SNAKE-ARM ROBOTS ACCESS THE INACCESSIBLE

OC Robotics

In summer 2003 Ringhals AB discovered a leak in a critical system of pipework below the reactor of the Ringhals 1 nuclear power plant, a boiling water reactor on the west coast of Sweden. A year later the pipe repair was successfully completed thanks to a novel solution using two snake-arm robots to carry out a first-of-a-kind repair in an extremely confined space with limited access.

The snake-arm robot is a technology developed by UK-based OC Robotics for use in a wide range of sectors 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 OC Robotics 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.

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. OC Robotics 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.

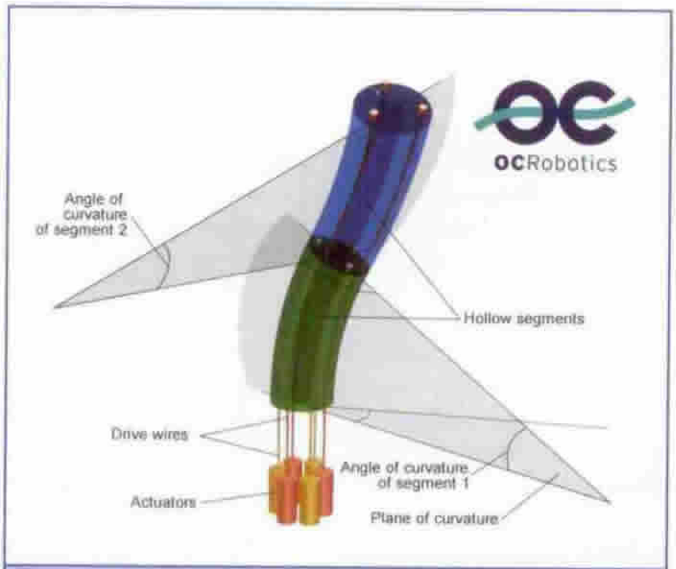

Figure 1: Snake-arm robots are slender, flexible manipulators that can follow a path into a confined space carrying cameras and other tools

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 while also making sure that the rest of the arm does not hit any of 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.

CRITICAL SYSTEM

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

The SCRAM pipes were never meant to be replaced or repaired. On discovery of the leak the inspectors allowed the pipe to be plugged temporarily so that the reactor could continue to operate 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.

The CRDM pipes and SCRAM pipes are located in a room called the Common Insulation Room (CIR). The CIR is directly

Figure 2: Overhead arm in the mock-up environment

below the reactor and is almost completely occupied by the CRDM pipes.

There are also three further pipe systems in the CIR 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 62 mm diameter holes through the 150 mm stainless steel floor.

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.

Uddcomb Engineering AB, working with OC Robotics 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.

OC Robotics 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 62 mm diameter holes in the floor of the CIR and snake around a CRDM pipe to the SCRAM nozzle.

MANIPULATION ARM

The widest part of the design was the 82 mm-wide manipulation arm box, which contained the drive mechanisms for the snake-arm. The arm itself is 60 mm in diameter and 800 mm 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. 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.

Once the operators were familiar with the basic operation of the manipulation, 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.

INSPECTION ARM

The second type of arm supplied by OC Robotics is called the inspection arm. It was designed to stand on the floor in the room beneath the CIR and, when fully extended, stands 4 m 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 500 g) around the back of the CRDM pipe to get a close-up view of the worksite.

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 operator creates the path 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.

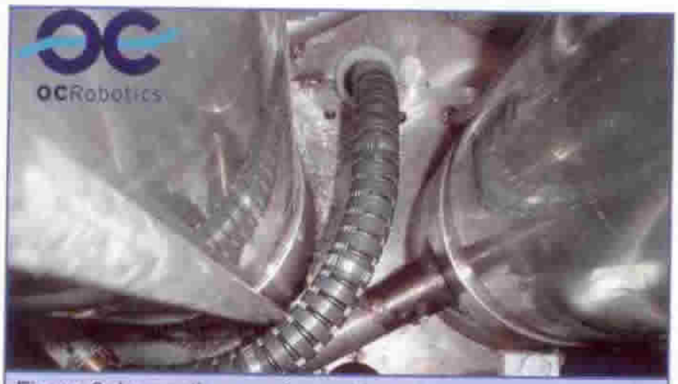

Figure 3: Inspection arm in position

PIPE REPAIR

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 data 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 15 mm 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

Figure 4: Snake-arm robots offer a novel solution in the confined spaces of nuclear power plants

with the CRDM end of the SCRAM pipe nozzle. Once held in plac by the mandrel, the manipulation arm was removed and the grippe replaced by a tack welding tool. This tool was used to make fo tack welds at 90 degree intervals around the new pipe to secu the new pipe in place. The mandrel could then be removed and th parent metal weld tool was internally introduced. The manipulatio arm positioned a gas shield around the pipe while the internal we was conducted. Once completed, the gas shield was removed an an inspection device was delivered that took a 360 degre radiographic image of the complete weld. Finally, the manipulatio arm removed all the fixtures and exited the scene.

TRIAL INSTALLATION

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

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

ON-LINE

By the end of September 2004 Ringhals 1 was back on line an 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.

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. ■

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