A SET OF MOBILE AND PORTABLE ROBOTS FOR NONDESTRUCTIVE INSPECTION WHICH COVER CRITICAL APPLICATIONS ACROSS ALL THE KEY USE INDUSTRIES

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This paper describes the prototyping of some world first designs of mobile, portable robots which between them cover important safety critical applications across the spectrum of key civil and industrial engineering structures such as aircraft, ships, dams, nuclear power plant and storage tanks located in hazardous environments. The systems include novel features such as being able to climb over surfaces of complex contour to deploy the inspection sensors at each test point, ability to change surfaces, to work submerged in hazardous liquids and to scan large test areas. The rationale for using a robotic approach to NDT data acquisition is presented, given that it does involve some complexity in instrumentation design compared with current practice. A modular approach using as great a proportion of off-the-shelf components as possible has been used to greatly reduce the prototyping time.

1. INTRODUCTION

Some essential inspection tasks require automation when the risk to human life of manual inspection is unacceptable. There are also many other areas of inspection where human operatives are still used at the inspection site when remote and automated data acquisition would be preferable. Examples are inspection sites that are very hazardous because of radiation, toxic fumes and danger of fire or explosion. Lesser hazards arise when there is bad weather or excessively high or low temperatures which causes human operatives to under-perform. Finally there are cases in which the amount of data to be collected is so huge that human tedium prejudices the quality of the data.

When these conditions arise at present, much manual inspection is still carried out by using many operatives for a short period to lower the hazard exposure for each individual, but this increases the inspection costs.

In other cases automated testing has been introduced but these usually take the form of large fixed robotic gantry systems or smaller jigs fixed round the test-object and carrying multi-axis manipulators to deploy the sensors. Examples of the former are assembly line inspection in many manufacturing industries and steel plate inspection in rolling mills. Examples of the former are inspection jigs fitted round nodal joints in nuclear power plant coolant circuits and pressure vessels.

These systems have the common characteristic that they are limited in the range of tasks that can be performed, being limited to one physical location and having a small in-service time with associated high inspection costs. For examples manipulators bespoke designed for a specific nodal geometry at a specific nuclear power plant nodal joints in nuclear inspection are out of service for most of the time, i.e. between outages.

In contrast human operatives, for all their limitations, have the virtue of flexibility, being able to move around to different locations on a test object and between different geographical locations.

Our research philosophy is thus to design new generation inspection systems base on mobile (walking, climbing and swimming) robots that combine the best features of automation with the complimentary advantages of human versatility that derive from their dexterity of their arms, hands and feet, whilst also improving on that dexterity. An overall economic aim is to produce systems that improve cost effectiveness of inspection by having a high in-service time that stems from their versatility. On the other hand in some cases these systems will also be the only means of carrying out an inspection in a remote and hazardous location and cost is not then the key issue.

We describe here, only briefly because of the space available, representative examples of our prototype systems for application in the nuclear, shipping, aerospace oil and petrochemical storage tanks.

2. WALL CLIMBING ROBOTS SUITABLE FOR INSPECTION OF FLAT OR SLIGHTLY CURVED SURFACES SUCH AS WALLS AND CEILINGS ON STORAGE TANKS AND LARGE SHIPS

Working with pneumatic suction theses are our simplest robot designs (Figure 1) which need only rigid ankles to climb flat or slightly curved surfaces. Many design factors combine to make the payload capability (including mass of hanging umbilical) increase roughly in proportion to the chassis cross sectional area. The largest, weighing 37kg, is shown carrying a 6-axis Puma arm weighing 13.5 Kg deploying an ultrasonic sensor and it can climb to a height of 30 metres with a safety factor of 3, given an umbilical mass of 0.5 kg per metre. A linear walking mechanism combined with a turntable allow movement in any direction and power is provided entirely by compressed air to permit operation in safety critical areas. These systems are readily put in their starting position by two operatives working within manual handling regulations (which advise no more than 15kg per person)

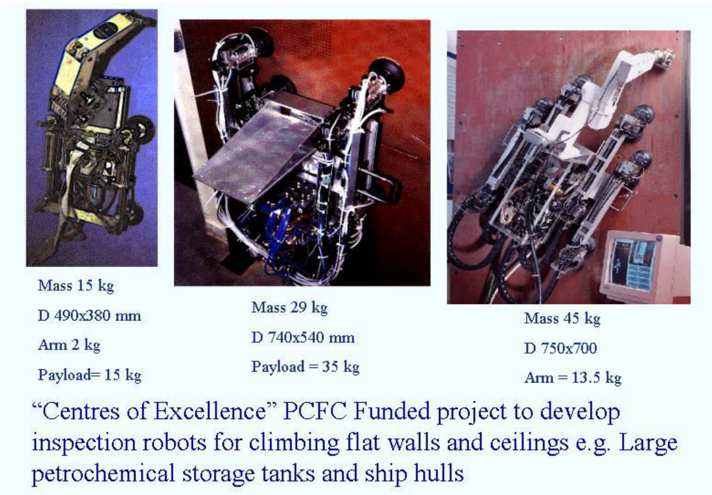

Figure 1 - Three prototypes of wall climbing robots for inspection of flat surfaces showing the trade-off between robot size and payload capability: the greater the payload the less compact and light the system can be

3. ROBOT FOR CLIMBING ON 3D SURFACES SUCH AS SPHERICAL STORAGE TANKS FILLED WITH AMMONIA AND OTHER INDUSTRIAL CHEMICALS

This robot (Figure 2), photographed with an empty payload platform, can climb over 3D Surfaces such as spherical storage tanks. This is achieved by means of two orthogonal walking (striding) mechanisms, 4 thigh joints and 8 universal flexible ankle joints, all operating under pneumatic power. The joints are made alternatively flexible for curved surface walking and rigid for carrying out inspection tasks, by means of a novel vacuum locking mechanism integrated into the control software for the walking mechanism. The 3D climbing facility limits the payload to about 13kg with a safety factor of 3. Pneumatic suction means that non-magnetic spherical objects such as ammonia storage tanks can be inspected.

The robot illustrated can climb over spheres with radius as small as 860 mm. However there is a severe trade off between payload and the introduction of this degree of adaptability to curved surfaces. Not only does the ankle joint have to be flexible but to complete a single walking step the thigh joint must be rotated and the feet must move forward. The length of the step cannot be too long otherwise the thigh joint rotation becomes excessive and is taken too far away from the curved surface, reducing the rigidity of the overall system and increasing the overturning moments, thus reducing the payload. The consequence of short steps is a slow moving vehicle. The multiple axis thigh and ankle joint mechanism also adds to the system weight and the complexity of the on board electronic and pneumatic control system. In summary this research has shown that load bearing robots can be made to circumnavigate very highly curved surfaces made of any material composition (for ferrous structures magnetic rather than vacuum adhesion would make for a much simpler robot) but only at slow speeds and with much less payload capability than is possible with rigid ankle robots.

Figure 2 - Robot for climbing on 3D surfaces

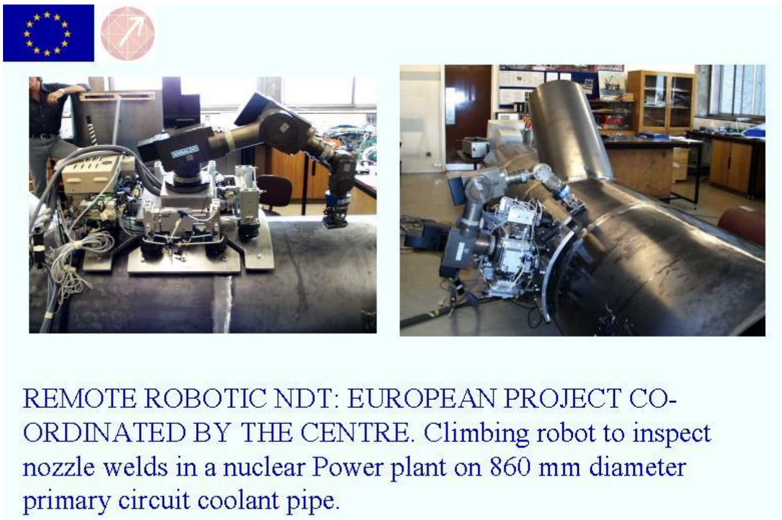

Figure 3 - Pipe climbing robot for weld inspection in lab tests

3. PIPE CLIMBING ROBOT FOR WELD INSPECTION IN NUCLEAR POWER PLANT

This robot (Figures 3-4) carries a 7-axis arm which deploys an ultrasonic sensor array at its end effector. This produces an inspection versatility greater than the human arm and wrist, permitting scans round very small pipe diameters. Also the arm can be programmed to perform an infinite variety of test scans such as TOFD, phased array. The vehicle itself is derived from the generic robot described in section 3. Two thigh joints have been removed and ankle joint movement restricted to one plane to permit greater suction feet area and rigidity and hence greater payload capability. The vehicle can climb over 2D curved structures such as pipes of any diameter, convex or concave, down to 860 mm carrying the 7 axis arm, to a height of 30m with a safety factor of 3, the maximum payload being 65 kg The arm weighs 22 kg and has an umbilical weight of 1kg per metre. The robot is illustrated testing a mock up of the 45 degree nodal joint on the primary feeder pipe in the Sizewell B Nuclear power plant. The vehicle can climb to any position on the feeder pipe so that the arm can scan completely round the weld line by the use of 8 vehicle locations. The whole system can be put in place in 2 minutes compared with the 10 minutes needed for the existing fixed jig automated system. This greatly reduces the time that operatives are exposed to radiation. Demonstrating its flexibility the robot is also indicated inspecting welds on a 6-ton mock up of a nuclear pressure vessel at the Trino nuclear power plant in Italy. Stainless steel structures are common in nuclear power plant and the robot is able to walk over these because adhesion is produced by pneumatic suction.

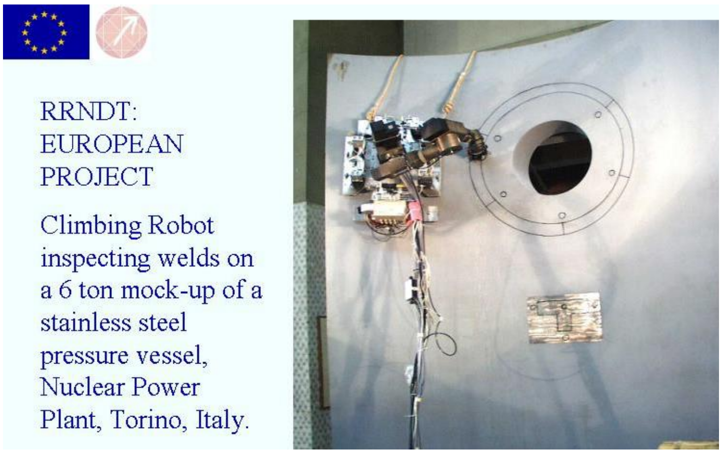

Figure - 4 Pipe climbing robot operating on internal surfaces of the mock-up of a reactor in nuclear power plant, Trino, Italy

5. MAGNETICALLY ADHERING ROBOT FOR INSPECTION OF LARGE AREAS SUCH AS CONTAINER SHIP HULLS

On ferrous surfaces it is advantageous to use magnetic suction for a climbing vehicle because up to a factor of 9 improvement in adhesion pressure can be obtained and generally design is simpler, avoiding the complexity of pneumatic control circuits for example, although electric power consumption can be problematical. A magnetic vehicle prototype carrying the 7-axis arm described earlier is shown in Figure 5. Fail-safe adhesion is obtained by the use of rare earth magnet feet which are removed from the climbing surface during walking steps by means of linear screws and rotary electric motors. Steps are achieved by means of two linear electric motors whilst are turntable permits vehicle movement in any direction. This vehicle is being developed further for simultaneous welding and inspection on the outside of container ships.

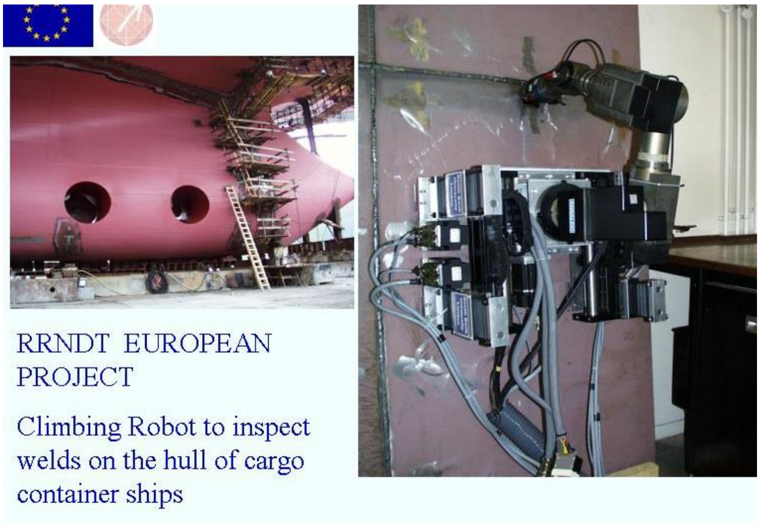

Figure - 5 Magnetically adhering robot for inspection of large areas such as weld lines on container ship hulls. In the illustration an ultrasonic sensor deployed by a 7-axis arm can be seen engaging a weld line.

6. TANK INSPECTION ROBOT

There is a need to inspect large petrochemical storage tanks without emptying them as at present as it is very expensive to empty a tank just for that purpose (£500,000 - £1,000,000). Figure 6 shows our prototype robot for inspection of the wall and floors of tanks from the inside whilst full of oil. Designed to intrinsic safety legislation this robot is small enough to fit through the smallest access hole in the world supply of storage tanks (300mm). With an estimated 400,000 large tanks in the world this provides a large potential inspection market and opportunities for environmental protection. There has been a case of a major tank leak which led to the evacuation of a medium sized town in the USA. It can move on wheels over the entire floor area of a tank in programmed paths, avoiding tank furniture with an on board navigation system. It can also change surfaces and climb tank walls up to the liquid surface by balancing propeller suction forces against buoyancy. An array of 20 ultrasound probes including two long-range probes, carry out the corrosion inspection of the entire structure including welds and overlapping plate join.

7. PLATE INSPECTION ROBOT

Presently steel plate in rolling mills is carried out by placing the plate under a large gantry inspection system which is a fixed installation. Our prototype mobile plate inspection robot shown in Figure 7 has the advantage that it can be moved around to any plate in any factory. When placed on the edge of a plate it navigates itself round the entire surface area of the plate in a raster scan, an on board eddy current edge detection system preventing it from falling over the sides of the plate. A linear wheel mechanism and a turntable allow movement in any direction. An array of 16 ultrasound probes along the back and front edges of the vehicle chassis captures the corrosion and delamination data.

Figure - 6 'Swimming' robot for tank inspection which can automatically change surfaces, scanning the entire floor area and then climbing trhe tank walls

Figure 7 - Plate inspection robot which self navigates itself round the entire surface area of metallic plates of arbitrary size when initially located on a near one edge. Designed originally for deployment in steel rolling mills

8. AIRCRAFT INSPECTION ROBOT

Presently military and civil aircraft are inspected almost entirely by traditional manual techniques. Where automation is used it takes the form of c-scan frames held on to a particular section of wing or fuselage by pneumatic suction pads. Flexible c-scan frames with suction pads have also been developed to cope with modest surface curvature. However the disadvantage is that the frame has to be moved manually to different test areas. The underneath of large structures such as the VC 10 tailplane are particularly difficult for manual operatives with strain to neck and head.

The robot prototype illustrated in Figure 8 has been designed to move over all curved surfaces of an aircraft with a curvature down to the fuselage of a Boeing 737. A four axis robot/c-scan frame is mounted on the flat payload platform illustrated. The design is effectively a hybrid between the flat surface wall climbing robots of Figure 1 and the design for highly curved surfaces (Figure 2 with thigh and universal ankle joints). Special design features include the mechanism to correct the vehicle movement errors, a new type of bionic suction feet like the super flexible octopus suckers to fit the different surface curvatures. Each foot has 4 suckers on independent suspensions which move like universal joints. However there are no flexible ankle joints like the robot described in Figure 2. This reduces the weight substantially and increases the walking step length and payload to weight ratio. But the curved surface adaptability is reduced. However, able to cope with the 737 size and upwards, as already mentioned, this robot covers most of the world's civil airline fleet (approximately 20,000 aircraft). Also introduced was an in-series control strategy to reduce remarkably the size and weight of the conventional umbilical.

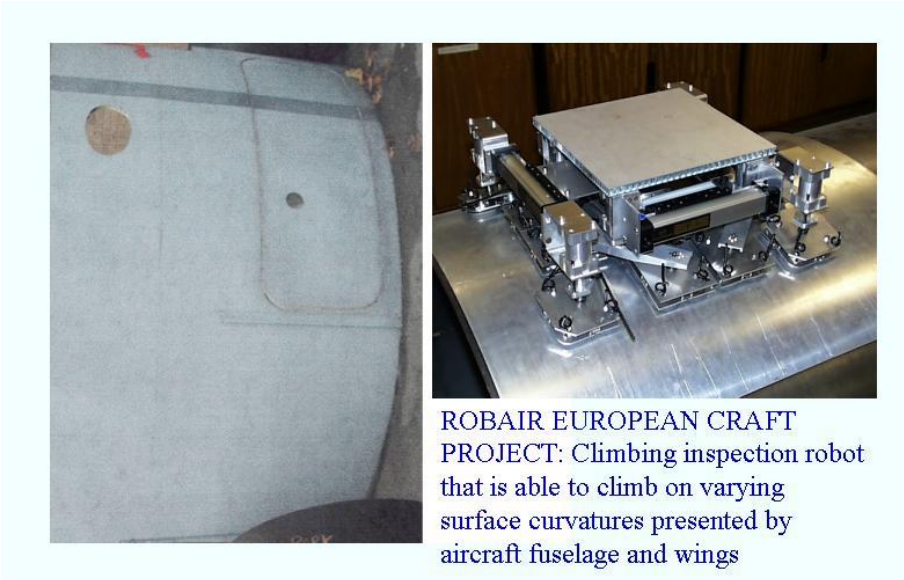

Figure 8 - Aircraft inspection robot on the mock-up of fuselage. This robot will climb over cylindrically curved surfaces of all aircraft the same size as or larger than the Boeing 737

9. CONCLUSIONS

A number of prototype mobile robotic non-destructive testing instruments have been described which between them are potentially applicable to a wide range, if not most inspection situations arising in the key use industries. Trial results to date are very promising and demonstrate exciting new possibilities.

In their design modularity principles have been applied, using off the shelf components as far as possible for cost effectiveness and speed in the design stages. A general performance principle is that the simpler the structure to be inspected the greater is the possible inspection speed (i.e. step speed) and/or sensor payload that can be deployed, for a given chassis size. All other things being equal payloads can be increased at the expense of vehicle chassis size and weight. In some situations very heavy sensors such as X ray tubes, Gamma ray imaging collimators for Compton scatter imaging, magnetic flux leakage coils and SQUID magnetometers could be deployed. Climbing over highly curved surfaces, however payloads for a given chassis size and also reduces inspection speed. Much research remains to be done to seek better compromises between the many design variables, especially in the design of dedicated sub components, especially ones with lighter weight.

Indeed the production of materials with greatly enhanced strength to weight ratio, is one of the greatest challenges. This is also the gaol of nanotechnology as applied to structural materials. Whilst the key aim of such nanotechnolgy research is to produce improved i.e. more economical airframes, as a spin off the kind of robotic ndt solutions that we have proposed could be revolutionised.

10. ACKNOWLEDGEMENTS

The projects described above were funded by the EU under the projects REMOTE ROBOTIC NDT, ROBTANKINSPEC, ROBAIR, and by British Steel (plates division) and the PCFCE (Centres of Excellence Award) and by the EPSRC.

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