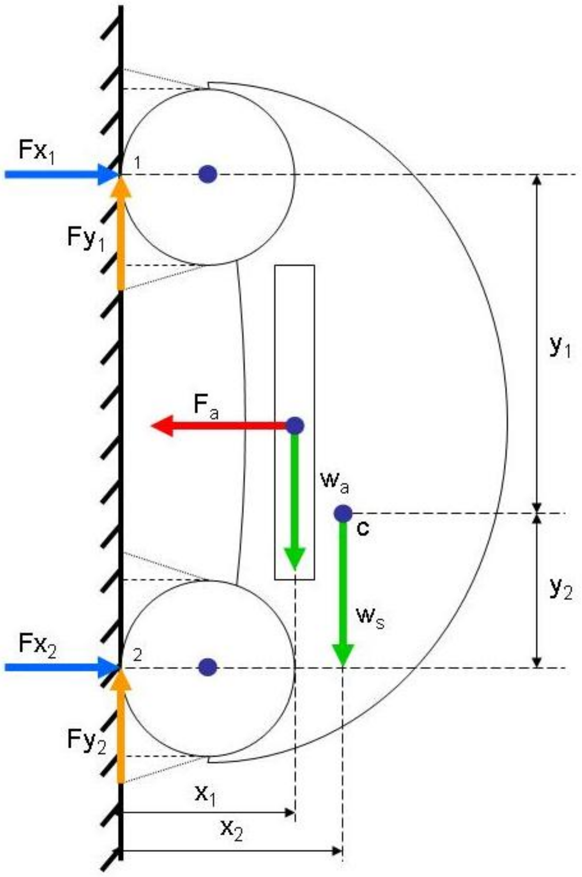

Figure 1.7 Conceptual static forces for climbing robots.

Where,

$$W_T = W_a + W_S + ...+ W_m + W_b$$

W_T= Weight of full robot

W_a= Weight of adhesion system

W_s= Weight of structure

W_m=Weight of motors

W_b= Weight of batteries

$$Fx_1 = F_{N1}$$

$$Fx_2 = F_{N2}$$

Where, F_{N1} and F_{N2} are the Normal forces at points 1-2 respectively, these two forces can be equal or F_{N1}=0, but F_{N2} always exists and both depend directly on the adhesive force.

Fy_1 and Fy_2 are the friction forces acting at the robot/surface contact points.

$$Fy_1 = F_{N1} \times \mu_s$$

$$Fy_2 = F_{N2} \times \mu_s$$

Where, Fy_1 and Fy_2 = friction force directly proportion to the coefficient of friction between wheels or leg support at the points 1-2 with the wall. However this force depends considerably on the type of adhesion and traction, because these are the forces that hold the robot on the wall.

This analysis determines the minimum necessary force of adhesion (F_a) to obtain static equilibrium of a climbing robot on the wall.

The equation of moments shows; if the distance increases from the wall to the centre of gravity, the adhesion force system has to apply a bigger force to support the same weight of the robot. In other words, a small distance of the robot to the wall will increase adhesion.

A common approximation of force of friction is $F = \mu \times F_N$. 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. The friction force is of course determined by the adhesion force F_a.

1.3.5 Types of Adhesion

Wall climbing robots generally use one of seven types of adhesion force to stick the robots on the wall. These forces are:

i. Magnetic force
ii. Vacuum suction force
iii. Attraction force by propeller action
iv. Needles or gripper forces
v. Glue or adhesive tape forces
vi. Van der Waal's forces
vii. Electrostatic 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 as follows:

Neodymium magnets **-** The second generation of rare-earth magnets are 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. These are commonly used for computer rigid disk drives, speakers, linear actuators, DC motors and other electronic equipment.

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. Similar to Neodymium, The difference between Samarium Cobalt and Neodymium is mainly its corrosion resistance and temperature sensitivity. Samarium Cobalt has excellent corrosion resistance and can be used in high temperatures. Because of these characteristics they are very expensive and are commonly used in servo motors, pump couplings, and sensors.

Alnico magnets **-** These are made with Aluminium, Nickel and Cobalt and have higher temperature resistance, but not as strong as the previous two magnets. The price of Alnico magnets is much lower, and these are often used to perform mechanical to mechanical applications like separators, holders, coin separators, clutches, bearings and different types of electronic equipment.

Ceramic magnets – these are made from low cost sintered magnet materials with iron oxide and barium/strontium carbonate. These are the most fragile, least power and only available in simple forms. These are used for magnets in lawnmowers and garden tractors, Magnetic Resonance Imaging, etc.

Injection moulded / bonded - A magnet made by the combination of resins and magnetic powder to form a soft and flexible magnetic material.

Plastic magnets – these are a non-metallic magnets made from polymers, which are combination of tetracyanoquinodimethane and emeraldine-based polyaniline. These magnets were created by the University of Durham in 2004 [20]. 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. Considering vacuum is by definition a negative pressure, the common terminology of high-vacuum and low-vacuum can be confusing so the preferred terminology is deep-vacuum or shallow-vacuum and both are relative to local atmospheric pressure [21]. 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.

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 more supple 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.

Most wall climbing robots use 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.

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. Additional measures are required to ensure permanent safety of the robot and instruments. [22]

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. Its 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. [23]

A vortex can be seen in the spiralling motion of air or liquid around a center of rotation, see Figure 1.8. Turbulent flow makes many vortices. A good example of a vortex is the atmospheric phenomenon of a whirlwind or a tornado.

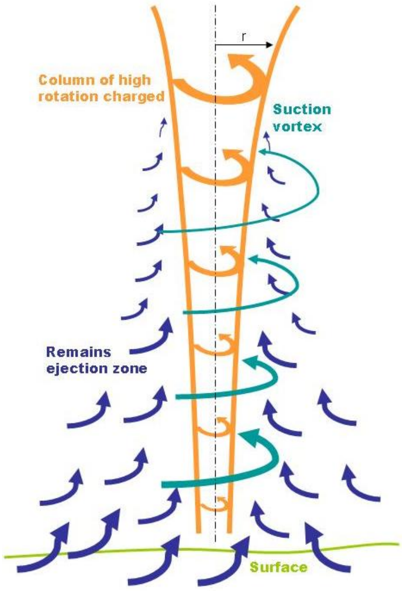

Figure 1.8 Vortex phenomenon.

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 is the vacuum. 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, which involves arrays of micro-spines to catch the surface asperities. 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.

The anatomy and dynamic analyses of biologically inspired appendages using needles and grippers adhesive force for climbing hard vertical surfaces is explored in. [24]

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 of a very light climbing robot on vertical glass surfaces. The tapes have significant orthogonal forces to the substrate.

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.

Analysis suggests that, for vertical surface walking; only the upper (front) feet require adhesive tape [25]. However, adhesive on the lower feet permit walking in different directions on vertical surfaces; moreover provides traction when transitioning between surfaces and helps prevent slipping.

vi. Van der Waal's forces

Nature can be an inspiration for innovations in robotics science. One such inspiration comes from the gecko lizard which can climb on walls and ceilings of almost any surface texture. Rather than using its 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. The dry adhesion force comes from surface contact forces such as Van der Waal forces which act on all materials in contact.

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. [26]

vii. Electrostatic forces

This method of adhesion consists to generate and carry charges positive and negative. When the wall has any charges the system automatically swaps and generates the opposite charge. The climbing robot can then clamp onto those charges from on-board battery power. The technique named compliant electro-adhesion uses a very small amount of power and the robots can crawl at a speed of about one body length per second.

Electro-adhesion offers advantages over other types of techniques of adhesion, this include robust clamping over a variety of surfaces (rough or smooth, conductive or insulating), low power, resistance to dust, and fast, electrically controllable clamping and unclamping. [27]

1.4 The Author’s Contribution to Wall Climbing Robots

This work has investigated wall climbing robots by developing six prototypes with different technologies. Two main robot prototypes were developed with fully NDT automated system inspection capability. The details of these two wall climbing/swimming robots represent the body of this work and are described in the rest of the thesis. The aim has been to test different adhesion methods by developing compact, lightweight robots that can be easily deployed by one operator. However, four additional prototype robots have been developed that use different methods of adhesion to climb vertical surfaces. These methods are magnetic adhesion, vortex vacuum adhesion, hydraulic-vacuum adhesion and force grippers. These four prototypes are described as follows.

1.4.1 Surface changing, wall climbing robot with permanent magnet adhesion

The first 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.

The contribution to the wall climbing robots is uses two hinged platforms that enable transfer between horizontal/vertical surfaces and vertical/vertical surfaces (figure 1.9). During a surface change, one platform crosses over to the new surface while the other platform remains on the old surface (figure 1.10). 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 × 240 × 200 *mm* and it weighs 6 *kg*. Motion is actuated by two 150 *W* DC motors with each motor transmitting drive to all three wheels on one side of the robot with a belt and pulley system.

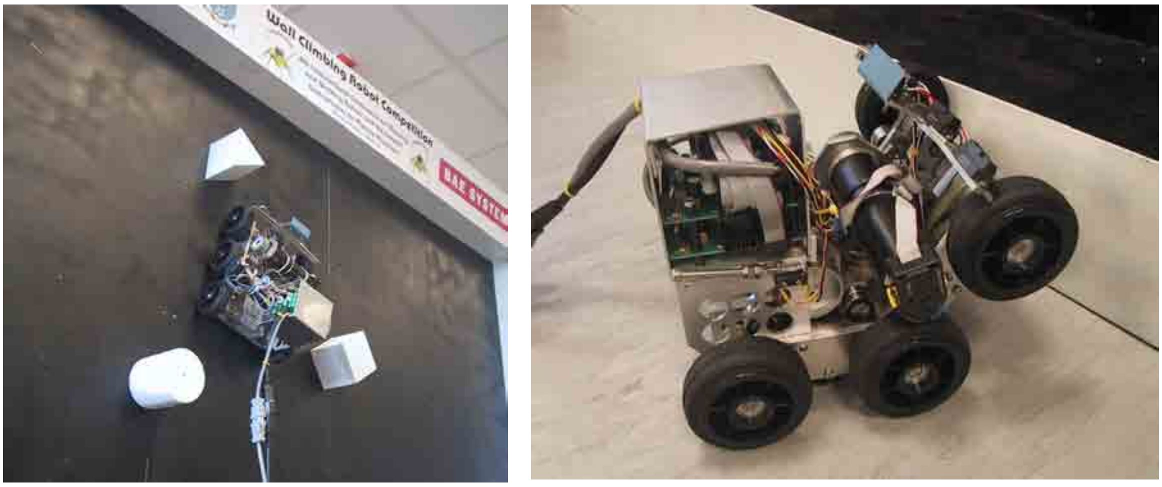

Figure 1.9 Obstacle avoidance by WALLEXPLOR on the competition wall (left); surface change from floor to wall (right).

An I/O card and two PIC servo controllers are carried on-board the robot. The robot umbilical is composed of a 24 *V* DC 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.

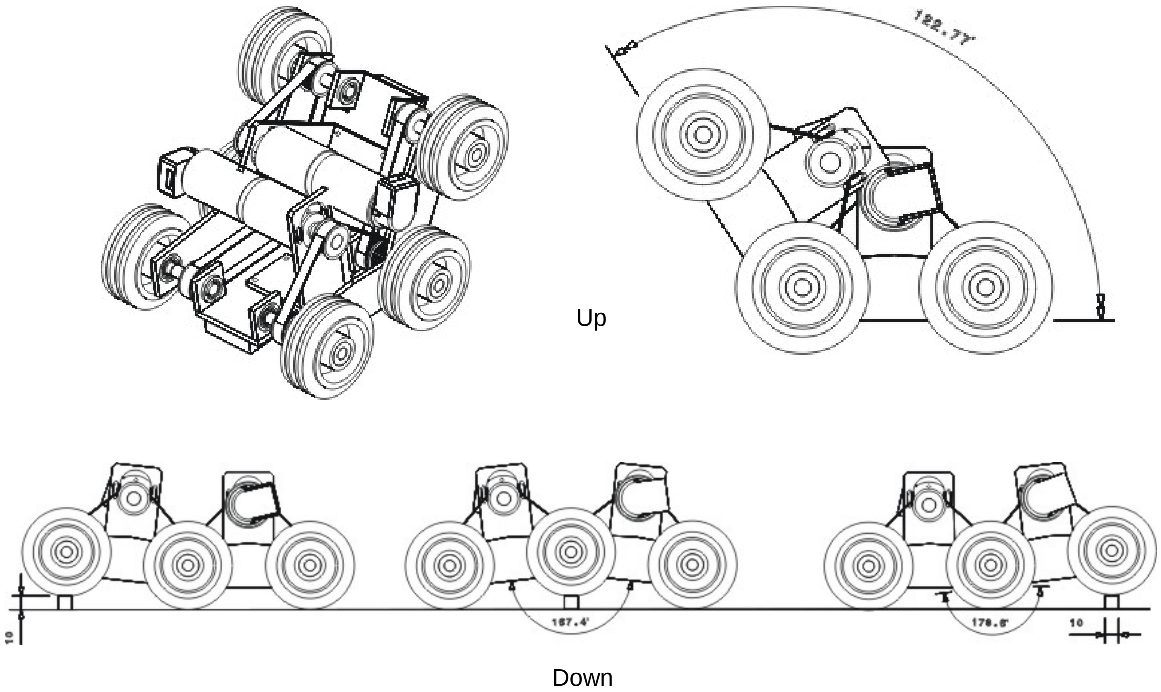

Figure 1.10 Drawings of platforms folded during surface transition (Up); climbing over the one centimetre high and one centimetre wide strip on the wall (Down).

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.

1.4.2 Wireless wall climbing robot with vortex-vacuum adhesion

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.

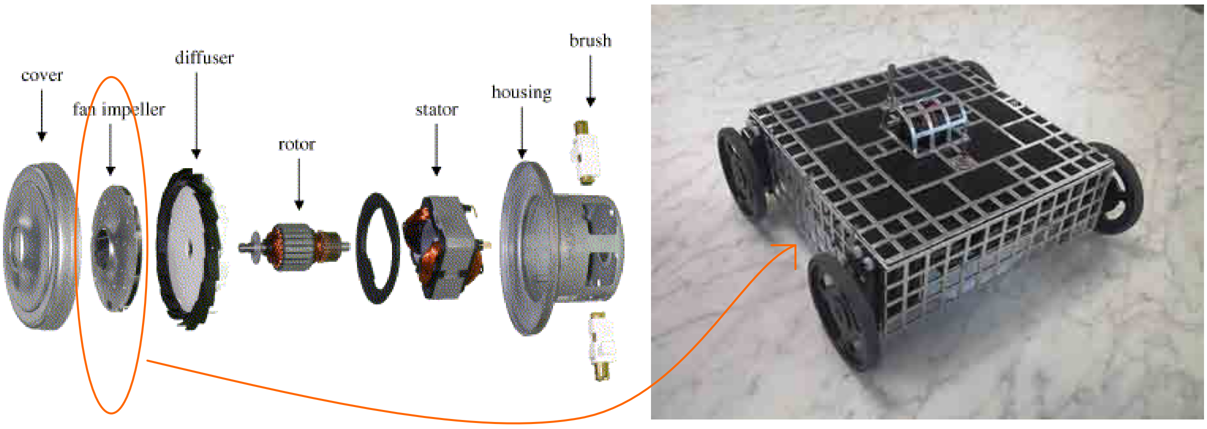

Figure 1.11 Components of the vacuum cleaner motor (left); wall climbing robot with vortex attraction technique (right).

The body structure of the robot was made with perforated aluminium (figure 1.11), 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.

1.4.3 Underwater wall climbing robot with hydraulic vacuum adhesion

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. 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.

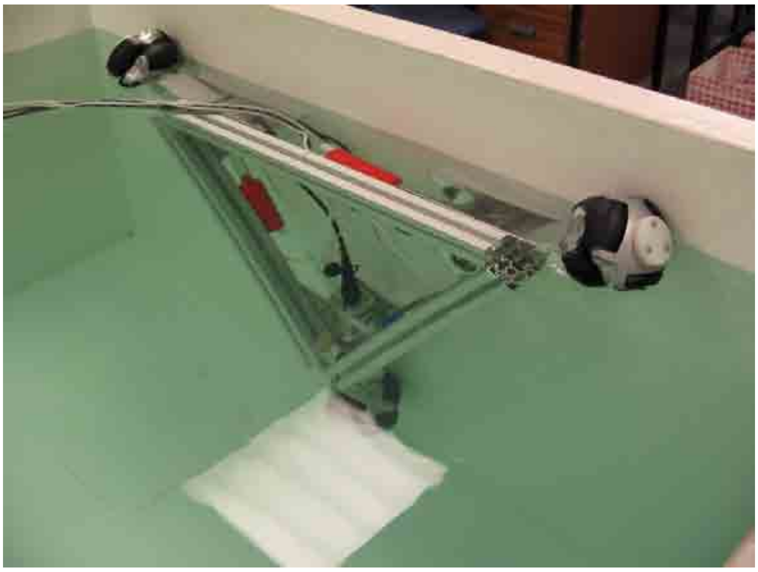

Figure 1.12 Underwater wall climbing robot.

1.4.4 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.

Figure 1.13 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.

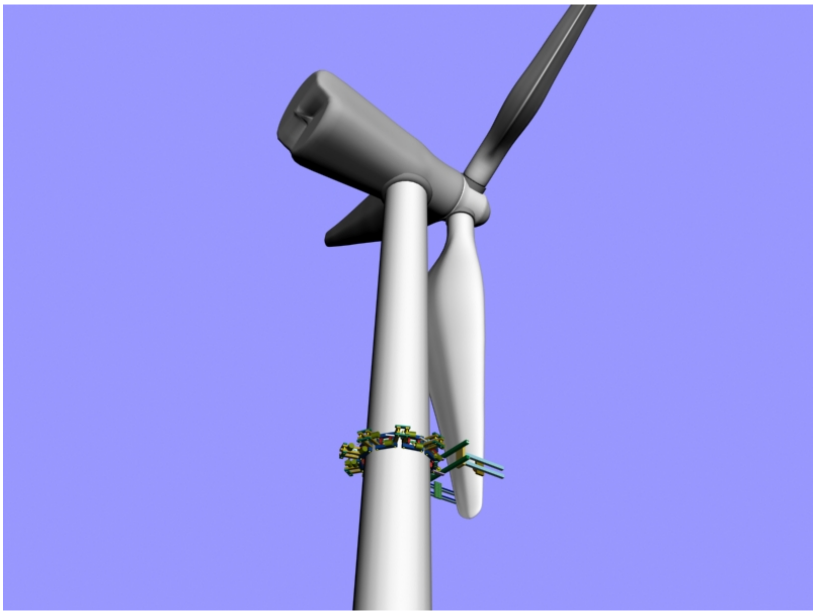

Figure 1.13 Conceptual designs of a wind generator and climbing robot.

Figures 1.14 shows a novel ‘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.

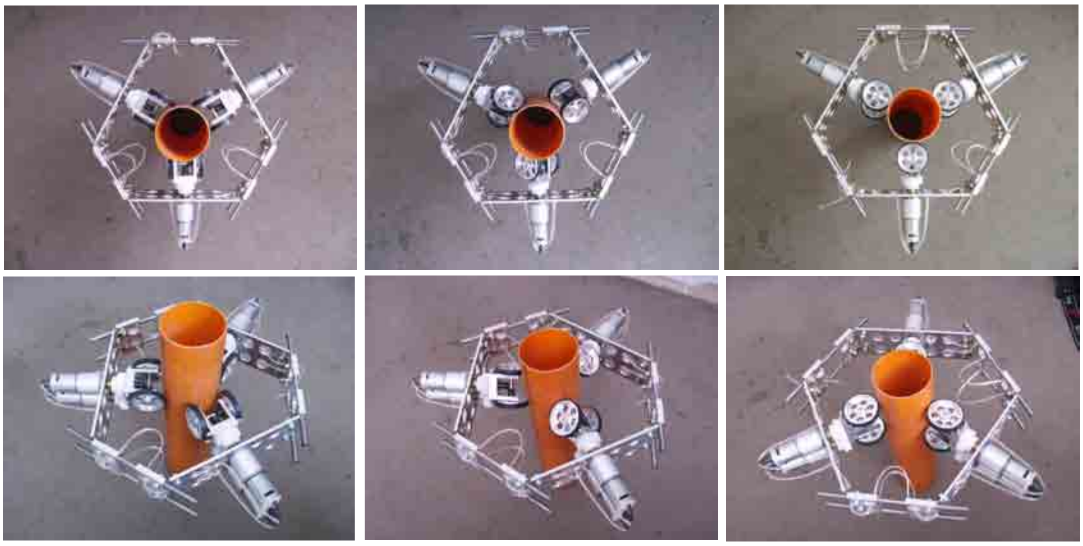
(a) up/down motion (b) spiral motion (c) on-the-spot rotation

Figure 1.14 Prototype design in small scale of wind turbine climbing robot.

The prototype has three modules which are completely identical and can be easily joined together to climb on any circumferential tube. The tower has a tapering radius. The robot is placed around the tower and it uses spring forces to grip it. Active force control could also be used to adapt to changing radius but this method has not been used here.

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 is spiral. The robot has the capability to face the driver wheels in different angles which means that the robot can either climb along the tube, see figure 1.14 (column a), or with a certain pitch angle it can spiral around the tube, figure 1.14 (column b), or if the wheel is turned through 90 *degrees* then the robot will not climb but it will rotate around the tube in the same spot, figure 1.14 (column c).

The prototype has been built to a scale 1:10 and tested successfully performing the three types of motion i.e. up/down, spiral, and rotation on the spot.

1.5 Summary and Remarks

This chapter gives the rationale for developing climbing robots for remote NDT, and describes some recent developments to achieve the aims and objectives of robotic NDT. A brief history of wall climbing robots is presented and the technology required for climbing robots is described. Wall climbing robots developed by the author that use four different adhesion methods suitable for industrial applications are presented (permanent magnets, vortex vacuum, hydraulic vacuum, and force grippers), which contribute to improve the climbing robots for industrial environments and the development of better motion performs in underwater applications.

1.6 Organisation of the Remainder of the Thesis

Chapter 2: This chapter describes the requirements for in-service non-destructive testing of welds on strengthening steel plates in FPSO tanks. It describes the environment in which the robot will operate and identifies the NDT sensor payload and deployment requirements.

Chapter 3: This chapter describes the fundamental principles and analysis leading to the development of an amphibious and swimming robot for Floating Production Storage and Offloading Tank (FPSO).

Chapter 4: This chapter describes the results of tests performed with the FPSO robot swimming in a diver's water tank and inspecting its floor. Results of NDT inspection of welds are presented that have been obtained in air on a mock-up of FPSO strengthening plates.

Chapter 5: This chapter describes the requirements for the development of an underwater wall climbing robot called RIMINI that will be used to inspect welds located inside nozzles in nuclear pressure vessel tanks. Requirements are determined for the robot's motion on curved vessel walls, payload capacity, intrinsic safety, and travelling speed.

Chapter 6: This chapter describes the development of the underwater RIMINI climbing robot to meet the requirements identified in chapter 5. A kinematics analysis of the robot is performed; the development of sliding suction cups and a control system for the tele-operation of the climbing robot is reported. Additionally, the final results of NDT inspection performed by the RIMINI automated system in the mock-up.

Chapter 7: Conclusions, further work and references.

Chapter 8: Appendices of further information, software developed and technical drawings.

Chapter 2: Requirements of Swimming NDT Robotic System

The first of the two main robots designed and built in this work is called the Floating Production Storage and Offloading Tank (FPSO-Robot). The related research started with the development of a number of conceptual designs that were presented to Research and Technological Development (RTD) partners of the EC Framework 6 project[1], which has the same name as the robot involved, namely FPSO [28].

The aim of the FPSO project is to build a prototype amphibious robot vehicle that can carry Non-destructive Testing (NDT) sensors from an entry port in the top of an FPSO vessel tank, to the floor or sides of the tank, where the NDT sensors can be deployed from a scanner to detect either fatigue cracks in the stiffener to tank shell fillet welds, or corrosion in the shell plates.

This chapter describes the requirements of the FPSO robot. This robot has to be amphibious, able to swim in water or oil and capable of carrying Non-destructive Test (NDT) sensors from an entry port in the top of a FPSO vessel tank to the floor of sides of the tank, where the NDT sensors can be deployed to detect either fatigue crack in the stiffness tank. The requirements of the system will be described in terms of its payload capacity, the environments in which it will operate; its ability to conform to legislation on intrinsic safety in these environments, its required travelling speed, and its ability to move in a predetermined trajectory.

2.1 What is an FPSO System?

An FPSO system is an offshore production facility that is typically ship-shaped and stores crude oil in tanks located in the hull of the vessel. The crude oil is periodically offloaded to shuttle tankers or ocean-going barges for transport to shore. FPSO systems may be used as production facilities to develop marginal oil fields or fields in deepwater areas remote from the existing OCS[2] pipeline infrastructure (figure 2.1). They are used to store oil before transportation to the mainland.

FPSOs have been used to develop offshore fields around the world since the late 1970’s. They have been used predominately in the North Sea, Brazil, Southeast Asian/South China Seas, the Mediterranean Sea, Australia, and off the West Coast of Africa. There are currently 70 FPSOs in operation or under construction worldwide. In addition to FPSOs, there have been a number of ship-shaped Floating Storage and Offloading (FSO) systems (vessels with no production processing equipment) used in these same areas to support oil and gas developments.

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[1] http://cordis.europa.eu/fp6/

[2] Outer Continental Shelf