Wall Climbing Crawlers for Nondestructive Testing

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1 Rationale for automated NDT that uses wall-climbing crawlers

There is a strong international trend that uses robots as a strategic technology for automated inspection and maintenance work in hazardous environments such as in chemical plants and the nuclear power industry [Fukuda, 1990, Roman, 1993, Takehara, 1989]. The main plant components that benefit from automated inspection are long pipelines and the walls of storage or buffer tanks that are inspected either from the outside or the inside. Large benefits in performance and cost savings are possible. For example, an electric utility has reported a saving of five million dollars within eight years on two plants with a capital spend on robotic hardware of two million dollars [Proc. Int. Conf. on Intelligent Robots and Systems, 1993].

At the present time, in-service inspection is a very costly and time-consuming activity, especially in nuclear power plants or other hazardous (or not accessible) environments. A fundamental inspection problem is to monitor possible weld faults and to assess the trend of these faults, and subsequently to take decisions affecting maintenance procedures. The only automation attempted for these kinds of operations has been for simple situations, such as linear welds, where dedicated systems are typically used. These systems consist of a straight rack, permanently installed near a welded seam, carrying an ultrasonic probe with a scanning device that is moved along the rack. Although these systems allow repeatable and accurate monitoring of the welded seams, they are not flexible and not suitable in many cases, especially when complex profiles have to be inspected. Surfaces of complex geometry are still currently inspected manually by human operators using equipment that is not very accurate, with the risk of high levels of radiation exposure, and with an evident lack of precision and repeatability.

Most commercially available automated inspection systems are tailored to do just one task, frequently in just one place, and with Cartesian type scanning arms that allow a limited range of scanning routines to be implemented on flat or gently contoured surfaces. The inspection of more complex surfaces is performed by systems that use multi-axis serial link arms but these are usually dedicated fixed site systems, for example robots constrained to translation movement on mono rails alongside a factory production line or a long welded seam.
Instruments dedicated to the automation of one particular task, whilst being very expensive, are incapable of being adapted to other tasks. A typical task might be as narrow as the inspection of just one type of nodal joint in a feeder network to a nuclear pressure vessel. A typical instrument cost for a current instrument dedicated to just this task might be £100,000 to over £1,000,000. More than five different instruments are required to inspect other types of nodal joints around the pressure vessel. Therefore there are large potential cost benefits to be gained from the development of a single, multi-purpose automatic inspection instrument that could do all the required tasks. Completely automated inspection devices should speed up operations, thus allowing reduction in running costs and reduction of radiation exposure for human operators.

There is, therefore, a need throughout industry for automated inspection systems that can move freely or be transported easily from one application to another and perform in service inspection with far more versatility and task repeatability than has been achieved hitherto by

- providing access to test areas on large surfaces such as walls and ceilings
- enabling the inspection of long lengths of test area with a small and compact device that simply travels along any length of the area
- providing greater flexibility, inspection task accuracy and repeatability than current automated inspection systems

The above requirements are considered further in the following sections.

1.1 Provision of access to large remote surfaces

Many inspection tasks in industry are performed on large surfaces such as structural walls and ceilings. Examples are the inspection of welds on the walls of nuclear pressure vessels and the hulls of large ships, the detecting of wall thinning on petrochemical and process storage tanks, the inspection of cracks in concrete structures such as bridges, etc. Access to these inspection surfaces can be difficult and expensive due to remoteness, cramped conditions, or a hazardous environment. Presently, inspection in non-hazardous environments is done manually by abseiling onto the surface or by erecting expensive scaffolding, whereas in hazardous environments the inspection is automated with dedicated scanning devices that are limited to do a single specialized task.

Most automation currently available for the inspection of large vertical surfaces and ceilings, tends to be of a Cartesian flat bed type moved on vertical surfaces with vehicles that have magnetic wheels e.g. p-scan vehicles with two axis robot manipulators or at most a four axis manipulator for probe skewing. The payload carrying capability of magnet-adhesion vehicles is small. Only light arms with limited degrees of freedom can be carried. Hence they are very limited in application. Long three dimension weld runs can not be scanned with these devices and inspection of non-ferrous surfaces is not possible. There are few reported developments of climbing robots that are equipped with anthropomorphic scanning or manipulator arms and certainly none that are specifically designed to address the issues of inspection and scanning with accuracy and repeatability on remote and uncertain surfaces.

1.2 Inspection of long 3D runs with small inspection devices

The automated inspection of long welded seams in fixed installations such as nuclear power plants is currently performed by installing dedicated inspection devices that are restricted to move along the seams on mono rails, gantries, racks, etc. Scanning of large 3D runs on a surface (e.g. the inspection of large three dimension runs at the junctions of structural T-bars in ship construction) is a problem. Obviously, permanently installed devices cannot inspect very large structures such as ships. More flexible, easily transportable and hence compact automation is required that can move freely along any length of the inspection surface.

1.3 Flexibility, accuracy and repeatability improvement

Industry has a need for automated robotic inspection systems that are far more flexible in application than has been achieved hitherto. Many automated systems are tailored to do just one task with scanning arms that have limited degrees of freedom and hence a limited range of scanning capability. Most automation available for scanning purposes uses Cartesian manipulators, which limits their application to flat or gently contoured surfaces.

Structures with complex surface contours are usually inspected manually by human operators with an evident lack of precision and repeatability. A multi axis serial link robot manipulator, while not as flexible as a human operator, can scan complex structural geometry’s with dexterity approaching that of a human arm and with much greater precision and repeatability in well structured environments. Their use at remote locations has been limited by their lack of precision due to uncertain knowledge of the environment. For robotic scanning arms to become more widely used in automated inspection equipment, developments in robot arm technology are necessary so that the arm

- has the versatility characteristic of a human arm to perform a variety of scanning routines with sufficient spatial positioning accuracy
- is light weight and hence easily transportable on a mobile platform
- can obtain greater task repeatability by keeping a variety of NDT probes at the required approach angle to a remote inspection surface while obtaining a desired standoff or contact force to the surface. The approach angle, standoff or contact force should be maintained despite uncertain knowledge of the environment and invalid assumptions of perfect knowledge of robot dynamics and kinematics models.

Thus the inspection instrument should have all the versatility of a human operative while at the same time providing faster inspection speed, the ability to work in hazardous environments, greater accuracy and task repeatability and without the measurement errors caused by human tedium. At the same time the multitasking capability of the instrument should make it more cost effective over existing automated NDT by doing the work of several dedicated automated systems.

The requirements in section 3.3.1 could be satisfied by building an inspection instrument which consists of a compact climbing vehicle that carries a flexible robot arm to deploy NDT probes to gather data at remote locations. This instrument could move freely over large vertical walls or ceilings and explore structures of complex geometry with a robot arm that has six or more degrees of freedom. The instrument should be portable so that it can be easily moved from task to task. For example, it could be used to inspect (in sequence) a ship hull, a nodal joint on a nuclear pressure vessel, a pipeline, a storage tank, etc. The drawing of figure 1 illustrates such instruments fulfilling the requirements of section 3.3.1 by performing weld inspection on the hull of a large container ship. In this application the instruments provide access to remote locations on a large vertical surface (up to 30 meters high), inspect long weld seams (500 millimeter long cross welds where four adjacent steel plates are joined), and provide flexible deployment of sensor probes with a multi-jointed serial-link arm.

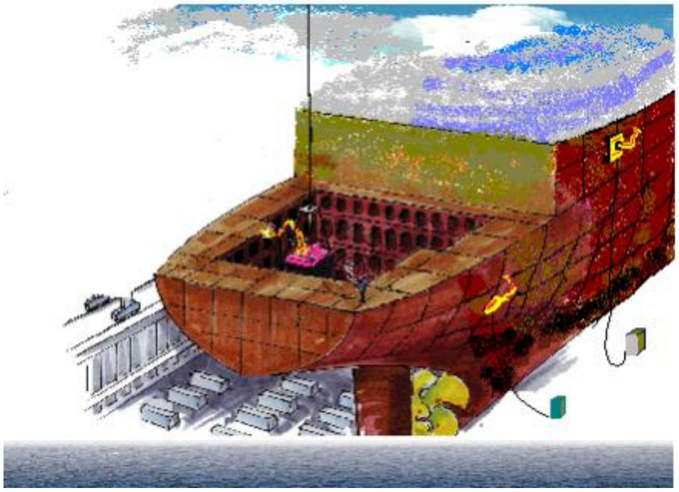

Figure 1: Wall-climbing robots carrying anthropomorphic arms and NDT probes inspect 500 millimeter lengths of horizontal and vertical cross welds on the hull of a cargo container ship.

2 The ideal wall-climbing robotic inspection system

2.1 Versatile, dexterous and cost-effective inspection instruments

To meet the industrial requirements described in section 3.3.1, automated instrumentation should attempt to match the following key characteristics of the human operative that obtains this versatility and dexterity

- easy mobility to carry out inspection from site to site. Thus in principle the same operator can, for example, inspect in turn a ships hull, an oil storage tank, an air frame, a nuclear pressure vessel, etc.
- a multi-jointed and flexible arm, which can deploy sensor probes with a range of scanning techniques to suit the problem. The human arm and hand can reach into fairly constricted gaps between neighboring structures such as pipe work.

- a range of sensors and intelligence which enable adaptation during an inspection to structures of complex geometry and different material composition.

Recent developments have aimed to produce automated inspection systems that have these key human characteristics. Figure 2 shows a conceptual drawing of such a robotic NDT system performing a likely remote inspection task. The system comprises of a mobile robotic vehicle that can climb over large areas of vertical walls and horizontal ceilings thus providing access to remote areas that normally require the erection of expensive scaffolding or the use of abseiling techniques or boson's chairs. The vehicle carries a dexterous anthropomorphic scanning arm (human-like arm with six or more joints) to deploy the inspection sensor and inspect the test surface with a variety of scanning routines.

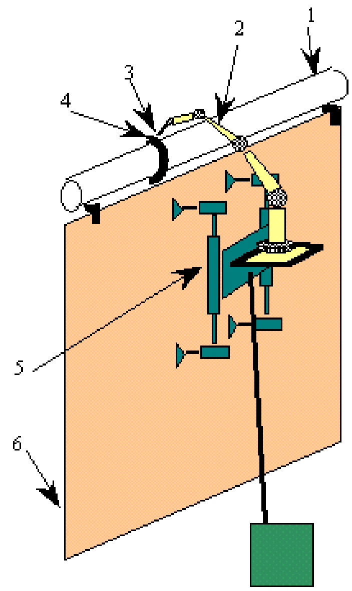

Figure 2: Wall-climbing Robotic Inspection System (1. Circular pipe, 2. Robotic arm, 3. NDT sensor, 4. Weld, 5. Pneumatic Climbing vehicle, 6. Vertical surface)

The climbing vehicle uses pneumatic adhesion to climb the smooth vertical surface that could be constructed from different materials e.g. steel, glass fiber, carbon composites, stainless steel, concrete, etc. Upon reaching the pipe weld it inspects it with a ultrasonic pulse echo or TOFD sensor deployed by a sufficiently dexterous arm that can move the sensor around the circumference of the pipe. To perform this inspection the tool should consist of

- a compact pneumatic climbing vehicle that can move freely on large surfaces and provide access to vertical walls and ceilings of large structures. The vehicle should be capable of fast speed and large payload carrying capability
- a multi axis robot arm designed to perform inspection on almost any remote structural geometry with a variety of scanning routines, with similar dexterity to a human operator and deploy a variety of inspection sensors with far greater speed and spatial resolution. It should use sensor-based control to maintain NDT probes at desired surface contact forces or stand off and allow real-time path modification to follow unknown surface contours
- accurate task control schemes for the scanning arm with the main objective of accurate and repeatable tracking of 3D trajectories which correspond to welded seams in nuclear power plants, ship yards, etc.
- a flaw detector that gathers data from a range of NDT sensors, provides real-time defect detection, and visually displays defect images.

2.2 Application areas for this type of inspection system:

Versatile automated nondestructive inspection instruments will find immediate use to test the safety of environmentally critical engineering structures such as large ship hulls, nuclear pressure vessels, and oil storage tanks with particular application to the

- inspection of large welded cross seams (up to 4 meters long) on the hulls of ships and 3D welded seams at the junctions of structural T-bars/ transverse plates used in ship construction.
- inspection of nodal joint welds on nuclear vessels and the inspection of different sized 45 degrees nodal weld joints on feeder pipes.
- measurement of corrosion thinning on 6 to 10 mm thick steel plates on large crude oil storage tanks to a resolution of one millimeter.

These inspection tasks have to be carried out with automated equipment because the use of human operatives is inappropriate either because there is a health hazards from fumes, nuclear radiation, or because of the enormous amount of inspection data to be collected and processed. The next section identifies some of the requirements of a general purpose, low cost remote-inspection system that is readily transportable between different geographical locations, is able to climb over large areas of vertical walls and ceilings of any material composition, particularly in remote and hazardous environments.

3 Multipurpose instrument for remote inspection of large 3D surfaces

3.1 Climbing robot

For successful application it is important to develop a climbing vehicle plus arm that is on the one hand constrained in mass and dimensions so that the instrument can be transported manually by at most two operators and easily manhandled through constricted spaces. On the other hand the vehicle actuators and suction feet areas should be large enough to safely carry the arm, its umbilical and a payload of NDT sensors up to required heights. In addition, for versatility, the same vehicle should be able to travel on flat surfaces, on curved surfaces presented by pipes, on convex surfaces presented by LPG spheres, and on concave surfaces presented by the inside of cylindrical tanks such as pressure vessels. For the general-purpose inspection instrument to be cost competitive with manual inspection it is required to have some or all of the following features:

- The cost of construction and on-site operation should be comparable with manual inspection
- It should provide access to areas prohibited to human operators
- It should provide its multipurpose services for an overall cost less than that of using a number of dedicated automated systems covering the same range of tasks

For increased versatility the inspection instrument should have climbing capability on a wide range of surfaces such as:

- Concrete and brick in order to find application in the civil engineering and construction industries that have a requirement for the inspection of large surfaces such as bridges, dams, chimneys, high rise buildings, port and harbor facilities.
- Glass fiber, stainless steel, and aluminum in order to find testing, paint spraying or cleaning applications on ships hulls, storage tanks, aircraft frames, etc.

A pneumatic adhesion technique is essential to cover this range of surfaces. The power to weight ratio of the climbing robot should be as high as possible to carry a large payload to heights of up to thirty meters or more. Other features that the general inspection instruments should have are:

- The ability to avoid or surmount small obstacles such as studs, welded seams, rivet heads, counter sinks or slots on the surface on which it is climbing. It should also be able to adjust to as small a surface curvature as possible.
- Fault tolerance to ensure that the climbing robot does not fall off in the event of pneumatic supply or controller failure and that it can be retrieved in the case of electrical failure.
- A system to determine the global co-ordinates of the climbing robot on a large surface so that defects discovered by NDT can be mapped.

3.2 Robot manipulator or scanning arm

The manipulator or scanning arm should have the following features:

- It should be anthropomorphic with at least six degrees of freedom and be programmable to mimic the scanning techniques of a skilled operator.
- The repeatability with which the spatial co-ordinates of the sensors can be changed should be good enough to achieve the desired image spatial resolution i.e. precision of defect location. For ultrasonic testing (the most common NDT technique) the spatial resolution is ultimately limited by diffraction effects. In the best possible case it is given approximately (using the Rayleigh Criterion) by the product of the wavelength and the ratio of the depth of defect to probe radius i.e. typically the diffraction limited resolution is the order of the wavelength. The shortest wavelength likely to be encountered in most testing applications is about 300μm (10MHz ultrasonic shear wave propagation in steel) so that sensor placement errors of the robot arm should be small compared with this. A ±50 micrometer repeatability of a robot arm is therefore adequate for the most testing applications.
- Raster scans with a robot arm on structures such as cylindrical pipes and spheres also require the robot to adapt its trajectory to the surface curvature [Broome, Wang, Greig, 1993]. So far the possibility of using robotic devices for remote inspection purposes has been limited by their intrinsic lack of precision, due to the invalid assumption of perfect knowledge of the environment and robot dynamical and kinematics models adopted by traditional planning/ control methodologies. In fact robot control problems for industrial applications have been traditionally solved using a two stages approach. Firstly a proper desired motion is planned (basically in the operational space of the robot's end-effector) and proper joint reference signals are defined corresponding to the desired planned motion [Fu, Gonzalez, Lee, 1987]. Secondly suitable joint level position control techniques are established with the objective of guaranteeing the most accurate possible tracking of the planned reference joint trajectories [Kathib, 1987]. Consequently this approach has two major drawbacks leading in practice to large inaccuracy or unacceptable performance (e.g. risks of collisions, damage etc.). On one hand the planning phase is performed off-line on the basis of the assumption of perfect knowledge of the robot's kinematics and of the structure of the environment surrounding it. On the other hand, the joint level controller cannot in general properly handle possible unexpected, and unavoidable, uncertainties or changes in the environment, and in world models.

In order to overcome the limitations of the previously sketched approach, a new scenario has been proposed in recent years, firstly with the introduction of the so called "Operational Space Formulation" [Samson, Le Borgne, Espiau, 1991], and more recently with the so called "Task

Function" control formulation [Aicardi, Cannata, Casalino, 1996, Aicardi, Caiti, Cannata, Casalino, 1995]. In the latter case motion planning is performed only at task level and no explicit kinematics inversion is needed, thus reducing the required computational burden. Moreover, through properly chosen "exteroceptive" sensors, to be integrated with standard "proprioceptive" ones, the robot control schemes can be now designed and implemented at task level. This fact then makes it possible to obtain better performances in terms of positioning and tracking accuracy despite possible mismatches in the parameters of the robots' models, or uncertainties in the environment models.

- Most existing robot control systems are designed with the arm mounted in a particular orientation. For example the Puma 260 robot arm allows operation with only a maximum of six degrees tilt in its base column from the vertical. Use of the arm with its base column in a horizontal position, for example, would change its dynamics and de-tune the control system. Hence, the control system for the scanning arm should have the capability to adapt to changes in the dynamics of the arm, for example when its operation is changed from a wall to a ceiling.
- The scanning arm should be capable of adaptively keeping a NDT sensor in contact with an uncertain surface with a given contact force while performing scanning movements on the surface. A major problem encountered by automated inspection systems when scanning at remote distances is not knowing the exact profile of the inspection surface. This uncertainty about the surface prevents the exercising of a pre-planned c-scan trajectory. Surface undulations on even supposedly flat surfaces will result in a sensor probe (deployed by a rigid manipulator) either losing contact with the surface or experiencing large reaction forces. Loss of signal or damage to the sensor will result. Spring loaded passive compliance at the wrist of the scanning arm can deal with small variations in surface profile. However, for large surface variations, active force control is required in order to maintain a desired contact force with the surface by changing arm configuration sufficiently to take out their effect. The required contact force can be considerable, for example 10 Newton, when ultrasonic dry contact probes are used. On the other hand, testing with EMAT's requires a constant standoff distance to be maintained between the sensor and a test surface.

3.3 Contact coupling for deployment of NDT sensors on large remote surfaces

Inspection using a payload of different types of NDT sensors e.g. ultrasonic, eddy current, radiological, gas and optical, etc. requires that the scanning arm should be able to present each sensor in a particular way to an inspection surface. The method of presentation may be non-contact or it may require wet or dry contact. When performing ultrasonic wet contact c-scans on large, remote structures at substantial heights a problem arises of supplying couplant in sufficient quantity for the job. Couplant can be piped up, but this increases the weight of umbilical. Alternatively an on-board reservoir could be used but this could imply a substantial increase in on-board payload. Also, wet contact techniques, with either water or more viscous couplant are very messy and may generate substantial extra costs in either frequent cleaning of the robot or in building the latter out of corrosion free components. Supply of water couplant can be obviated by the use of dry contact methods.

Recent development of rubbers that act as a couplant promises to be a way forward. In order to build a c-scan image, rigid rubber-tipped dry contact probes have to be picked and placed on the surface at all the grid points as continuous scanning causes unacceptably rapid abrasion of the rubber, which is very soft. This slows down the inspection. A better solution is to use dry contact roller probes that can be wheeled over the surface in a continuous scan. Roller probes have to maintain a given contact force with the surface. Too little and the signal is lost, too much and the rubber distorts leading to a change in the measured transit time of the pulse. They also have to be held in a particular orientation with respect to the surface or the received signal is lost due to the transmitted pulse being reflected away from the receiving transducer. This is hard to do manually but the robot arm is particularly suited to this task being much more rigid than a human arm. This will be particularly true of non-contact methods of probe deployment where a fixed stand off is maintained during a scan, for example when using EMAT's.

With the present state of the art (which is continuously improving with new rubber formulations) dry contact techniques produce, from any given defect, back wall echoes of typically 30 dB less signal to noise ratio then wet contact techniques. Signals reflected or scattered from any defect are 30 dB (i.e. 1000 times) less than that achievable with wet contact methods. Thus assuming Rayleigh scattering (scattered power proportional to defect volume), the minimum detectable volume of defect (mdvd) is $\cong (5\lambda)^3$ rather than $\cong (\lambda/2)^3$ achievable with a wet contact technique. In practice this will provide a pessimistic estimate of the mdvd for the dry contact technique at 2.5MHz measurement frequencies because directional back-scatter or reflection will take over from Rayleigh scattering at the mdvd dimensions predicted by the above formula. For many purposes the reduced sensitivity is acceptable, but for maximum flexibility a robot should be designed to accommodate both a dry contact system and a wet contact system. The wet contact system should be used less frequently with supply of couplant from a relatively small on-board reservoir.

4 Existing robotic automated NDT systems

Existing robotic automated NDT systems, whilst often expensive, are in general able to inspect only one type of structure for which they have been custom designed. Usually they are based on Cartesian (2 to 3 axes) robots, which restrict inspection to flat or gently contoured surfaces. Multi-axis robotic inspection systems with more than three axes do exist (but are rarely anthropomorphic) and are usually fixed site systems. The robot arm travels on a monorail alongside factory production lines or is simply fitted round one particular test piece of awkward shape and is thus not transferable to tests on structures of different size and shape. Other systems can be moved from site to site but they are still constrained in movement, for example to advance along welds on the circumference of pipelines.

The components of mobile inspection systems i.e. mobile robots, dexterous and redundant axis manipulator arms, and remote sensor based learning systems have received increasing attention recently [Broome, Wang, Greig, 1993, Proc. IEEE Int. Conf. on Robotics and Automation, 1994]. Almost all the work that integrates mobile vehicles with dexterous manipulator arms has been done for ground moving vehicles. This has included the analysis of the stability of such systems [Sugano, Huang, Kato, 1993)], the removal of dynamical interactions for end-effector positioning accuracy [Minami, Tomikawa, Fujiwara, Kanbara, 1993], dexterous manipulation in hazardous environments with remote systems integration of sensors, computing and control [Boissiere, 1994], high mobility platforms combined with high strength manipulators [Morse, Hayward, Jones, Sanchez, Shirley, 1994], etc.

More than thirty wall-climbing robots that have been developed in the World since the 1980's. A breakdown of wall climbing crawler development country by country is shown in figure 3. Very few of these climbing crawlers have been equipped with an anthropomorphic scanning arm. A pneumatic climbing robot carrying a six-axis PUMA 260 industrial manipulator arm and an ultrasonic flaw detector has been developed specifically for NDT inspection [Sattar, Chen, Khalid, Bridge, 1995, Sattar, Chen, Khalid, Bridge, 1996, Bridge, Sattar, Chen, Khalid, 1997]. The nearest development with similar objectives of manipulation, maintenance and inspection is a pilot space robot that incorporates mobility and manipulation in one body with a seven degrees of freedom arm [Xu, Brown, Aoki, Kanade, 1994]. A selection of wall climbing design variants for a number of representative tasks are described in [Briones, Bustamante, Serna, 1994], for inspection of nuclear power plants in [Yamamoto, 1992], and for inspection of aging aircraft in [Siegel, Kaufman, Alberts, 1993]. For a study of wall surface climbing mobile robots see [Fukuda, Nishibori, Matsuura, Arai, Sakai, Kanasige, 1994].

The development of four different types of adhesion methods for wall climbing crawlers is described in [Nishi, 1996]. The first method uses large suckers that employ the inverse thrust force provided by propellers to adhere to irregular vertical walls. The second method uses small suction cups at the end of each leg in biped walking mechanisms. The third method employs large suckers that use the inverse mechanism of a hovercraft to adhere to a wall. Finally, the fourth method uses suction pressures and air flight to move the robot for a short distance when required. Other developments are reported in [Bach, Rachkov, Seevers, Hahn, 1995, Bahr, Wu, 1994].

Wall climbing robots can be classified into three types depending upon the method of adhesion of the robot to a wall: a vacuum suction type, a magnetic adhesion type and a propulsive force (by propeller) type.

4.1 Vacuum adhesion type of wall-climbing robots

A vacuum adhesion type of wall-climbing robot uses rubber suction pads to generate adhesion forces with which the climbing vehicle is able to move or stay on vertical surfaces. This type of robot comprises 55 to 65 % of the climbing robot family. The rubber suction pads used as the robot feet are pneumatically powered to generate a pulling force on the wall by using vacuum ejectors or pumps. The pulling force is up to 65 to 80 % of atmospheric pressure and for a 100 mm diameter suction pad this is equivalent to a 350 to 400 N force [Chen, 1999]. This force should overcome the overturning moments applied by gravity forces on the vehicle. As result of this suction force, a tangential force is available at the surface (which is a product of a normal pulling force and the coefficient of friction). The tangential force holds the climbing vehicle on the wall by counter balancing all rotating moments and sliding forces.

Figure 4 shows a compact pneumatic climbing crawler developed at the Institute of Problems in Mechanics, Russian Academy of Sciences, Moscow in 1988. The robot size is 300 mm x 200 mm x 150 mm. It weighs 5 kg. It is able to climb on smooth vertical walls and horizontal ceilings at a maximum speed of 1 meter per minute, whilst carrying a 7 kg payload. The robot uses the simplest possible type of actuating mechanism for its motion. This consists essentially of two platforms that step forward alternately by attaching themselves to the climbing surface using rubber suction cups. This motion is achieved with two pneumatic linear-cylinders for forward or backward motion. An electrical servomotor rotates the central platform to change the direction of travel of the crawler. The climbing robot is compact and light so that it can operate in small spaces. The crawler was originally built as a fire-fighting robot to operate on petroleum tanks. It was modified at the South Bank University, London to carry a very lightweight 5 DOF robot arm and deploy a 5 MHz ultrasonic probe for the inspection of corrosion thinning on the 10 mm thick steel walls of storage tanks. The suction cup arrangement of a second-generation crawler developed in 1994 by the Moscow Institute is shown on the right in figure 4.

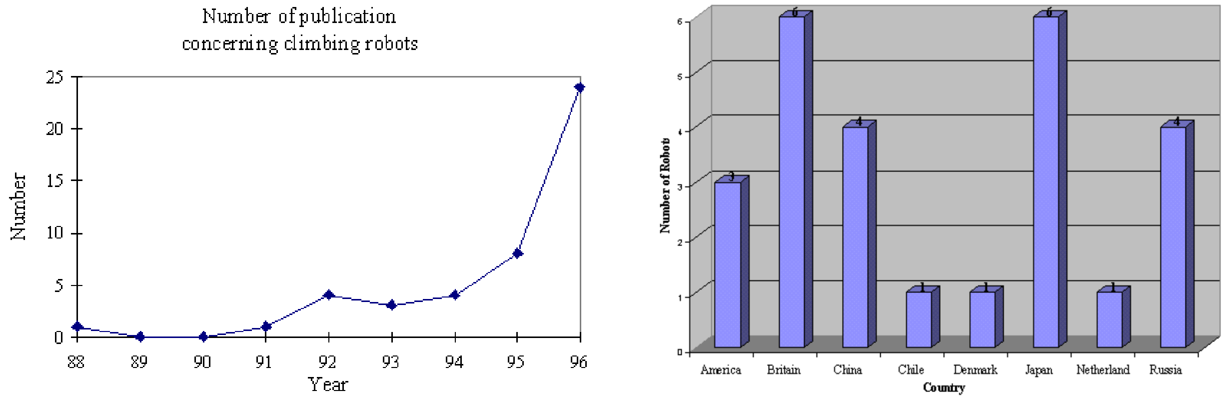

Figure 3: Right chart - Number of climbing robots developed by different countries (1984-96). Left chart: International publications covering climbing robots (1988-96)

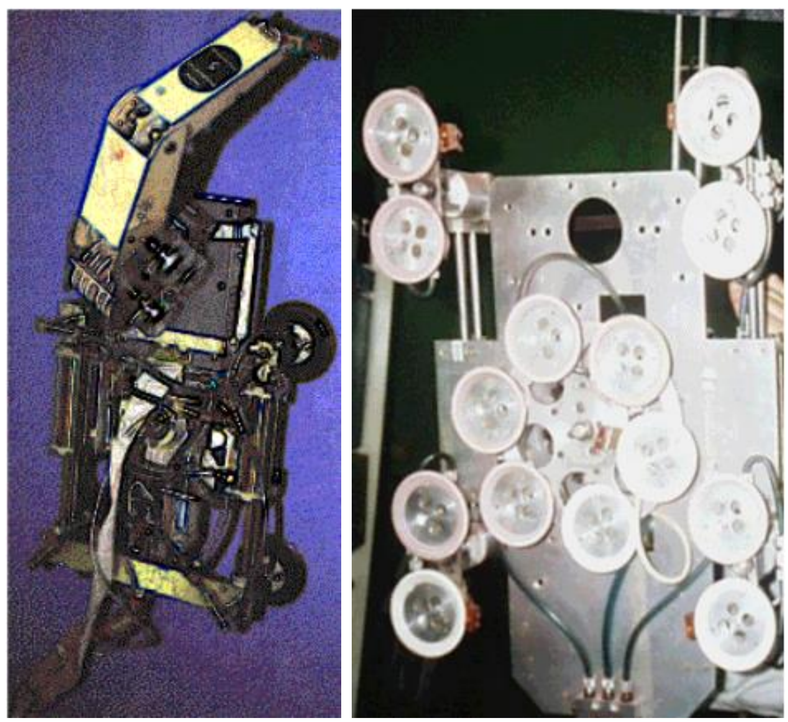

Figure 4: On the left, one of the earliest climbing crawlers in the World, developed by the Institute for Problems in Mechanics (IPM), Moscow in 1988. The robot was modified at the South Bank University, London to build a wall-climbing robotic NDT system by mounting a 5 jointed arm on the crawler. On the right is the suction cup arrangement of a robot built by IPM in 1994.

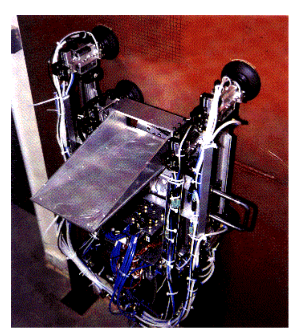

Figure 5: A typical design of wall-climbing robot that uses two alternately moving and adhering platforms to obtain climbing motion. Developed in 1995 at the South Bank University, London.

Figure 5 shows a typical design of pneumatic climbing robot that uses off-the-shelf components to construct a simple mechanism that uses two alternately moving and adhering platforms to obtain climbing motion. Linear motion of the platforms, relative to each other, is obtained by pneumatic cylinders while the robot changes direction by rotating one of the platforms with an air motor. A departure from this type of robot was the development of Robug II, which is described in [Collie, 1990, Collie, 1992]. This prototype was designed to demonstrate the feasibility of an articulated-limb crawler. Its architecture mirrors the structure of an insect. A central body that supports inspection or other equipment is carried to the required location by four (or more) 3 joint legs that are mounted at the corners of a platform and suspend the body clear of the surface. Every leg has a rubber suction cup. Suction pressure is created in the cup by an ejector vacuum pump. Suction feet are fitted to the main body so that it may be locked in place while inspection is taking place, or when the terrain is difficult and additional adhesion is required. Intelligence for control of the crawler is distributed, each leg being provided with individual microprocessor control. A foothold is tested before weight is transferred. The legs are able to step over obstacles and negotiate changes in surface level. The advantage of this crawler is its capacity to surmount obstacles but it may be difficult to keep the NDT sensor deployment platform steady during inspection.

4.2 Magnetic adhesion type of wall-climbing robots

There are many examples of mobile inspection systems that are designed to climb freely on vertical ferrous surfaces. They are usually electromagnetic wheeled vehicles that use magnetic adhesion. Some are equipped with 2-axis Cartesian robot arms and in a very few cases with 4-axis robot arms. The strong electromagnets used for adhesion pose problems of intrinsic safety in hazardous environments. There are no reports of the use of anthropomorphic arms possibly because the payload capacity available thus far is inadequate to cope with them.

Magnetic adhesion type of wall-climbing crawlers use either electromagnets or strong permanent magnets to generate adhesion force for the climbing vehicle. This type of robot makes up nearly 10% of the climbing robot family. The development of a wall climbing robot with two drive wheels and a single magnetic disc that is used to adhere the robot to a surface is described in [Men, Zhao, Xu, Wang, 1995]. Permanent magnets developed recently from rare earth materials produce tremendous attraction forces. The robots exhibit a high ratio (from 2 to 5) of adhesion force to robot weight. Hence, their payload capacity can be increased dramatically over the pneumatic adhesion type of climbing robot for the same adhesion surface area. Adhesion with permanent magnets during the motion of the crawler relies on maintaining an air gap between the magnet and the surface to which the robot is adhering. The size of the air gap determines both the actual adhesion force and the height of surface irregularities the robot can clear during motion.

The high adhesion force/robot weight ratio of magnetic crawlers enables their size to be more compact, e.g., a crawler of size 200 mm x 150 mm x 100 mm and mass 2 kg is capable of carrying a payload of 8 kg [Khalid, Wang, Rakocevic, Chen, Sattar, Bridge, 1996]. Permanent magnet robots possess a permanent safety property that is very important to some end-users that use high-value inspection instruments. The principal disadvantage of this type of robot is its inability to climb on non-ferromagnetic materials. It also attracts loose ferrite scales from inspection surfaces that are difficult to remove. Accumulation of ferrite scales in the air gap between the magnets and the adhesion surface interferes with the correct motion of the vehicle.

Figure 6 shows a tracked wheel type of magnetic wall-climbing robot developed at the Harbin Institute of Technology, China in 1993 [Wang, Liu, 1996] which allows its permanent magnets to come in contact with the climbing surface. It is shown climbing on a storage tank surface. It is equipped with two magnetic tracks arranged parallel to each other, each of which has eleven strong permanent magnetic blocks. The dimensions of each block are 30 mm x 30 mm x 20 mm. There are always eight blocks in adhesion with the surface while the vehicle is moving. The friction force that prevents the robot from sliding down the surface is tangential to the surface and is a product of the friction coefficient and the magnetic force normal to the surface. In order to increase the coefficient of friction between the wall surface and the tracks the blocks are covered with rubber. The robot can carry a payload of 20 kg at speeds of 2 to 8 meters per minute.

The use of wheel tracks brings three advantages over other methods. Firstly, the travelling speed of the robot can be up to 3 to 5 times faster than that of other types of climbing robot. Secondly, their ability to better surmount obstacles like rivets and welds on the surface without reducing the magnetic forces. Thirdly, tracked wheels can bridge air gaps in the surface. On the other hand, the disadvantages of this type of robot are that the tracks may damage soft layers of the climbing surface when the vehicle is turning to change direction, for example, the rubber lining on the inner wall of scrubbing tanks.

Models equipped with electromagnets do not have the favorable adhesion force/weight ratio of permanent magnets as electromagnets are very much heavier although they can be brought into contact with the surface and hence generate a large adhesion force. They lose their adhesion to the wall in the event of power failure and hence do not retain the safety advantage of permanent magnets.

Figure 6: The magnetic crawler developed at the Harbin Institute of Technology, China. The crawler uses permanent magnets in its wheel tracks to carry a payload of 20 kg.

4.3 Propeller type of wall-climbing robots

A propeller type of wall-climbing robot uses propellers to generate a propulsive force to lift a payload and the weight of the climbing vehicle. The first prototype crawler was developed in Japan in [Nishi, Miyagi, 1994]. The robot consists of a wing-shaped body (10m x 5.5m x 3m with wheels and propellers. Twenty-eight wheels are mounted on frames fitted longitudinally on

both sides of the body, with which the robot can move on the wall. Two propellers are symmetrically mounted on the body providing propulsive forces to drive the vehicle. The wing shape of the body generates a force to counterbalance wind turbulence.
This type of robot can be used in high temperature environments such as that encountered during fire-fighting activities. It is also able to climb on untidy and uneven surfaces, e.g., a brick wall surface.

4.4 Analysis and theoretical design of wall-climbing robots

A rising number of international publications on wall-climbing robotic technology from 1988 to 1996 present results in the areas of mechanics, kinematics, automatic control and principles of new mechanisms used for wall-climbing robots. An approach to designing climbing robotic systems in a modular fashion is proposed by [Collie, 1986]. A conceptual model of a wall-climbing robotic NDT system and its requirements are summarized, and the feasibility of using off-the shelf components to build robotic NDT systems is shown in [Chen, Sattar, Khalid, Fan, Bridge, 1994, Sattar, Chen, Khalid, Bridge, 1995]. The latter approach is useful for designers to minimize development time and subsequent batch production costs.

A detailed analysis of a pneumatically powered walking robot and an adaptive control strategy for its pneumatic actuators is given in [Collie, 1986]. The design and analysis of a wall climbing robot to find its most vulnerable position, the extent of stress distribution of the flexible suction cups due to the gravitation force and the load distribution of the robot via an AutoCAD simulation is reported in [Wen, Bahr, 1992]. The simulation is able to provide a realistic representation of motions of a newly designed robot and solve some design problems such as avoidance of structural collision. Analysis of the mechanics of climbing robots and equilibrium equations are derived in [Dransfield, et al, 1988, Abarinov, et al, 1989, Chernosusko, et al, 1990, Bolotnik, Nandi, 1992] which establish some fundamentals for the design of climbing robots.

The response capabilities of electric, hydraulic and pneumatic servo-drives to position a payload of 20 kg (which represents an industrial robot) are examined and a set of curves to illustrate their comparisons in performance are given in [Dransfield, et al, 1988], from which an adequate control method can be selected. Study of adhesion methods to generate a large pulling force is an important aspect in the design of wall-climbing robots. Comparisons of vacuum suction pads, permanent magnet feet and electromagnet feet are made in both principle and actual performance, to establish a criterion for selection of an adequate adhesion method for a prospective climbing robot [Sugiyama, 1986]. A scanning type of suction cup is developed to adhere to any wall surface across a crack or a gap [Ikeda, et al, 1988].

Accurate positioning of a robot end-effector is required to obtain good signal output from the NDT sensors but this has to be obtained in conjunction with fast speed of operation of the robotic instrumentation to gather data in reasonable time. Normally the slower a robotic device is operated the more accurate is it’s positioning. To balance these two aspects for any task, an approach for employing a macro-manipulator and a micro-manipulator is proposed [Kochekali, et al, 1991]. The macro-manipulator is used to transport the end-effector at fast speeds while the micro-manipulator is used for fine location and accurate poisoning. This approach may be potentially applied for fast and accurate deployment of sensors by robotic NDT systems.

5 A climbing robot approximating the ideal system

A prototype inspection system that meets some of the requirements described in section 3.3.1 is shown in figure 7. The system is designed in a modular fashion with off-the-shelf components to minimize development and subsequent batch production costs. The system consists of a pneumatically powered climbing vehicle that carries an anthropomorphic arm, the PUMA 260, with six degrees of freedom to replicate some relevant advantageous characteristics of the human arm. The PUMA 260 with a mass of 13.5 kg and a capacity of 15 N actuator load is capable of deploying a single dry contact ultrasonic probe with a position repeatability of better than 100 micrometers.

A static analysis of the turning moments tending to pull the climbing vehicle off the surface is carried out in [Bridge, Sattar, Chen, Khalid, 1997, Chen, 1999]. A rigid mechanism is assumed with zero compliance at the suction feet and the points of attachment of the climbing vehicle to the surface. Dynamic effects such as coriolis and centrifugal forces due to motion of the arm are ignored as the scanning action is performed relatively slowly. Also, when the arm is being moved to perform scanning procedures all the suction feet (central and side cups) are placed on the surface to provide a stable and secure base. The climbing vehicle experiences a rotating moment on the central and side suction cups when it is climbing at some non-zero angle to the vertical. It simultaneously experiences a sliding force and an overturning moment due to the weights of the climbing vehicle, robot arm and the umbilical chord. The two moments and the sliding force are all functions of the climbing height of the robot. This is due to the changing length and therefore mass of the umbilical between the vehicle and the point where the supply end of the umbilical is supported, and also the angle θ of the climbing vehicle's front-back axis to the horizontal.

Figure 7: Wall-climbing robotic NDT system developed at the South Bank University, London seen performing ultrasonic inspection of corrosion thinning on a 10 mm thick steel wall.

The design and theoretical analysis of the complete system is performed in [Chen, 1999] by establishing the kinematics and dynamics equations that describe changes of the center of gravity of an anthropomorphic robot arm and the effects of these changes on the performance of the wall-climbing robotic vehicle. The climbing robot is built with a new mechanism that doubles its travelling speed over that of other robots equipped with pneumatic cylinders of similar size. It uses a new intrinsically safe low power pneumatic device to rotate the robot (when changing its direction of travel) that replaces electric servomotors and hence it is able to work in flammable environments.

During vehicle motion the central suction cups and the side suction cups are placed on the surface alternatively. Therefore the weight carrying capability depends on either the central cups or the side cups (whichever has a smaller suction force). [Chen, 1999] shows that the sliding forces determine the maximum payload that can be safely carried by the climbing robot and that the rotation moments are comparatively negligible. The analysis establishes the functional relationship between the maximum theoretical payload, operational safety factor and climbing height. The payload and climbing height data given in table 1 has been derived from this analysis. The maximum height to which the crawler can climb is 39.5 meters for a design safety factor of 2.

The prototype inspection system is able to climb a variety of surfaces rapidly, deliver a large payload of NDT sensors with an industry standard anthropomorphic arm, and obtain c-scan images using wet and dry contact ultrasonic methods. It thus meets most of the requirements identified in section 3.3.2. Resolution tests give images of defect quality comparable with those obtainable with much less versatile Cartesian robots.

TABLE 1 Technical Specifications of the Climbing Robot System

Mass and weight (climbing robot)	23 kg, 226 N
Size (climbing robot)	740 x 540 x 250 mm
Maximum vehicle payload (on-board plus umbilical)	113/S - 23 kg (S = safety factor) e.g., 14.6 to 33.5 kg for S=3 to 2
Maximum climbing height with PUMA arm load of 13.5 Kg plus umbilical	225/S - 73 m (S = safety factor) e.g., 2 to 35.5 m for S=3 to 2
Stride (max.)	300 mm
Maximum climbing speed	2.5 meters/min
Rotation	±90°
Air consumption (max.)	240 liters/min. at 8 bars
Umbilical length	Depending on tank height
Umbilical mass and weight	0.5 kg/m, 4.91 N/m
Maximum available normal suction force by 4 side foot cups	1,848N
Maximum available normal suction force by 4 central foot cups	2,240N
Maximum available force per pair of actuators. There are two pairs of actuators	576N at 6 bar
Feet cup size. Side foot cups	100 mm diameter
Feet cup size. Central foot cups	110 mm
Feet cup material	Rubber NPV50
Maximum available friction force per side foot cup	280N on smooth metal

Maximum available friction force per central foot cups	300N on smooth metal
Inspection rate (area covered by the Robotic arm per unit time) of PUMA arm	Maximum scan speed 100 mm/sec, corresponding to 0.6 m/min for a 10 mm x 10-mm ultrasound probe
Maximum dimensions of system perpendicular to the climbing direction for the normal working envelope of the Robotic arm	350 mm
Mass and weight of the industrial Robotic arm (PUMA 260)	13.5 kg, 132 N
Scan area of arm for a fixed vehicle position	630 mm x 200 mm (max.)
Repeatability of the sensor placement	±50μm
Maximum length of the stretched Puma 260	570 mm
Scanning profiles	The arm can be programmed to scan areas of changing and unknown profiles by using the real time path modification procedures provided by the robot's operating system.

5.1 Prototype Tests: ultrasonic inspection of ferrous oil storage tank walls

The manual inspection of large storage tanks can be an expensive and time consuming activity involving suspended work platforms or the erection of scaffolding. A promising approach is to use the SBU inspection system to perform the task of detection of corrosion thinning on the walls of large storage tanks of the type used in the petrochemical industry. The PUMA arm is fitted with several ultrasonic probe holders to allow wet contact, dry contact (pick and place) and dry contact (roller probe) techniques to be implemented. The maximum contact force capability of the Puma 260 arm, at 15 Newton, is adequate enough to apply the 10 Newton force required for ultrasonic probes.

Typical c-scans (with continuous robot arm motion) obtained from a simulated wall thinning defect (due to inner tank wall corrosion) machined into the back wall of a vertical steel plate, are shown in figures 8 and 9 respectively. These images have been taken with a 5 MHz wet contact probe (8mm diameter single transducer) and 2.5 MHz dry contact roller probe (supplied by SILVER WING, a UK company). The latter had separate transmitter and receiver transducers (rectangular 10 mm x 10 mm) set in coaxial and parallel wheels with a 5degree angle between converging beam axes. These probe performances are validly compared (i) because the frequency in each case is the highest that would ordinarily be used taking into account the variety of surface conditions to be overcome in practice (i.e. surface corrosion and erosion and the need to propagate through multiple painted layers in various states of decay) and (ii) the near field beam cross sections are roughly comparable.

The defect is L shaped, 50 mm wide and covers a large fraction of the image area taken which was 200 x 130 mm. The depth varies from 0 to 6-mm i.e. to over the half the wall thickness. The defect is typical of the distributed wall thickness corrosion found on periodic tests of tanks in service. The c-scan image pixel size is 2 mm x 2 mm, determined by the corresponding intervals between pulse echo transit time readings. Transit time data corresponding to depths of 0-6 mm in from the normal back wall echo are quantised on a 16 color scale i.e. adjacent colors represent 0.375 mm thickness steps. This is a fine enough color-thickness scale for the particular defect and set of transducers under examination because the thickness to be observed will vary typically by 1 mm across the transducer beam in the direction of the defect width.

Edge resolution, i.e. definition of the sharp boundaries between the edge of the defect and the surrounding uncorroded back wall is evidently much better with the wet-contact probe, the resolution for which is mostly better than ± one image pixel i.e. 2 mm. The low trigger threshold used for the DSP card (6% of echo amplitude) and small spatial interval between successive time measurements allows the edge resolution to be much finer than the probe diameter.

Edge resolution for the dry contact probe appears to be about ± 4 mm. Comparison of figs 8 and 9 shows that over significant areas, the defect image varies by one color (but rarely more) from the color at the corresponding point in the image produced by the wet contact probe. Thus assuming that the latter image is the more reliable, the depth resolution with the dry contact probe is about ± 0.4 mm. One can infer that for the dry technique the minimum detectable thickness change is about 0.4 mm over a minimum cross sectional area of 4 x 4 mm.

Robotic scans of small volume defects e.g. flat bottomed holes (not illustrated here) using a finer color scale than in figure 8 and 9, showed that the wet contact technique can detect corrosion pits as small as 0.25 mm deep by 1 mm across. For the dry contact technique these dimensions are increased to 0.4 mm deep by 3.5 mm across.

The sensitivity achieved by the dry contact technique is good enough for general tank wall inspection. In this application a large area coverage is required and acceptable figures for minimum detectable size of corrosion defects are less stringent (typically 0.5 mm thickness change over an area of 10 mm x 10 mm). It is clear that the robotic system is able to detect these defects and is able to maintain a sufficiently stable contact pressure for this sensitivity to have been obtained.

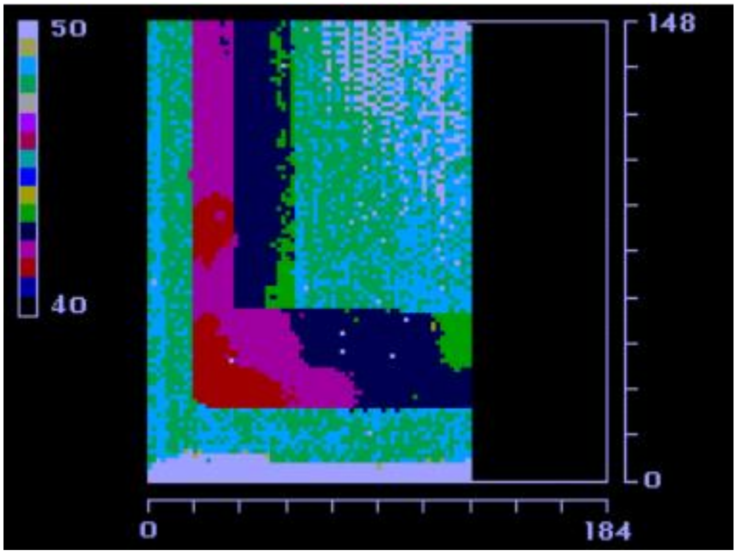

Figure 8: C-scan image of corrosion thinning in L shape cross section and of variable thickness 0 - 6 mm measured from the back wall, adjacent colors corresponding to thickness steps of 0.375 mm. Data obtained with 5 MHz compression wave 8mm diameter wet contact (immersion) probe

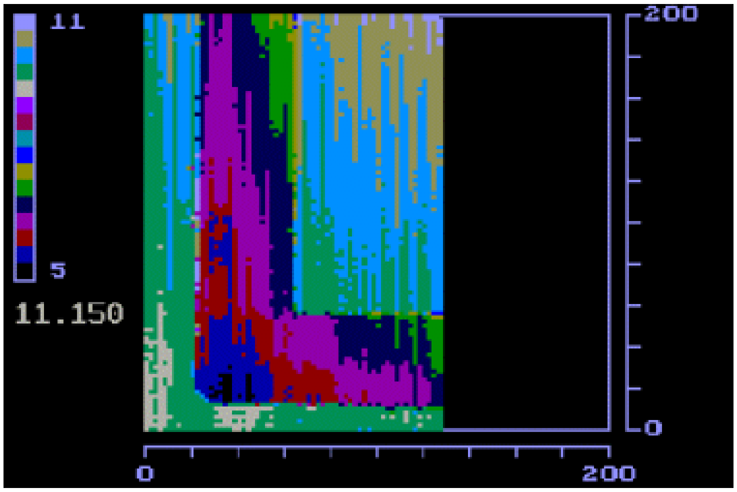

Figure 9: As figure 8 but obtained with a twin transducer dry contact wheel probe (2.5MHz compression, transducer dimensions 10mm x 8mm)

6 A more versatile wall-climbing robotic inspection system

A European funded project is developing a more versatile climbing robot and scanning arm to perform multi task inspection. The pneumatically actuated crawler shown in figure 10 deals with small convex curvature on a pipe of minimum one meter diameter as well as concave curvatures on cylindrical tanks of minimum two meters diameter. The suction feet have a pneumatically lockable ball and socket joint to adapt to these curvatures. A motor driven central hinge in the vehicle keeps one set of suction feet on the test surface with full purchase. All hinges have a locking capability for each surface curvature. For example, in nuclear pressure plant inspection activities at present six different automatic manipulators are used to test the complete pipe network with each manipulator being able to work on only one weld on one pipe diameter/nodal joint. The new instrument will be able to replace all six existing automated systems, with obvious potential improvement in cost effectiveness. Its use in a shipyard to inspect weld on the hull of a container ship will lead to the replacement of hundreds of manual scanning operations and eliminate operator fatigue and injury to neck muscles. Cost savings (in scaffolding costs) will be made by the new instrument during the inspection of LPG spheres and storage tanks. A conceptual drawing of the inspection system is shown in figure 11. The same instrument will test welds on the hulls of container ships, perform corrosion thinning inspection on LPG spheres and storage tanks in the process industries, and test nozzle welds from the inside on nuclear pressure vessels in the nuclear industry.

Figure 10: Prototype wall-climbing crawler developed by a European project that is capable of walking on the outside of pipes of minimum diameter one meter as well as on concave surfaces such as the inside of pressure vessels with minimum diameter of 2 meters. The crawler will carry a 7 DOF scanning arm capable of delivering an NDT payload of 5 kg.

The crawler carries a seven-axis serial link robot arm to scan a payload of NDT sensors in orbits round pipe works, including circumference welds with a placement precision of 0,5 millimeter. The payload of the arm is 50 N and is capable of deploying a small array of sensors (e.g. typically a set of 3 probes with a mass equivalent of 50 N when testing nodal joints on pressure vessels). The lowest conceivable mass of this arm built for industrial usage is 20-22 kg using presently available motors. The lightest presently available 7 DOF industrial arm suitable for NDT purposes (i.e. having sufficient precision, contact force and robustness) is a Mitsubishi arm at 35 kg, and a Hitachi arm at 30 kg with a reach of 1 meter. Hence, the arm being developed by the European project represents a significant advance for NDT inspection. The chassis dimensions of the crawler are constrained to be less than 560 mm x 380 mm so that it can be deployed through access holes in container ship constructions.

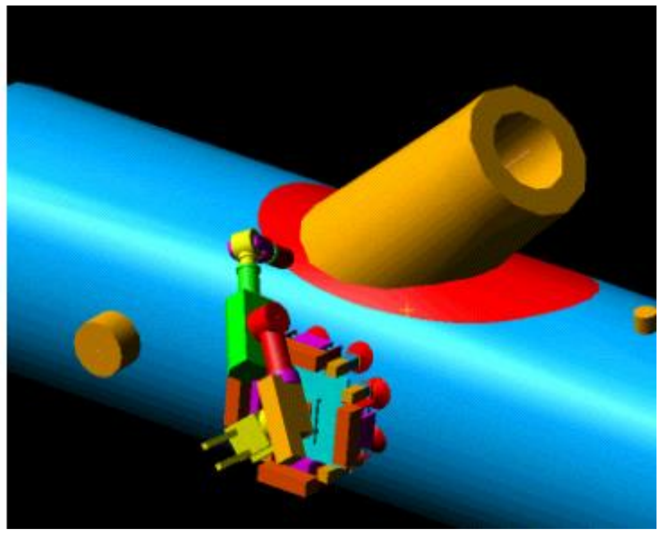

Figure 11: An AutoCAD drawing of the European funded development of a versatile climbing vehicle with a 7 DOF scanning arm capable of inspecting welds on nodal pipe joints and hulls of container ships, corrosion thinning on large storage tanks and LPG spheres.

The arm and crawler components of the system are designed to be transportable to the start of an inspection trajectory by no more than two operators, a common working practice requiring that no single worker should carry a weight of greater than 15 kg. The arm and vehicle are carried separately to the test and assembled together with a simple clip on mechanism in about one or two minutes. The main design problem is resolution of the essential conflict between the specifications for the arm and the vehicle. For the robotic arm,

(i) The repeatability of the end-effector position decreases with increasing number of degrees of freedom and overall arm length.
(ii) At the same time the mass of the arm increases with overall length and number of arm joints because of increasing weight of arm frame and because of the weight of the motors needed for each joint.
(iii) The arm weight also increases with the NDT probe contact force requirement.

Clearly (i) to (iii) mean that the greater the versatility of scanning of the arm, its load capacity and end-effector repeatability, the greater will be the weight of the arm and therefore the greater is the on board payload requirement for the wall climbing vehicle. However, detailed analysis shows that

(i) The load carrying capacity increases linearly with the total area of suction feet, and in turn the maximum possible area of suction feet that can be 'close packed' into a chassis cross section, will increase more or less linearly with the chassis cross sectional area.
(ii) But the vehicle mass increases, also roughly linearly with the cross sectional area (for a constant third dimension of the vehicle).

Thus increasing arm weight implies both increased vehicle mass and cross sectional area - but by the specifications of the end-users in the project:
(i) The cross sectional dimensions of the vehicle must be limited to be less than 560 mm x 360 mm.
(ii) The vehicle mass must be limited to be less than 30 kg, so that two persons can carry it.

7 Economic and industrial opportunities

Robotic automation of inspection throughout industry is a strategic technology for improved quality of flaw detection to obtain plant and operator safety, improvement of product reliability, and productivity enhancement by reduction of inspection time. The potential applications are numerous and still await suitable robotics technology. The versatility, dexterity and task repeatability that could be built into a single instrument will result in direct application to a whole host of applications. The World market for all sorts of diverse automated inspection equipment is worth about 1000 MECU annually. Replacement of manual inspection and improvement in task accuracy and repeatability with automation will improve the quality of remote inspection and give a competitive advantage over existing methods. For example, in commercial shipbuilding (cargo vessels) NDT&E is almost always performed manually, especially in the assembly areas of greater ship hull blocks and the dock area. The total number of man-hours used on manual NDT in a shipyard in Denmark costs 0.7 MECU. The economic benefit of introducing automation is substantial. A saving of 500 KECU per ship per year is possible and inspection productivity can be increased by 100-150 %. It is expected that automatic inspection will give a total saving of ECU 0.3 to 0.4 MECU per year or 1.5 to 2.0 MECU in five years. For testing of shell plate welds in the dock assembly area of a shipyard, as many as 330 cross section welds have to be inspected per ship. Hence, it is important that the inspection is fast, and fully automated once the climbing robot has been placed across the Block weld.

There are a large number of nuclear power plant, process storage tanks, civil engineering structures, and high rise buildings operated throughout the World. Their inspection is normally subcontracted to service inspection organizations that are expected to be the beneficiaries of technology developed. A definite area of application without much further modification of this type of inspection instrument is the civil engineering and construction industry which has a need for the remote inspection of tall structures such as bridges, dams, chimneys, high rise buildings, etc. The instrument would be useful for the visual inspection of the outside of these buildings. The potential market here is huge with almost every major country in the World having similar requirements.

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