Proceedings of the 32nd ISR(International Symposium on Robotics), 19-21 April 2001

Climbing Service Robot for Duct Inspection and Maintenance Applications in a Nuclear Reactor

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Abstract

SADIE climbing 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 in the UK. The size of the vehicle was 640 mm x 400 mm x 180 mm and was able to carry the necessary equipment for the range of tasks required, including pre-inspection preparation and ultrasonic weld inspection. The robot uses a sliding frame mechanism actuated by servo motors for precise position of the frames, and pneumatic cylinders for compliant leg control. Vacuum grippers are used for climbing vertical surfaces and magnetic rollers are used for stabling the robot during maintenance operations where large vibration forces can be generated by the tool packages. The vehicles can operate at any orientation whilst negotiating compound curves. 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 in order to prevent the robot to push itself off the climbing surface.

1. Introduction

Tall buildings and large structures are often required regular inspection and maintenance in order to ensure the safety of the buildings. Failing to carry out proper maintenance could cause life, damages to property and most importantly criminal charges. The traditional manual method is normally required the construction of costly scaffoldings. Human workers will stand on these scaffoldings to carry out inspections and repairs. Inevitably, this will increase the cost and slow down the maintenance process. Also, in some industries, such as off-shore industries, the nuclear industry, the chemical industry and the power generation industry where inspection by human workers is hazardous and difficult if not impossible. The usual way of carrying out inspection in these hazardous environments is 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. In recent years, the inspection programme carried out at Trawsfynydd nuclear power station [1] has demonstrated the successful use of such robots for remote inspection in hazardous environments. The usefulness of these robots has also been validated and confirmed by other similar projects [2] [3].

This paper describes a new teleoperated walking-climbing robot, SADIE, which shares many of the same concepts as its predecessors, the NERO series robots[1] and Tribot[2]. There were also many enhancements introduced based on the experiences from previous inspection works.

2. Operational Requirements

The robot was commissioned by Magnox Electric 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. 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 further develop the force controlled foot change over sequence designed for Tribot.

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 1.

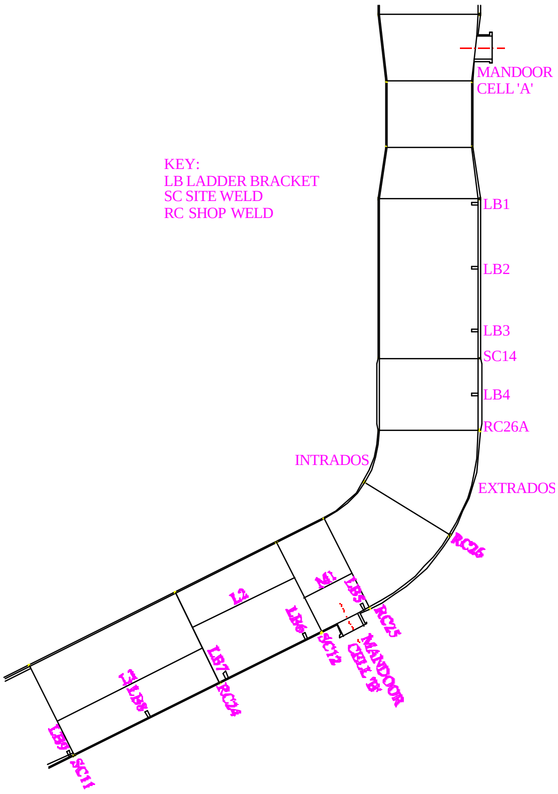

Figure 1. Schematic of the Gas Duct

3. Mechanical Design

The SADIE robot comprised a 'FRAME' and a 'SHUTTLE'. The 'FRAME' was formed from two parallel Titanium tubes secured at each end with support frames. The 'SHUTTLE' sub-assembly was a carriage that was driven along the parallel tubes by a servo motor and lead screw. Rotary movement was achieved by rotary joint embedded into the shuttle driven by a second servo motor and gear assembly.

At the front corners and rear centre of the frame were fitted pneumatic 'Leg' cylinders each comprising a vacuum gripper 'Foot' mounted on ball joints. The ball joint allowed the vehicle to negotiate curved or uneven surfaces. The shuttle had three feet arranged in pairs at the ends of a tripod boss. In order to provide additional stability during difficult manoeuvre and cutting operation, four magnetic feet were installed on the FRAME. Figure 2 shows an outline design schematic for the vehicle.

By optimising the design of the framework and the drive mechanisms the vehicle geometry was arranged so that without the work package it had an overall length of 640 mm, a width of 400 mm and a height of 180 mm. This balanced the deployment and curve travelling capability of the vehicle. The concept of the design was validated by using the robot solid modelling package Telegrip before the actual robot was built.

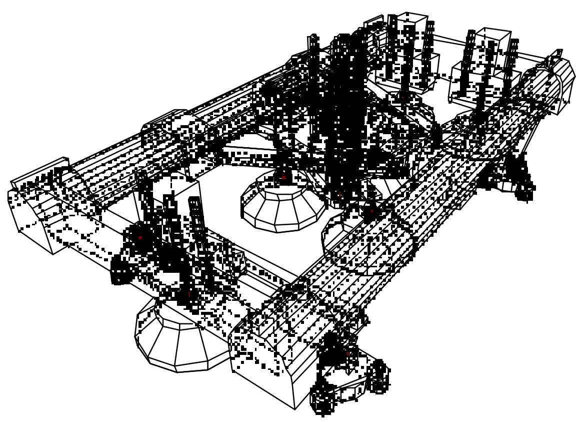

Figure 2. Mechanical Structure of SADIE

2.1 Vacuum Gripper Feet

Each of the vacuum feet had 3-degrees of freedom (although one is restricted) which enabled the vehicle to negotiate both internal and external radii surfaces as well as flat areas.

An important factor in the design of the vacuum feet was the requirement for the feet to be able to grip on a surface covered with ultra-sonic couplant. The couplant was a water based gel which made the surface slippery. The feet needed to have a good performance in shear. The pull off performance of the feet was not effected by the gel on the surface: in some cases it is improved.

The vacuum grippers comprised a rubber seal and an aluminium housing although for the shuttle and frame the design was manifestly different. This was because issues of torsional rigidity and shear performance need to be balanced. The resultant designs used the OEM pads in an epoxy shrouded for the frame vacuum grippers and a ‘spiked’ EPDM type gripper for the shuttle. The latter design used a high seal section and de-coupled the loading and sealing functions. This gave adequate shear and torsional performance.

An ejector pump was used to provide the vacuum. The foot was constantly supplied with air and can either 'suck' or 'blow'. The blowing action has the following effects :-

• Cleaning the filters in the foot

• Clearing the loose material from the area beneath the foot prior to placing it on the surface
• Self alignment of the gripper normal to the surface to obtain optimum placement.

In the event of a total electrical power failure, the arrangement of the control valves was designed such that the robot stops and 'sucks' with all six feet.

2.2 Magnetic Feet

Four magnetic roller assemblies, each with a gripping force of at least 800N were used. The purpose of the magnetic rollers was to provide additional gripping force to ensure vehicle to wall adhesion under all conditions of duct geometry.

Each Foot assembly was mounted individually on a swivel castor. Two of the units were mounted on the front of the frame and the other two were mounted as a pair on an articulated cross beam at the rear. This provided the vehicle the ability to turn in the duct (ie compound curve). Thus when the vehicle was required to undertake a steering frame rotation the Foot is able to align to the new direction of vehicle travel without forcing one of the magnetic feet from the surface. Since the robot weighs under 50kg, this magnet design provides ample adhesion for the arrangement of feet on the vehicle.

The magnetic feet had an additional benefit to the robots design, it stabilised the movement of the front of the robot. The front of the robot always remained tangential to the center of the curvature of duct between the front two rollers. This simplified the mounting of the tool packages and controlled the attitude of the tool package to the surface.

3 Control System

3.1 Computer System

The SADIE computer system consisted of two specially designed onboard embedded microcontrollers and a PC based Operator Console (see Figure 3). The robot was connected to the operator console via an umbilical cable which contained an electric power cable, two RS422 communication channels, a compressed air hose and two video camera cables.

The operator console consisted of a Pentium PC, a Visual Display Unit (VDU), a computer keyboard, a joystick, a mouse, four video recorders, four TV video monitors, switches and indicators, two head set units and a speaker. The Console is normally situated in a secured remote area and all these equipment provided the necessary information for the operator to operate the robot in a safe manner. Commands were issued by the operator through switches, key locks and a joystick on the console and also via the computer keyboard and mouse. The status and the movement of the robot were displayed as an animated mimic diagram on the VDU.

Figure 3 SADIE Control Console

The two on-board microcontroller units provided low-level control for all aspects of the robot's motion. Solenoid valves operated the cylinders and were controlled by discrete pressure pulses with force and position feedback. The quality of the vacuum was fed back to the microprocessor, via a signal derived from a pressure sensor, to ensure that the integrity of the grip is maintained during the foot changeover sequence. The on-board controllers also provided facilities for operating various tool packages, which could be attached to the front of the vehicle.

3.2 Control Software System

The SADIE control software system was divided into two main parts - SADIE operating system and SADIE supervisory control system. The SADIE operating system formed the firmware of the two embedded microcontrollers and was responsible for all the low level control and housekeeping of the robot. It handled the access to all sensors and controllable parts of the robot. The robot uses two micro-controllers each of which was used for different functions. One of the microprocessors controlled the pneumatic functions while the other controlled the servo motors.

The SADIE supervisory control system implemented on the Operator Console PC provided a human-machine interface to the operator. It allowed the operator to issue commands from the console control panel, PC keyboard and mouse. The program interpreted these commands and generated the required operating system protocol to control the robot. Since safety was essential for remote inspection, all the commands were checked before execution to ensure the safety of the operation.

4. Grinding Application

During the initial design of the SADIE robot it was identified that some of the weld which required inspection where 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.

4.1 General Description and Principle of Operation

The ladder bracket removal package (LBRP) was mounted on the front frame of the vehicle and consisted of two main elements. An air powered disk grinder mounted on a cross feed, and a pneumatically operated grab mechanism. A schematic drawing is shown in figure 4.

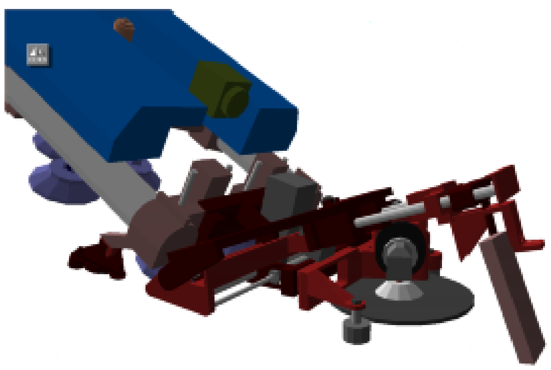

Figure 4 Solid Model of LBRP

The grinding tool and cross feed was hinged about the axis of the cross feed. A pivot allowed the cross feed to rotate on about 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 disk 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 in to 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 a lift/lower and extended/retract functions.

The mechanism uses 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.

4.2 Removal and Retrieval Sequence

The sequence used to remove a bracket was as follows.

a) The vehicle was manoeuvred into position by approaching the ladder bracket on a circumferential path and aligning the grab with the hole in the ladder brackets. The cross feed was at the left hand end of its travel and the grab arm lifted.
b) When in position the arm was lowered and the grab was actuated so that the arm was locked on to the bracket.
c) All the feet of the vehicle are attached to the surface and the cutter was started. Cutting was achieved by taking fine steps with the grinder cutting across the face of the bracket and returning to the start position. The vehicle is indexed forward to take the next cut. The indexing was repeated unit the cut is complete
d) During each cut all the feet of the vehicle had to be down. The grab arm will have a slight forward pressure so that when the cut is complete the bracket moves away from the cutting disk
e) On completion of the cut the grinder was stopped and the arm was lifted. The vehicle was now manoeuvred to the launching scoop which will contain the ladder bracket box. The ladder bracket was lowered into the box and released from the grab
f) The sequence was complete and may be repeated for the removal of other ladder brackets.

4.3 Cutter and Grab Control

The LBRP was controlled by the operator from the SADIE control console. The console provides a graphical interface and television views from the on board camera system. Operation was achieved by a series of pull down menus and control button. Cutter controls are only available if the operator had access to the correct password.

The operations selected by the user were interpreted by the console PC and sent to the vehicles on board microcontroller via a serial communications link in the umbilical. The onboard microcontroller switched the valves and other devices which control the tool.

4.4 Design Considerations

To assure safe reliable operation of the LBRP the following design features were included.

a) The grinder cross feed's ball transfer units were setup to provide a physical stop preventing the cutting disk from touching the parent metal.
b) The force control of the cross feed allowed only gentle cutting forces to be applied and thus minimise the risk of stalling
c) The cut was made in small indexed steps to allow precise control of the cutting process.
d) The grinding disk could only be started if the correct password is entered. Interlocks with the Emergency stop button and the grip of the vacuum feet were included.
e) In the event of electrical power failure the grinder automatically stoped and the grabs bolt pin released the ladder bracket
f) In the event of failure of the vehicle such that the grab bolt pin does not release the grab bracket was designed to have a weak link which will bend as the vehicle is recovered.
g) A camera was mounted on the grab to provide a close up view of alignment to the bracket and cutting disk.
h) The ladder lug box had a spring return lid to trap ladder brackets inside.
i) A grinder speed sensor was used so that cross feed force could be reduced if disk speed reduced to a level at which it may stall.

5 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 was 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 which as previously described necessitated that the vehicle used specially designed feet.

6 Deployment

A major part of the operation was the deployment of the vehicle. A specially designed deployment system was constructed which comprised of 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 was 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 be 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. The control of this used an existing Portech design of Linear Cable Engine Unit.

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

7 Conclusion

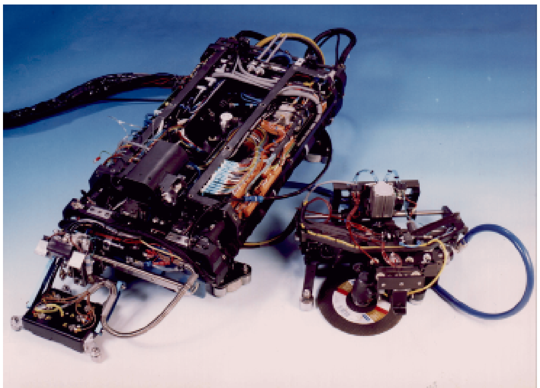

Figure 5 SADIE Robot with Work Packages

This paper described the design and the operation of a new teleoperated walking-climbing robot, SADIE (see figure 5). The robot have been used successfully to remove all the ladder brackets which have hindered the inspection process and inspect many metres of welds and operate for hundreds of hours in main cooling gas ducts at Sizewell ‘A’ nuclear power station. The SADIE project has demonstrated the usefulness of walking-climbing robots for remote inspection application. Although the robot was originally designed to be used in a nuclear reactor, the flexibility of the hardware and software structures mean that this kind of robots can be used in other industries. With the ability to carry wide variety of tool packages, the robot is a good delivery platform for various kind of applications. Maintenance, fire fighting and cleaning tall structures are some of the many examples of applications which these robots can be used.

8. References

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