Snake-arm robots to support plant life extension

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Life extension and plant management of nuclear assets is a critical issue for nuclear operators. There is a growing requirement to ascertain the state of the nuclear systems by means of direct plant measurement, with the consequential requirement to conduct in-situ repairs. These requirements have driven the development of new remote handling techniques.

This article considers the application of a new design of remote handling systems to two different tasks within different reactor types. The first task involved removal and replacement of a section of SCRAM pipe within a BWR. The second task involves the first deployment of a new inspection tool to access primary circuit feeder pipes within the Upper Feeder Cabinets of CANDU reactors. Both tasks have confined space, limited access requirements, in addition to nuclear radiation hazards. The snake-arm technology presented in this article demonstrates an increased ability to conduct remote handling operations within confined spaces; spaces that might otherwise have been considered too awkward and dangerous to access.

Snake-arm robots

A snake-arm robot is a long slender, tele-operated manipulator that uses some clever software to 'nose-follow' into confined spaces and snake around obstacles. Motors and electronics are located at the base of the arm with mechanical power being delivered to the arm joints by flexible wire ropes. Services to fixed tools or insertable/replaceable tools are carried within the arm so that the external surface is smooth and continuous. The result is a lightweight arm with constant arm diameter and a smooth exterior. The arm has been designed for reliable extraction. www.ocrobotics.com/catalogue has more details of the Explorer range of snake-arms.

Ringhals SCRAM pipe repair

In late 2003 a leak was found in a critical pipe at Ringhals 1 nuclear power plant, Sweden. As a short term measure the pipe was plugged and output reduced, but the inspectors required the operator to repair the pipe and demonstrate a generic capability to replace any of the 156 similar pipes if examination revealed a more widespread problem.

The challenges were two-fold. Firstly, a repair of this kind - replacing the leaking section of pipe with a new piece using a new 'parent metal' welding technique - had never been done before. Secondly, the leak was close to the control rod drive mechanism (CRDM) pipes in a section called the SCRAM nozzle. Access is limited, and the repair had to be made in an extremely confined space.

CRDM and SCRAM pipes are located in the Common Insulation Room, nicknamed 'The Jungle'. The Jungle is located below the reactor and is completely occupied by 157, 205mm diameter stainless steel CRDM pipes space on a square grid with pitch 305.5mm. Access to the leaking SCRAM nozzle was either by cutting out CRDM pipes or reaching between the pipes using specially designed tools. The latter option was chosen as it presented the lowest risk to continued plant operation.

Two snake-arm robots were commissioned and designed to gain access to the very restricted space. The smaller 40mm diameter, more flexible arm was design to gain access through holes in the floor and to reach up and around the CDRM pipes. This inspection arm carried cameras to provide a stand-off view of the work site. The manipulation arm was a larger 60 mm diameter arm which placed and held various components during the cutting and welding procedure. Two arms working cooperatively are often a better approach than using just one arm for the simple fact that camera views can easily become blocked by the process tools and the environment.

The pipe repair involved replacing a section of the original pipe by making cuts on either side of the fault, removing the pipe and then welding in a new section of pipe. The cutting and final welding were both done from within the pipe providing the ability to use reliable geometric datums and build stiff mechanisms to achieve the precision required. Using both internal and external access made maximum use of the available workspace.

The task of the snake-arm robots was to perform all external supporting tasks. This included securing three fixtures - which were not much smaller than the space in which they had to be manipulated - around the SCRAM pipe to immobilize it during cutting. The manipulation arm was retracted and the end effecter changed to a gripper, which grasped the pipe section during cutting and removed it once complete.

The next phase involved delivering and locating a weld prep cutting tool which was used 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 involved the manipulation arm introducing the new pipe, which was held in position by an internal mandrel. The manipulation arm returned with a tack welding tool, and made four tack welds at 90 degrees on both of the welds - this secured the new pipe in position and enabled the metal welding process to begin. The manipulation arm was then used to place a gas shield around the new pipe to prevent oxidation of the weld.

Having removed the gas shield the manipulation arm was then used to deliver an inspection device that took a radiographic image of the complete 360 degrees of each weld. The final task of the manipulation arm was to remove all the fixtures and exit the scene. The complete repair was conducted in less than 24 hours.

CANDU reactor feeder pipe inspections

In a CANDU reactor, pressurised heavy water enters at the core at 250°C and exits at 290°C. The outflow feeder pipes converge on header tanks within Upper Feeder Cabinets (UFC) before rising into the steam generators. Access to the UFC is via a narrow staircase adjacent to the reactor face inside the reactor vault. Inside the UFC there are three suspended catwalks that run between the feeders. The feeder pipes themselves are densely packed.

The integrity of the feeder pipes is essential to safe operation of the plant. Because the pipes are 10's of meter in length they have to be supported and in CANDU reactors the interaction between the pipe supports and the feeders is an area of concern.

The potential for fretting necessitates direct examination to establish the presence and extent of any damage. Inspections are conducted during outages when the reactor operates at low power and requires people to enter the vault with measurement equipment and conduct inspections as fast as possible in order to minimize the dose received. For example, to reach the hangers an inspector must lie on the catwalk and reach down under the catwalk with a camera on a stick and take pictures. There are some areas that cannot be viewed and it is also difficult to revisit specific points of concern.

Snake-arm Feeder Inspection Robot Equipment (SAFIRE) is justified as a dose reduction tool with the potential to shorten the outage critical path. A further significant advantage is that once installed a robot can work around the clock with an availability of 100% whereas an operator may only be able to work for a few hours before their annual dose limited is reached. This time pressure affects the quality of data captured and does not allow operators to gain experience.

SAFIRE is a remotely controlled machine that is equipped with a 2.2m long, 12.5mm wide, 19 degree of freedom arm that can snake under the catwalk and between the hangers to deliver cameras to take images of the pipe work. The arm is mounted on a vehicle

Snake-arm robots CANDU

Snake-arm robots: BWR

Inspection arm cameras viewing the work site

Upper Feeder Cabinet

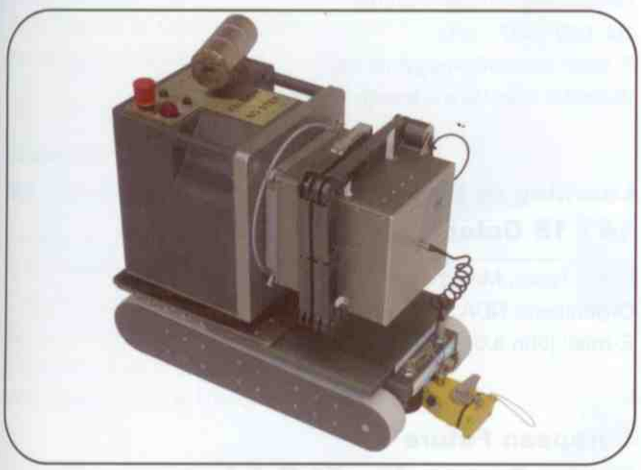
which can be driven along the catwalks allowing SAFIRE to view the complete cabinet without manual intervention. The arm can also reach above the catwalk to inspect the header tanks and other systems within the feeder cabinet.

SAFIRE is controlled from within a trailer parked near the reactor buildings. The operators are able to sit in the comfort of the trailer and drive SAFIRE remotely. This gives the right people the opportunity to collect the right information in an environment which enables thought and conversation, without incurring dose.

Materials were chosen and factors of safety and failure modes were optimized in the design of the system to minimize the risk and consequences of failure. These concerns must be balanced with ease of installation and operation, both of which might be a more significant contributor to the overall safety and reliability of the system. SAFIRE uses commercial grade electronics which should have a life of around 10,000 hours in the radiation field expected. Non "rad-hard" cameras are designed to be changed more frequently.

SAFIRE is not a high risk device since it does not pose a danger to the pressure boundary itself. SAFIRE, like the manipulator and inspection arms used at Ringhals, was designed so that the arm is compliant. The arm is effectively too weak to cause significant damage. The motors and actuator mechanisms were designed to enable the arm to reach into the pipe work systems but the in line and lateral force that the arm can exert on the pipe work is limited.

SAFIRE was deployed for the first time at Pickering, Canada, during May 2010. Set up time was 70 minutes from the time the operators entered the vault with the equipment to the system taking live images under control of the same operators sat in the remote trailer. The inspections were conducted over a twelve hour period using two operators who received no further dose. Breakdown was completed in 30 minutes.



SAFIRE with arm stowed coiled

SAFIRE with arm deployed below the walkway (in mock up)

Two operators are used to fly the arm, with one responsible for motion and the other responsible for gathering data. SAFIRE uses proprietary nose-following software which allows the operator to control the 19 degree of freedom arm with ease. The operator uses a twin analogue joystick controller to fly the tip of the device whilst the computer ensures that the remainder of the arm follows the path of the tip. Operation is intuitive: the basics can be learnt in minutes.

SAFIRE has a number of cameras and lighting systems. Two identical compact PTZ cameras with matched lights are mounted one each on the vehicle and a fixed base station. The main inspection tool is a tip mounted camera tool which contains three fixed focal length cameras - two pointing forward and one facing sideways - and high power LEDs. The tool is the size of a large matchbox and includes a motor to rotate the tool around its longitudinal axis to enable different views to be obtained from the side camera. Video from the cameras is transferred over 0.5km of fiber to the operator console, allowing the video streams to be recorded, time stamped and annotated. Further variants of SAFIRE will include different tools including UT probes.

Since the arm is stable it was possible to review images and then decide to re-take pictures or change the angle of view. This resulted in inspections recording images of parts of the reactor system that have not been seen since the reactor was built.

Conclusion

At Ringhals the pipe replacement enabled the reactor to be brought back on line and operated at a higher power. If the replacement had been unsuccessful the future operation of Ringhals 1 would have been in doubt. It is reasonable to state that OC Robotics' technology was instrumental in keeping the plant operational, thus safeguarding this asset.

SAFIRE demonstrated the expected benefits of replacing manual inspection with automated inspection including: rapid set-up and tear down and remote operation that enabled considerable operator dose reduction; high quality images acquired from new vantage points; and, video captured from a stable platform. The less tangible results include the ability of the most experienced inspectors to view and re-view plant condition in real time.

Extending nuclear plant life is now a key issue for nuclear operators as it secures base load electricity production. Inspection of plant condition will be an increasingly important element of assessing plant integrity as a part of license renewal. Snake-arm robots create the opportunity to deploy existing and new replacement and repair technologies.

Nuclear power plants are substantial investments which with careful management and investment can be operated safely for decades to come. Snake-arm robot technology will enable plant life to be extended both by conducting necessary repairs and by providing high quality data about the physical condition of the plant.

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