Remote devices for inspection of process vessel and conduits


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Abstract

Nuclear fuel reprocessing plants necessitate remote operations for the inspection of critical equipment. The monitoring of components is necessary in order to ensure that service-induced defects and abnormalities are detected and remedied at an early stage. The highly disordered nature of the workspace and the approach constraints, in nuclear plants give impetus to design and develop specialized equipment to achieve the objective. Working along these lines, this paper presents two developments for the in-service inspection (ISI) of internals of process vessel and pipes respectively. The ISI system for the dissolver vessel has been successfully demonstrated and the design for the pipe inspection system has been consolidated through simulations in a multi-body dynamics (MBD) tool and described herein.

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1. Introduction

In-service inspection (ISI) plays a major role in monitoring the condition of nuclear plant structures and components. It is possible to assess the extent of damage and take corrective measures, to keep effects of ageing under control, based on the information gathered during inspection, and from the studies carried out subsequently. Remote operation and handling methods are adopted to execute inspection campaigns in reprocessing plants. The use of remote devices and robotic systems is indispensable for ISI of nuclear fuel reprocessing plants due to the presence of high radiation levels and limited access. These devices are, more often than not, specially developed and highly customized for use in reprocessing plants. Advancements in technology by way of miniaturization, high
degree of control / automation, advanced vision and tactile sensors coupled with novel non-destructive evaluation (NDE) methodologies are facilitating applications in the ISI or repair/maintenance of nuclear plants. These demands of the nuclear industry are driving the evolution of remote handling technologies. Consequently, development and implementation of new improved techniques and equipment to carry out remote ISI is essential and could be justified by maximum availability and safe operation of the plant for the successful closing of the nuclear fuel cycle. Radioactive fuel handling, inspection and repair of reprocessing plants with robotics are major areas of developmental activities.

It is important to identify critical areas of plants and structures for ISI using remote devices and the access for such an inspection, along with the strategies for inspection has to be incorporated in the design stage and demonstrated before the final commissioning of the plant. In one such instance, for a plant, there was a requirement to inspect the internals of a cylindrical process vessel of vertical orientation, with limited length, where branches are also present. It is necessary to ensure that the ISI device does not enter the branches. In such plants, straight long pipes of various orientations also need to be inspected and these pipes may have minor diameter variations. In many of these cases, the pipes may not have branches.

A manually actuated multi-link manipulator consisting of series of small links was developed with the end-effector having two degree of freedom, the visual inspection of the space below the containment box where tanks and vessels containing highly active process solution [1]. Manipulators such as snake/elephant’s trunk manipulator and multi-link manipulator have been developed and used worldwide for deploying fibrescopes and miniature CCTV cameras to examine areas of interest in regions of restricted access as in the case of nuclear reactor internals [2, 3]. A remote inspection device, with five telescoping stages was developed and the visual inspection of the dissolver vessel limb was successfully carried out, using a camera at the CORAL (Compact facility for Reprocessing of Advanced Fuels in Lead cells) [4]. In keeping with these developments, a comprehensive 3-axis scanner, for a cylindrical process vessel, with branches, has been successfully developed at IGCAR, Kalpakkam and presented in this work.

A new pipe inspection device/robot is required for the internals of a long pipe. Hence, this has received active attention from designers and developers alike. Predominantly, they use crawling or wheeled mechanisms. A review of the work in this direction was also published [5]. Many of these designs derive inspiration from the biological world [6, 7]. A typical case is the pipe-inspection robot with two pneumatic hands. This was developed by Toshiba Corporation [8]. The design was created for inspecting pipes of 0.0254m size. A robot design with sixteen motors, mounted on eight legs was moved with a walking gait [9]. It had the capability of negotiating junctions using bending joints. Steering ability was also provided by attaching the driving motors to the wheel joints [10]. Adaptable quad arm mechanisms have also been reported as developments to negotiate branched pipes [11]. Though, research in these directions has proposed extremely articulate mechanisms [12], it is desirable to simplify the design to reduce the controllable parameters. This is predominantly due to the fact that the developments reported in literature consistently show that complex subsystems, including multiple motors, are used to take care of different functionalities. This also has a direct bearing on the kind of drives/control systems needed to operate these robots, with other spill-off effects on the kind of energy requirements. Keeping these issues, in mind the need to reduce bottle-necks makes the search for a design of a simplistic mechanism for inspection of pipes very pertinent. Hence, the design proposed in this work builds up on this ethos to present a novel internal pipe inspection robot.

2. Development of 3-Axis Scanner for Process Vessel

The dissolution of spent fuel in a dissolver vessel is one of the critical steps in reprocessing. Corrosion is the predominant mode of failure anticipated in the DFRP dissolver vessel, where dissolution of spent fuel, in nitric acid, is planned as a continuous operation. In order to conduct the ISI of the DFRP dissolver vessel, operators must resort to remote handling techniques, in view of the factors mentioned above.
2.1. Cell arrangements and dissolver vessel–layout & constraints

The dissolver essentially consists of three cylindrical limbs about 1.5 m high with branched connectors stemming out at various points. The cylindrical limbs are the annular tank, hot limb and cold limb (electrolyser). These have been shown in Fig 1(a). Both the hot limb and cold limbs are to be inspected periodically using remote handling tools. The dissolver is located in the cell as shown in the Fig 1(b).

![Fig. 1. Depiction of (a) dissolver vessel and (b) dissolver cell layout at plant.](image)

The location of the dissolver is within the work envelope of the master-slave manipulator and the in-cell crane for remote operation and maintenance. In order to perform testing and validation of the scanner, a mock-up dissolver vessel in SS 304L was fabricated. The internal diameter of the vessel is Ø0.102 m with flange at the top (diameter, Ø0.122 m). The thickness of the vessel is 0.01m.

2.2. Technical description of 3-axis scanner

The geometry and arrangement of the dissolver gave rise to the design of the gadget with the capability of covering a cylindrical work-space. Hence, considering the operation under remote conditions, the device is designed with three major degrees of freedom – along 3 axes for scanning the inner surface of the vessel.

![Fig. 2. (a) Axes for the azimuth rotation and probe elevation and (b) assembly for Z-axis and (c) 3-Axis scanner assembly.](image)
In this 3-Axis scanner, the primary motion along the length of the vessel (Z-axis) provides the measurements at various depths. A chain and sprocket mechanism driven by an AC servo motor lowers a helical pulley block down the ‘Z’ axis in a rectilinear manner. This makes it capable of covering 1.55 m along this direction. A spin along the ‘Z’ axis provides the azimuth rotation, in steps of 0.1 º, enabling the ultrasonic probe to cover the full circumference at a particular depth. This motion, with a full range of 360º, is actuated by an AC servo motor with a wire rope on a capstan pulley. A similar AC servo motor actuates the probe elevation providing the tilt to the ultrasonic probe in the vertical plane, with a range of ±90º. The various modules of the scanner are shown in Fig 2.

The motors have been kept on the vessel top, and modularity is incorporated in the design by separating out the drive and motor for the axes from the respective joints. The separation of the motors is an innovative design step as the inspection head has to operate in water which will be used as the couplant for the immersion ultrasonic technique, and so motion transmission is done through chain-sprocket and wire-rope. The position feedback is provided by underwater compatible and magnetic type non-contact sensors for all axes. A PC-based user-interface has been designed to operate and monitor the device through motion controller. This unique system has been designed to operate in the harsh environs of a reprocessing plant where high radiation and contamination are the norm. This type of remote operation device for ISI has not been reported elsewhere. This is an essential development since the deployment is to be done for a radiologically active area, where the constraints cannot be eliminated by shut-downs/load-shedding or similar plant maintenance operations.

2.3. Experiments and representative results

As the scanner has also been designed to conduct ISI using immersion ultrasonic technique for detecting the wall thinning, with water as couplant, experiments were conducted to check the underwater performance.

Fig 3 shows the progress of experiments with the inspection head under water.

Fig 4. Trials on mock-up dissolver vessel using the 3-axis scanner
The integrated assembly of the 3-axis scanner during the visual examination trials using a camera on the mock-up dissolver vessel is shown in Fig 4 with the control console and the user-interface.

Fig 5 shows the internal surface (radial view) images and axial view images acquired by the camera during the trial runs. The various ports and the boundaries could be clearly seen. A 1/3” CMOS Camera, having a horizontal scan resolution of 380 lines has been used for visual examination of the inner surface of the mock-up vessel. In the initial trials, tests were successful in the mock-up vessel.

3. Development of internal conduit inspection device

In tune with the developments for the inspection of the dissolver vessel, there are many other components and sites at a nuclear plant that warrant similar surveys. Such plants usually contain many pipe-lines for the transmission of process fluids. In these pipes, there may not be branches present. Therefore, it is very necessary to develop a new device for automated traversal and internal inspection of pipes, capable of accommodating minor variation in the pipe diameters.

3.1. Motivation/Concept inception and design

In a nuclear power plant the remoteness of the site to be inspected is a major constraint, as discussed in the Section 1. This very aspect of remote access, dictates that the devices should be simplistic, thereby leaving very little or no room for faults and break-downs. In other words, the reliability of such systems should be made high by incorporating minimalist principles in design and deployment methods. This naturally gives incentive to try and design a mechanism where the compliance in the device aids the movement, all the while, thereby reducing the number of actuations to be performed. The design of such a device was done using the novel principle of movement along a helical locus and with friction gripping.

The design of the device consists of a rotating head actuated by a single motor. Three wheels are arranged in a triangular layout, on the head with a small pitch angle (5°) provided with the central axis of the device/conduit. In essence, the locus of the head wheels trace out a helical path inside the conduit and thereby proceed along the length of the pipe. There are three wheels arranged, similarly on a triangular layout on the passive follower body. The overall length of the device is 0.12 m (from end to end). The weight of the device is about 0.5kg.

It must be noted that all these wheels are loaded with helical compression springs. This provides the required pre-load to attach the wheels on to the internal surface of the pipe and to accommodate minor variations in the pipe diameter (Ø 0.1—0.115 m), along with small curvatures (if present) along the pipe length.
The design of the device is depicted in the models in Fig 6. Simple reversal of the motor actuation allows the device to retrace its path moving backwards.

3.2. Simulation Studies

In order to derive and validate the parametric requirements of the major components in the pipe inspection device, simulation studies were carried out in multi-body dynamics tool. In site operations, the extreme condition of operation would be the case of the device attempting to move up in a vertically oriented conduit, against gravity.

The static and dynamic coefficient of friction between the wheels and the pipe internal surface was taken as 0.4 and 0.3 respectively. The value of the contact stiffness was taken as $10^8$ N/m. The damping coefficient is taken as 1% of the stiffness value. The simulations are conducted with a preloaded condition of the spring with a force of 60 N. Forward dynamics reveals that a torque of 0.218 N.m is required, at least, in order to initiate the upward movement. In the present case, a torque of 0.225 N.m was applied for the studies. The duration of simulation is 1 s with 2000 step. The simulation is done for a pipe diameter of 0.1m.

At the start of the simulation, the pipe inspection device starts to fall due to the effect of gravity, until contact of the actuator head wheels is established with the internal surface. The preload in the spring ensures early contact as required. When torque is applied on the actuator shaft, device moves up against gravity as shown in Fig 7(a). Velocity is stabilized at 0.07 sec. and thereafter it is steady at 0.225 m/s. The deflection in the springs and force
exerted by them are shown in Fig 7(b). Initially, the device heads rotates with an angular acceleration and subsequently after 0.07 sec the velocity settles asymptotically at 500 rpm.

Fig. 8. Simulation with a pipe diameter of 0.114m (a) device position and velocity (b) spring deflection and force.

In order to exhibit the efficacy of the design, a similar simulation was carried out for a larger pipe diameter of 0.114m. It is important to note that after stable .0 velocity is achieved after ~ 0.07 s, Fig 8(a), the linear travel shows a difference in the same time duration, thereby showing a change in the acquired steady linear velocity. The spring force stabilizes at a value which is lower compared to the previous case of 0.1m diameter pipe as shown in Fig 8(b). This is because the larger diameter of the pipe effectively reduces the spring deflection during steady motion along the axis.

4. Conclusions

In this work, new development and a novel principle has been presented with a particular view of applying remote handling principles in a novel way for cylindrical workspaces. The simplicity and elegance of motion transmission, in each of these devices, coupled with their applicability in constrained regions make them appropriate. This aspect is dictated by issues of variation in diameters or depth of action required in the actual workspace. In the case of the 3-axis scanner,

There remain a few possible threads along which improvements are to be provided. These devices could be enhanced to negotiate bends in the path along the primary axis of motion. Moreover, by consolidating and finalizing improved designs after exhaustive experimentation, the signal channels could be dispensed with, for the convenience of a wireless system.

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