# Walking and climbing service robots for safety inspection of nuclear reactor pressure vessels

**B.L. Luk[a] , A.A. Collie[b], D. S. Cooke[c] and S. Chen[d]**
[a] *Department of Manufacturing Engineering and Engineering Management, City University of Hong Kong, Hong Kong,*
[b] *Climbing Robot Company Ltd, Hayling Island, Hants.*
[c] *BOC Edwards, HSM, West Sussex.*
[d] *Department of Electronics and Computer Science, University of Southampton.*

Inspection and maintenance are essential in the nuclear industry. Failure to carry out proper maintenance could increase the chance of accidents which could result in severe casualties not only inside the nuclear plant but also in the nearby community. However, it is not easy to carry out such maintenance tasks since the environments are usually highly radioactive and unsafe for humans to work in. The usual way of carrying out inspection and maintenance tasks in these hazardous environments is by using long-reach fixed base manipulators. However, these manipulators suffer from low payload capacity and relatively large end-point deflections. Also, the installation and the storage of these long manipulators could be costly. An alternative solution is to use walking-climbing robots, which overcome the problems encountered by the long-reach manipulators.

Over the years, a number of climbing robots have been developed for various applications [1-15]. However, most of these robots are only engineering prototypes and have not been used for any extensive inspection and maintenance operations. In this paper, we describe a number of teleoperated walking-climbing robots developed by the authors, which include NERO series and SADIE series. These robots have been designed for remote inspection and maintenance applications, especially for the nuclear industry. All of these robots have been applied successfully in practical applications.

## NERO series of climbing robots

Magnox-type nuclear reactors form the early generation of commercial nuclear reactors in the U.K. In order to extend the life of an early-built reactor, a Non-Destructive Test (NDT) programme was set up to inspect part of the reactor pressure vessel (RPV) at the Trawsfynydd nuclear power station. Since the design of this reactor only provided limited access for engineering servicing, fixed base manipulators with multiple linkages could not reach all the required areas of the RPV.

As a result, NERO was designed to carry out various tasks of the NDT programme. NERO (Nuclear Electric Robot Operator) was a pneumatically driven non-articulated legged vehicle. It used vacuum gripper feet to hold on the RPV surfaces. It was originally designed to assist the installation of additional thermocouples onto the RPV surface. Later designs, NERO II and NERO III, were fitted with a wire brush and metal cutter respectively for surface preparation. NERO had the ability to step over small obstacles and crawl under low overhangs.

### *Design constraints*

NERO was designed to work on the outside surface of an RPV. The RPV was an 18.7m diameter welded steel sphere structure. The vehicle had to cope with this curvature and with any local variations. A cooling hood was situated over the top of the vessel to direct a flow of cooling air over the crown of vessel (see *Figure 1*). The gap between the cooling hood and the vessel was approximately 250 mm (see *Figure 2*). This gap restricted the height of the mobile vehicle. There were a number of thermocouples installed on the surface which were up to 25 mm high and which the mobile vehicle was required to step over. Due to prohibited access to the RPV because of the radiation hazard, the vehicle had to be driven remotely by an operator at the end of a 50m

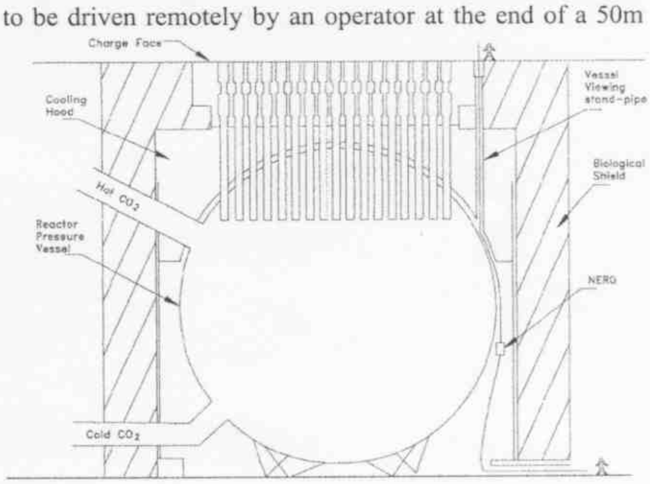


*Figure 1: Reactor pressure vessel.*

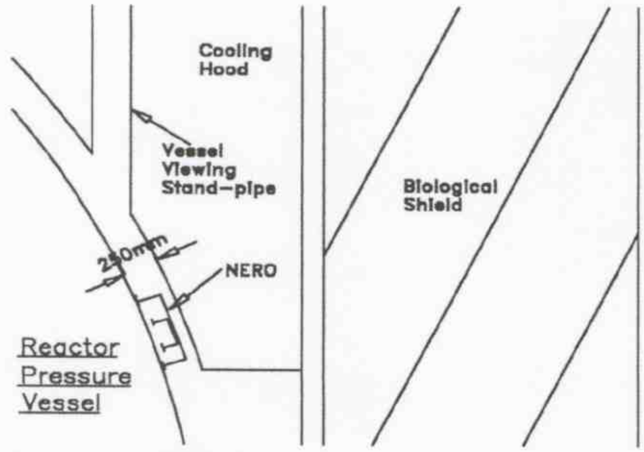


*Figure 2: RVP cooling hood.*

umbilical cable. Since the RPV surface was potentially covered with contaminated substances, it was an important design constraint that the feet did not collect loose material in order to allow the operators to service the vehicle. The surface preparation tools were heavy and together with the weight of the umbilical power and communication cable, NERO had to be powerful.

### *Mechanical system*

All the NERO type of tele-operated vehicles shared the same basic drive mechanism, consisting of two rectangular structures - a frame and a shuttle. The frame was the outer moving structure and the shuttle was the inner moving structure. Each structure carried four specially designed vacuum gripper feet which attached onto pneumatic extending 'leg' cylinders. This arrangement allowed the vehicle to step over 25 mm obstacles without the need of excessive headroom. In order to ensure that the vehicle could operate on uneven and rough surfaces, redundancy had been built into the system. The whole robot could be held onto the surface with only two front feet or a diagonal pair gripping. Compliance was obtained by adjustment of the leg cylinder pressures and was also provided by ball joints between the 'leg' cylinders and the gripper feet.

The translation movements of the structures were achieved by a double-acting pneumatic cylinder. The end of the cylinder rods were attached to the frame whilst the cylinder body was attached to a metal plate on the shuttle. This metal plate was connected to the shuttle rotary centre column. Rotary actuation was achieved by a further double-acting cylinder which was mounted on the shuttle plate and linked to the shuttle rotary centre column. Both translation and rotation pneumatic cylinders were controlled by solenoid valves. A pulse width modulation method was used to drive the cylinders in a force and position servo control system. The choice of pneumatic actuation gived the vehicle the high-power-to weight ratio and inherent compliance which had been found essential for climbing vehicles.

Motion was achieved by sequences of stepping, sliding and rotating movements. In order to move the vehicle, one structure would stand with its feet gripping on the surface whilst the feet of the other structure would be lifted and free to move. This allowed the structure with its feet lifted to rotate or translate. Movement in the same direction was achieved by swapping the raised structure with the gripping structure. An all-eight-feet gripping stage was implemented between swapping the gripping structure to ensure maximum safety while walking on the RPV surface.

In order to avoid picking up contaminated substances from the surface, the gripper foot developed its vacuum from a compressed air ejector pump. By reversing the flow, the air ejector cleaned the filter in the foot and at the same time cleared loose material on the surface prior to gripping.

Safety was one of the important issues in the design of the NERO system. The pneumatic control valves were arranged so that in the event of electrical power failure, the system would fail-safe by lowering the vehicle on to the surface so that it gripped with all eight feet in its lowest profile mode. The pneumatic supply system used two compressors and an automatic selection valve to protect the NERO system from pneumatic supply failure. Wherever possible a safety wire was taken up to avoid a damaging force in the event of a fall.

Three NERO type vehicles (see *Figure 3*) were built. NERO I carried a special tape feeder for installing additional thermocouples. NERO II had a rotating wire brush for removing loose materials from the RPV surface. NERO III (see *Figure 4*) had a 1.3 hp rotary disc grinder

*Figure 3 : NERO robot and its control console*

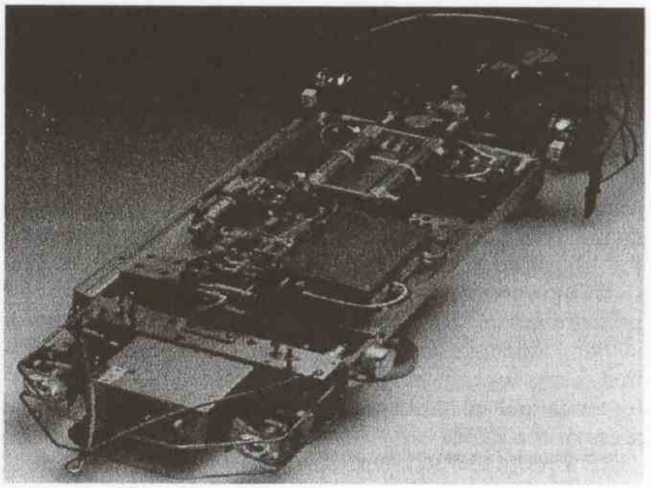

*Figure 4: NERO III.*

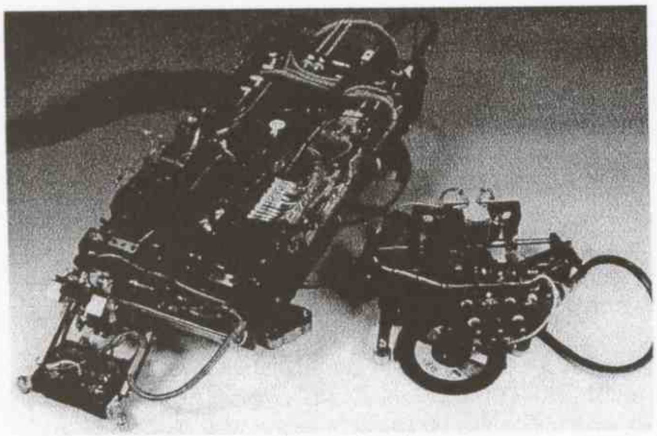

*Figure 5: SADIE robot and its tool packages.*

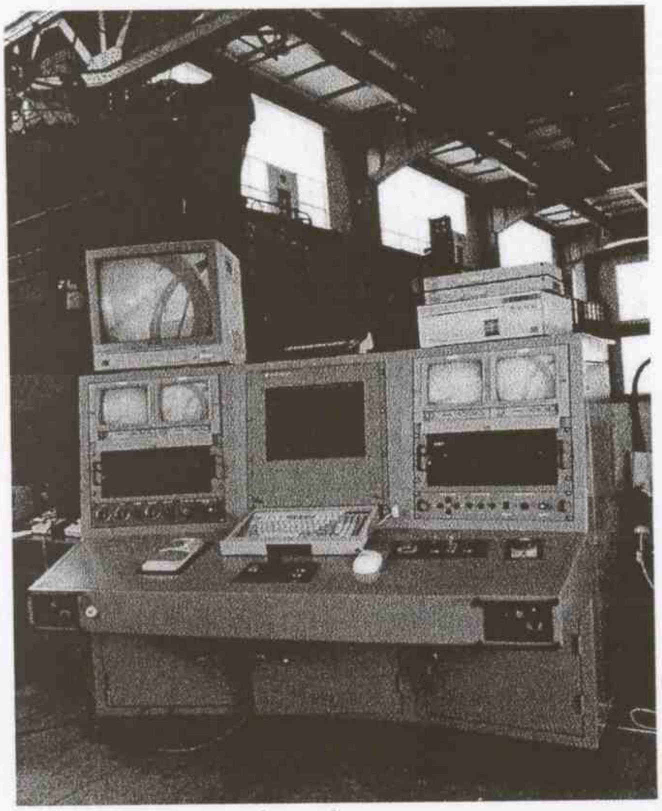

*Figure 6: SADIE control console.*

fitted on a swing arm and was mainly used for removing unwanted studs and weld splatter from the surface.

### Operational experience

Due to the limited access to the RPV, all the mobile vehicles had to enter the void containing the RPV from the 4 entrances at the base of the biological shield. Vehicles had to be hoisted up around the equator of the RPV before it was possible to place them onto the RPV surface. The 250 mm diameter vessel viewing stand-pipe was found suitable for feeding a steel cable from the charge face to hoist the vehicles. The umbilical cable of each vehicle was also fed through the vessel viewing stand-pipe. This arrangement allowed the operator to manoeuvre the position of the umbilical cable on the RPV surface and reduce the weight of the cables that the vehicle had to carry. Because of the convenience of hoisting NERO from this position, the vehicle control stations were placed on the charge face.

Since the radiation level at the entrance of the void was high, conveyor belts were set up at each entrance for transporting the vehicles into the void. Several ground mobile vehicles were also used to assist vehicle launching. Flat metal plates were installed on top of these ground mobile vehicles and the wall-climbing vehicle was placed on this plate during launching. The whole unit was then placed onto the conveyor. Once the ground mobile vehicle was transported inside the void by the conveyor, it carried the wall-climbing vehicle to a suitable location inside the void and the wall-climbing vehicle was then hoisted onto the RPV. Wires were attached at the rear side of the wall climbing vehicle. These wires were also connected to ground mobile vehicles and were used to manoeuvre the wall climbing vehicles onto the surface.

In-circuit television cameras and lights were placed inside the void to monitor all the launching operations. Cameras could also be inserted through the vessel viewing stand-pipe. However, all these cameras could only provide pictures around the equator area. As soon as the wall climbing vehicle climbed above the vessel viewing stand-pipe, it was solely dependent on its on-board cameras.

Once the vehicle had been launched onto the RPV surface, one operator was required to drive the vehicle, one worker was needed to handle the umbilical cable and one supervisor to oversee the operation. All the actions were conducted with extreme care to ensure the safety of the operations.

## Sadie climbing robot

The SADIE (Sizewell A Duct Inspection Equipment) robot was commissioned by Magnox Electric plc to perform non-destructive testing of various welds on the main reactor cooling gas ducts at Sizewell 'A' Power Station. It was determined that a vehicle similar in size (640 mm x 400 mm x 180 mm) and concept to NERO would be able to carry the necessary equipment for the range of tasks required, including pre-inspection preparation and ultrasonic weld inspection. The actual robot and its control console are shown in *Figures 5* and *6* respectively. A part of the requirement was that the robot would need to climb upside down at the top of the duct to inspect some of the welds. It was therefore necessary to develop a force controlled foot change-over sequence.

The welds which required preparation and inspection were RC 24, RC 25, RC 26, SC 12, M 1, L 1 and L 2. These are shown in *Figure 7*.

### Grinding application

During the initial design of the SADIE robot it was identified that some of the welds which required inspection were obscured by ladder brackets welded on or adjacent to them. A requirement of SADIE was to carry a specially designed grinding package to remove the ladder bracket. It was important that the ladder brackets were recovered from the duct and a grab mechanism was incorporated on to the cutting tool.

The ladder bracket removal package (LBRP) was mounted on the front frame of the vehicle and consisted of two main elements. An air-powered disc grinder mounted on a cross-feed, and a pneumatically operated grab mechanism.

The grinding tool and cross-feed were hinged about the axis of the cross-feed. A pivot allowed the cross-feed to rotate about an axis perpendicular to the cross-feed axis. These degrees of freedom allowed the grinder to follow the curves in the duct, providing compliance with the contours of the surface. This compliance was stabilised by ball transfer units on either side of the grinder disc and a centrally positioned pneumatic cylinder applying a steady force ensuring the transfer balls stayed on the surface. The pneumatic cylinder also provided lift to allow the grinder to be raised off the surface when manoeuvring into position. The cross-feed was driven by a force-controlled pneumatic cylinder.

The grab mechanism was positioned above the cross-feed. The ladder bracket was held in a U bracket with a spring-return piston actuating a bolt through the hole in the ladder bracket. The arm was actuated using additional pneumatic cylinders to provide lift/lower and extended/retract functions.

The mechanism used a camera for primary observation and micro-switches to indicate the ends of the cross fed travel. The cross-feed actuators utilised a differential pressure sensor to provide force sensing.

To allow more than one ladder bracket to be removed per deployment, a ladder bracket box was designed. This box was mounted on the deployment scoop. Its design incorporated a hinged lid which was kept shut with a spring. The lid traps the ladder bracket within the box.

### *Non-destructive testing application*

To inspect the welds, ultrasonic scanning was used. An inspection tool was designed by Magnox Electric for SADIE which could carry the ultrasonic transducers. An array of sensors were used in what was known as the probe pan. The probe pan used a gimbal joint to ensure that is followed the surface and was scanned across the weld by a servo-controlled linear axis mounted across the front of the vehicle.

The probe pan contained a system for squirting ultrasonic couplant around the transducers so that good quality signals were produced. The ultrasonic couplant was a water based gel to avoid the need for cleaning the gel after the inspection.

### *Deployment*

A major part of the operation was the deployment of the vehicle. A specially designed deployment system was constructed which comprised a framework and a radiation containment unit. This carried the vehicle deployment scoop, deployment cable and its associated winch and the umbilical management system. The vehicle deployment scoop was a four-sided box structure, on which the vehicle was positioned prior to deployment. Its angle was controlled by a winch drive and cable.

The vehicle was placed on the deployment scoop and the vacuum applied to the gripper feet. Having moved the frame towards the duct, the platform and vehicle were inserted through the duct access port and when the appropriate position was reached, the platform would be rotated to a vertical axis. The vehicle was then either driven off or lifted off (having first removed the gripper feet vacuum) by the umbilical/retrieval wire onto the landing zone, at the sloping surface of the duct bend. A combined umbilical and retrieval cable arrangement was used.

Retrieval was a reverse of this sequence, driving the vehicle up the duct until it was positioned on the scoop. Vacuum was then applied to cause the vehicle to attach itself to the plate. A rotation of the scoop when it reached the main door was executed to allow retrieval of the vehicle.

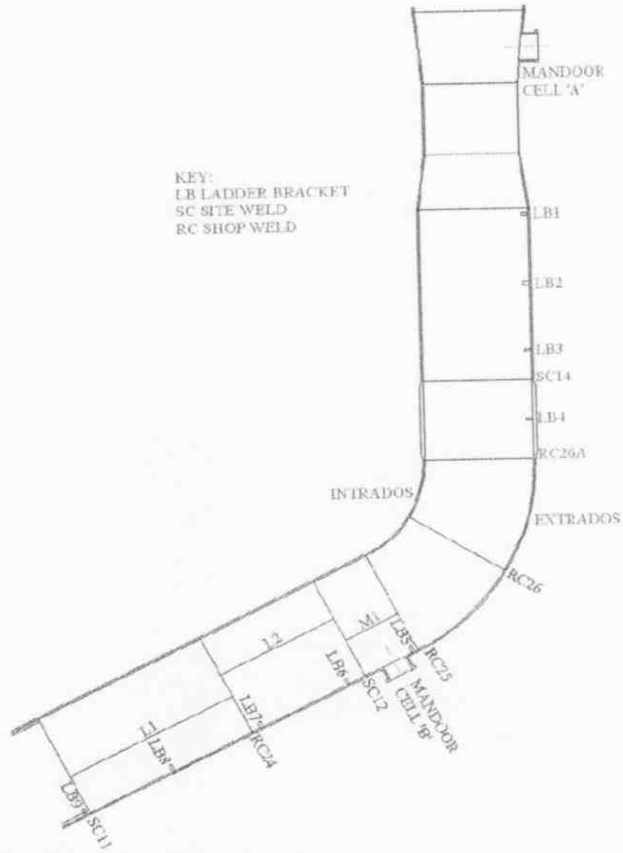

*Figure 7: Sizewell A air cooling duct.*

### Conclusions

This paper presented a number of climbing robots, which included NERO series and SADIE series. All the robots used the same sliding frame walking mechanism. In order to allow these robots to climb on different surfaces, vacuum gripping technology was used. For handling uneven or rough surfaces, force control was implemented to control the movements of the legs.

All these robots have been applied successfully in real applications and have confirmed the usefulness of these service robots for remote inspection and maintenance applications. However, the cost of these robots is still too expensive for many industries and they are mainly used in environments where there is no alternative method for carrying out the work. More effort will be needed to reduce the cost of the robots. With increasing demands in health and safety, there is no doubt that this kind of service robot will become essential in the near future.

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