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Snake-arm Robots Conduct Nuclear Maintenance

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ABSTRACT

In 2003, a leak was discovered in a critical section of pipe located amongst a complex system of pipework below the reactor of Ringhals 1, a boiling water reactor on the west coast of Sweden. Ringhals AB were not only required to repair the leaking pipe before the end of 2004, but also to provide a generic solution to maintain the other 156 similar pipes which could potentially suffer the same problem.

The contract was won by Uddcomb Engineering who proposed the novel solution of using OCRobotics' snake-arm robots to remotely access the pipe and repair the leaking section. OCRobotics designed two robots to conduct the repair: a Manipulation Arm to gain access from above the pipe along an 80mm wide, 800mm high corridor between rows of vertical pipes, and an Inspection Arm to access the room through 62mm diameter holes in the floor.

The single pipe repair was successfully completed in August 2004 and the generic solution, using snake-arm robots, fulfilled the Final Acceptance Tests one month later.

This new method is sufficiently flexible and versatile to be used to solve maintenance and repair issues across the industry.

1 INTRODUCTION – THE PROBLEM

In the regular summer shutdown of 2003, Ringhals AB discovered a leak in a strategic section of pipe located approximately 5m below the reactor vessel of Ringhals 1. The 42mm diameter SCRAM pipe forms part of a critical system activated during an automatic reactor trip and is situated near the base of the 205mm diameter, stainless steel control rod drive mechanism (CRDM) pipes. In the Ringhals design there are 157 CRDM pipes each with a corresponding SCRAM pipe.

These SCRAM pipes were never meant to be replaced or repaired. When Ringhals 1, a Boiling Water Reactor, came online in 1975 it was designed to have a life of 30 to 40 years. In the late 1990s, however, all Swedish reactors were assessed and found to be in better condition than expected. The Swedish government approved the continued use of the reactors provided that the reactors were maintained and operated to the highest possible safety standards and subjected to regular and thorough independent inspections.

On discovery of the leak the inspectors allowed the pipe to be plugged temporarily so that the reactor could continue to operate, albeit at a reduced output. The pipe had to be repaired before the end of 2004 and, additionally a capability to replace any of the other SCRAM pipes must also be demonstrated by this time. Further examination revealed a more widespread problem.

The CRDM pipes and SCRAM pipes are located in a room called the Common Insulation Room (CIR). The CIR is directly below the reactor and is almost completely occupied by the CRDM pipes. Figure 2 shows the access route to the CIR, although only a few of the CRDM pipes are shown.

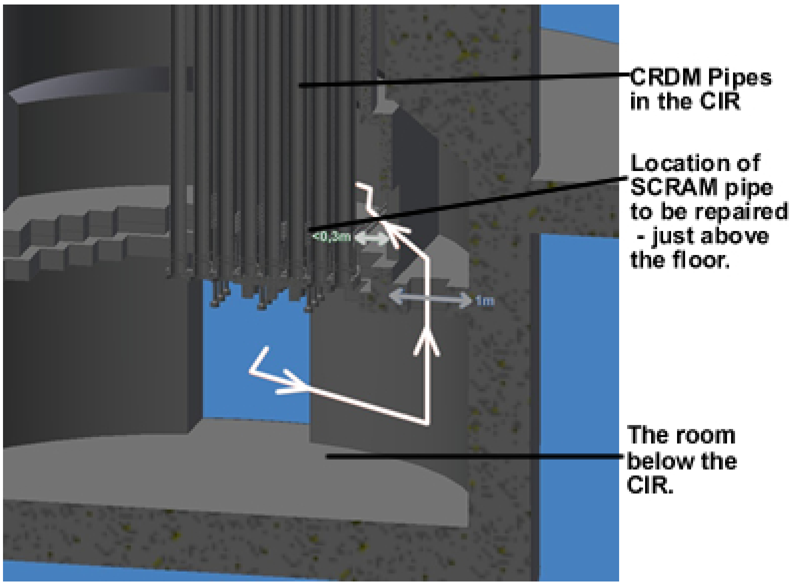

Figure 1: The route to the worksite

Figure 3 shows the grid of CRDM pipes cut down to reveal the network of 157 SCRAM pipes. There are also three further pipe systems in the CIR (removed from Figure 3) that further complicate the environment. There is no direct line of sight to the SCRAM pipes and access is possible via only two routes – from above, through alternate East-West corridors, or from below, through a series of 62mm diameter holes through the 150mm stainless steel floor.

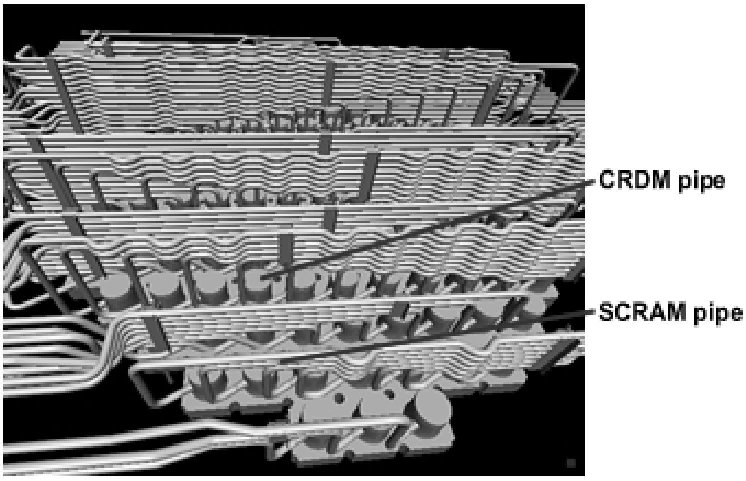

Figure 3: The pipework system in the CIR

In late 2003, when Ringhals AB asked companies to tender to conduct the repair, two of the three bidding companies proposed cutting down the CRDM pipes to create a man-sized access path in order to conduct a manual repair. It was recognised that, having cut down the CRDM pipes, it may have proved impossible to replace them to the required tolerances resulting in the shutdown of the reactor.

2 THE SOLUTION – SNAKE-ARM ROBOTS

OCRobotics has developed technology that has been used by a wide range of customers including the security forces, aerospace and nuclear industries. Snake-arm robots are specially designed to reach into awkward spaces such as jet engines and nuclear plants.

An OCRobotics snake-arm robot has a structure similar to the human spine: it is comprised of a large number of vertebrae. The arm is tendon driven with wires terminating at various points along its length. The result of this arrangement is that the curvature and plane of curvature of each segment can be independently controlled [1] as shown in Figure 1.

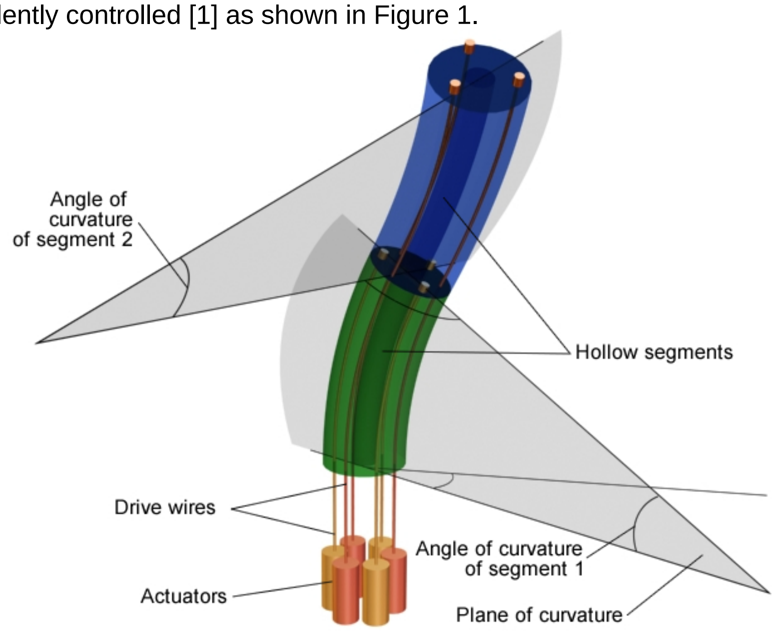

Figure 2: Segment curvature

A motor is used to control the length of each wire independently. The control software calculates the necessary lengths of all the wires to produce the desired shape.

OCRobotics has designed its own CAN enabled integrated intelligent amplifier servo controller that allows distributed control. All services are carried within the arm so that the external surface is smooth and continuous.

The user has three modes available for operating the robot:

Joystick path-following. The operator drives the tip of the arm using the tip camera views and the computer controls the rest of the device to follow the tip and, therefore, avoid any obstacles. Path following is achieved by coordinated motion of linear axis and the snake-arm axes. Stable motion is required for advancing and retracting.

Cartesian tip motion. Once at the work site the operator moves the tip of the arm in the Cartesian work space. This motion has to be achieved whilst also making sure that the rest of the arm does not hit any the obstacles previously avoided. It also means that the return path has to be modified for the arm to retract.

Joint mode. Individual joints are moved independently. This is used for 'in-situ' revision of the path and control of the final segment and wrist to optimise the view from a camera at the tip. Again we have dealt with the implications for retracting from the work space.

2.1 Collaboration

Uddcomb Engineering AB, working with OCRobotics Ltd and Climax Machine Tools Inc., won the contract by proposing a totally novel approach using snake-arm robots to gain access and repair the pipe. This approach removed the need to cut down any CRDM pipes. The Uddcomb bid received

100% support from Ringhals because the worst case scenario would be to replug the pipe and consider an alternative solution.

OCRobotics proposed using two robots: The Manipulation Arm gained access to the work area from above, along the corridor between the CRDM pipes and then down and around the other pipes to the SCRAM nozzle; the Inspection Arm was designed to enter through the 62mm diameter holes in the floor of the CIR and snake around a CRDM pipe to the SCRAM nozzle (Figure 4).

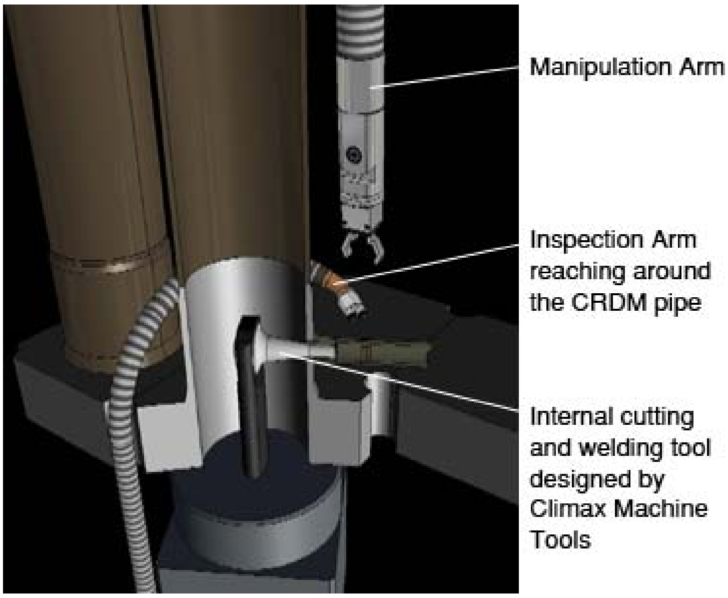

Figure 4: Pipe repair solution

2.2 Manipulation Arm

Figure 5 shows a CAD model of the Manipulation Arm system.

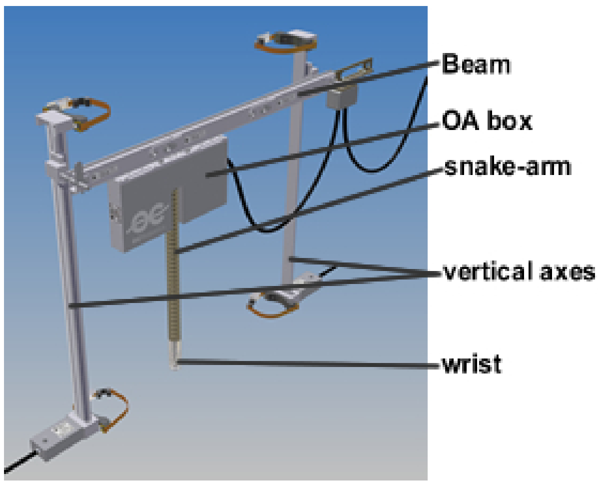

Figure 5: Manipulation Arm configuration

The widest part of the design was the 82mm wide Manipulation Arm Box which contained the drive mechanisms for the snake-arm. The arm itself is 60mm in diameter and 800mm long and has 9 degrees of freedom with a further 3 degrees of freedom available within a wire driven wrist of the same outer diameter. The arm and wrist axes are controlled by 16 motors and actuators located within the Manipulation Arm Box. This box is suspended on a rail on the underside of a horizontal beam made in modular sections for ease of installation and to cope with the different corridor lengths; the longest being 6m. The box moves along the beam using a friction drive driven by a motor and actuator within the box. Completing the system, the beam is suspended between two coupled vertical axes that lower the snake towards the work site. These vertical axes were secured to the CRDM pipes at each end of the corridor. The Manipulation Arm Box is completely sealed with a separate sealed channel for services leading directly into the hollow bore of the arm. Keeping all services within the arm avoids potential snagging problems and simplifies sealing against contamination.

In total, the Manipulation Arm employs 19 servo controlled motors to produce 13 degrees of freedom. To avoid the significant wiring problems associated with a centralised controller, OCRobotics developed its own CAN-enabled integrated intelligent amplifier and servo controller. This PCB allows distributed control which minimises wiring, heat output and enables a multi-layered approach to safety whilst at the same time being very small.

a. *b.*

Figure 6: Operator training on the Manipulation Arm

Figure 6 shows an operator driving the Manipulation Arm (a) in the initial training stage and (b) later on in the mock up. The horizontal scaffolding pipe represented the top of a stack of SCRAM pipes that had to be avoided. The operator is practising moving the fixtures into place around a dummy pipe. The operator has better than 50 micrometer motion resolution of any end effectors and is able to drive with respect to the pipe coordinate frame in Cartesian space. Computer controlled motion resolution (e.g. point to point) is better than 20 micrometers.

Once the operators were familiar with the basic operation of the Manipulation Arm amongst the scaffolding, it was disassembled and re-assembled in a purpose built mock-up of the real environment. The equipment had to pass Factory and Site Acceptance Tests before it could be used within the reactor. Figure 6b shows the partial representation of the CRDM pipes and the Manipulation Arm Box in position with the snake-arm starting to reach down to the worksite. Path-following motion is achieved by coordinating the motion of the two vertical axes with the snake-arm motion.

2.3 Inspection Arm

The second type of arm supplied by OCRobotics is called the Inspection Arm. It was designed to stand on the floor in the room beneath the CIR and, when fully extended, stands 4m tall.

The Inspection Arm is the more snake-like of the two with 23 degrees of freedom including a 2-axis wrist. The arm carried two cameras (together weighing 500g) around the back of the CRDM pipe to get a close-up view of the worksite (Figure 7).


a.

b.

Figure 7: Inspection Arm (a) reaching around a CRDM pipe in the mock up (b) viewing the worksite

Figure 7a shows the Inspection Arm gaining access through one of the 62mm diameter holes in the CIR floor and then reaching around the back of the CRDM pipe. Figure 7b shows the head of the snake with its two cameras of different fixed focal lengths pointing towards the SCRAM pipe nozzle. Figure 8 shows the view of the work site from the cameras.

Figure 8: View from the cameras on the Inspection Arm

The Inspection Arm was almost entirely controlled in path-following mode. The operator uses a twin joystick controller with one joystick being used to control progression and retraction along the path. The other joystick is used to pitch up/down and left/right. The path is created by the operator and the computer controls the robot to follow the path as closely as possible. The operator was also able to control individual segments of the arm. This was used to control the wire driven wrist and the final segment of the arm to optimise the viewing direction. The two different views offered by the cameras provided the operators with an excellent view of the Manipulation Arm gripper, the fixtures and all the tools as they entered the work site. Other cameras were mounted on the Manipulation Arm beam but their views were often obscured. Having an independent scene view was essential for working in such a congested environment and enabled the fully remote operation to be completed faster than was achieved with the operator standing next to the mock-up.

2.4 The Process

The pipe repair involved replacing a section of the original pipe by cutting either side of the fault and welding a new section of pipe in place. The cutting and final welding were done from within the pipe by tools gaining access from the room below the CIR, through the hollow bore of the CRDM pipe. Gaining access from within the pipe ensured that reliable geometric datums could be used and stiff mechanisms would achieve the precision required. Using a combination of both internal and external access made maximum use of the available workspace.

The robots were to conduct all of the necessary external tasks. The first task was to place fixtures around the SCRAM pipe to immobilise the end post-cut. FE analysis showed that, once cut, the free end might move by up to 15mm so it was agreed that the SCRAM pipe should not be allowed to move. The three fixtures placed around the pipe by the Manipulation Arm were little smaller than the space in which they had to be manipulated.

Once the fixtures were in place, the Manipulation Arm was withdrawn and the end effector was changed to a gripper to hold the section of pipe during cutting. Once the second cut was completed, the Manipulation Arm removed the section of pipe.

The next step was to locate weld preparation tools to reshape the outer surfaces of the cut pipe in preparation for the new pipe. This was one of the most demanding tasks due to the precise fit between the cutting tool and the cutting machine spindle.

The next task was to introduce the new section of pipe. The new pipe was then held in place by an internal mandrel which held the free end of the SCRAM pipe and the new section in compression with the CRDM end of the SCRAM pipe nozzle. Once held in place by the mandrel, the Manipulation Arm was removed and the gripper replaced by a tack welding tool. This tool was used to make four tack welds at 90 degree intervals around the new pipe to secure the new pipe in place. The mandrel could then be removed and the parent metal weld tool was internally introduced. The Manipulation Arm positioned a gas shield around the pipe while the internal weld was conducted. Once completed, the gas shield was removed and an inspection device was delivered that took a 360 degree radiographic image of the complete weld. Finally, the Manipulation Arm removed all the fixtures and exited the scene.

3 TRIAL INSTALLATION

After many weeks of training in the mock-up, the Manipulation Arm was taken into the reactor for a trial installation and operation as part of the independently assessed Acceptance Tests. This verified all the mechanical issues, the electrical subsystems and generally allowed the operators to become familiar with using the robot in the real environment.

Figure 9 shows the Manipulation Arm in the space around the CRDM pipes. A few SCRAM pipes are visible in the bottom right of the photograph.

Figure 9: Manipulation Arm in the CIR

The snake-arm had to be introduced in a bent configuration to avoid pipes that restricted access. The arm was then straightened once it was in the working corridor. Following the trial installation and operation the OA was decontaminated and taken back to the mock-up to complete the Acceptance Tests.

Figure 10: Manipulation Arm fully assembled in the CIR

Figure 10 show the Manipulation Arm fully assembled prior to moving along the corridor to the work site.

4 RESULTS

By the end of September 2004 Ringhals 1 was back on line and the pipe repair was declared a complete success.

The actual pipe repair was completed in three days; well ahead of schedule. Due to the incredibly tight timescales it was decided that the repair should be done manually as the leaking

SCRAM pipe was just within reach of an operator lying down and reaching between the CRDM pipes. The robots successfully replicated the manual process a few weeks later on the mock-up and the full process of replacing the pipe was completed in less than 24 hours. Completion of the Factory Acceptance Tests also required CE marking of the robots and the acceptance of a Risk Assessment. Both of these tasks were non-trivial for two completely new robots especially taking into account the lack of time to make any substantial changes to either design.

Ringhals has now installed a monitoring system that looks for any potential leaks among the SCRAM pipes and will conduct a thorough assessment of the state of all 157 nozzles during the annual summer shutdowns over the next few years. Whilst there have been no indications yet that any of the other 156 SCRAM pipes is leaking, should one be found then the robots will have to be instantly available to make the repair during the same shutdown.

5 CONCLUSIONS

Ringhals 1 is not an isolated case. With political opinion shifting back to nuclear power as a means to satisfy increasing power demands [2], the commercial future of the many reactors nearing the end of their original working life is dependent upon having the ability to maintain the reactor in excellent condition. It is now a key issue for all nuclear utilities to develop the necessary technologies to refurbish every part of these complex reactor systems. Snake-arm robots offer a flexible and versatile solution to numerous maintenance and repair issues across the industry.

ACKNOWLEDGEMENTS

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Thanks also go the Ringhals team, led by Finn Stenberg, for believing that the unreachable could indeed be reached.

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[2] Knight, R., 2005. What do the polls tell us?. *Nuclear Engineering International*, April 2005, p24-25.