ADVANCED ROBOTICS FOR INSPECTION AND MAINTENANCE APPLICATIONS – Ben Fisher

Abstract

The BOP inspection market provides unique and challenging environments for inspection. Intech has developed a flexible manipulator platform that supports these needs, namely accuracy and environmental hazards in a cost effective package.

Introduction - The existing environment

The focus on plant reliability and rehabilitation has been extended from the major components of the steam generation loop to other areas of concern, including the Balance of Plant Heat Exchangers. (BOP HX) To prevent the untimely failure of these components as they near the end of their service life, the nuclear industry has seen the need to mandate an increase in the periodic inspections of these units to ensure the greatest level of plant safety and performance. However, the inspection and maintenance of Balance of Plant Heat Exchangers in nuclear power plants often poses several problems for both inspection companies and utilities, namely accuracy, environmental hazards, and cost concerns.

A typical BOP HX inspection requires a technician to enter the vessel head and manually position the Eddy Current inspection probe over the correct tube location. The technician references the provided component layout maps, and physically counts the tubes to verify the tube location to be inspected. In most cases, the technician inside the vessel communicates with an operator on the outside, and together they verbally verify that the inspection probe is located at the correct tube position. In this situation, the experienced operator relies on the technician located in the vessel for feedback. Physical constraints, vessel conditions and technician experience make this traditional approach an error prone situation. Inspection positioning accuracy becomes dependent on the ability of the technician at the tube sheet face to properly identify the correct tube location out of the tubesheet pattern, and there is no secondary verification system currently deployed. Further, if a positioning error is made, the index error is compounded until it is identified. The realization of this inaccuracy forces the vessel operator to re-acquire tube data, thus unnecessarily extending inspection time. In the worst case situation, the operator might fail to identify the positioning error, resulting in defective tubes mistakenly left in service and clean tubes unnecessarily plugged, leading to potential leaks during operation.

In addition to the tube identification problems inherent with manual BOP heat exchanger inspections, there are significant biological and radiological concerns. The current inspection procedure requires the presence of a technician at all times near the tubesheet face. Depending on the configuration of the individual component, this presence may require confined space permits and the environment monitoring requirements that go hand in hand with such requirements. This can eventually be costly to the end customer because it requires extra manpower, supervision, and equipment. Further, in some situations hazardous environments exist that are not immediately identified, which can lead to worker injury and lost time accidents. Beyond the physical constraints, it is common for severe radiological hazards to exist in many of the BOP heat exchanges that require inspection. These hazards can range from high radiation fields, moderator D2O, air-born and loose contamination, hot particles, and radioactive gasses such as tritium. Many utilities encounter multiple personal contamination events during the inspection workscope due to these hazards, despite their best efforts to prevent them. With the high cost of radiation exposure[1] and contamination clean up, these hazards need to be minimized.

Furthermore, most BOP inspections are traditionally performed on a slim budget with little extra room for technological innovations beyond probe pushers and more advanced acquisition software. Due to the fact that a cost efficient solution was not available to address the considerations above, the industry has generally had to make the best of the situation and absorb any adverse cost of personal contamination events, injury, or erroneous tube encodes into the overall cost of operating the plant and performing the inspection.

While the same remote robotics that are generally used in the primary side loop solve many of these critical problems with BOP inspections, the use of automated manipulators for this work has been historically limited by a number of factors. First of all, these vessels are usually too varied in size, orientation, mounting configuration, and tubesheet pattern to allow traditional manipulators designed for the steam generator market to be used. Further, the typical provided manipulator software and control systems are usually too cumbersome to be deployed in a quick and cost effective manner to the multitude of BOP components. Even if such software could be adapted to the use, S/G manipulators have historically proven to bear too much deployment cost for consideration in the BOP market for inspection and analysis.

It became evident that an easily configurable, flexible manipulator was required to fit these requirements, but that the resultant product could not cost more than the market could bear. As a supplier of both equipment and services to this market, Intech was intimately aware of the problems and well suited to find a solution.

Spyder Manipulator Conceptual Design Requirements:

In order to meet all of the needs of the BOP inspection business, a critical evaluation of the parameters was required. By soliciting input from inspection customers, project managers and field technicians, a comprehensive technical specification was gradually developed. The following items were the critical factors used in the design process:

Flexibility

BOP components are extraordinarily varied from site to site, including such elements as:

- Overall size (19” dia to 120”+ square).
- Tube diameter, wall thickness, and count per component.

[1] The cost of radiation exposure is estimated as, 1Rem of human exposure = $25,000 of cost to the utility.

- Tubesheet pitch and pattern configuration. (Square, Tri-pitch)
- Access configuration, including removable head , integrated waterbox flange, and manway designs.
- Other internal obstructions not traditional with S/G Manipulators (4 pass baffle plates in the waterbox area, tight clearances between the component and the plant walls, human entries not possible through the current access doors, etc.)

Low Cost

BOP inspection programs traditionally not funded to the extent that S/G campaigns are, and thus the older manipulator strategy of customized piece-by-piece components won't apply. Components specified must have a lower cost than the competition and should be relatively easy to obtain with short lead times if possible. Moreover, maintenance on the components considered must be minimized to reduce overall cost to the site or facility that is performing the inspection. From the design perspective, the flexibility concern also drives cost, as a specific manipulator for each application will force the user to justify the cost of the manipulator on a single inspection component. Based on the inspection frequency and multiplicity of distinct components common in Nuclear Power Plants, the resulting manipulator must be adaptable to as many situations as possible for the system to make economic sense.

Ease of use and Integration with common acquisition software packages

The software designed for the BOP market must have a greater degree of flexibility than the usually deployed software for the S/G Manipulator Systems due to the vast array of component configurations:

- The software should be intuitive for the operator so that little training is required to operate the system.
- The display system should be far more detailed than the competing software products, so that the operator has a clear sense of exactly what the manipulator is doing at any time. External PTZ cameras are not common in the BOP inspection, so the display should digitally represent the entire work area.
- The component specific loading file should handle all variables that could be incorrectly entered, resulting in fewer errors.
- The system should be able to pass Row/Column or Section/Row/Tube encodes from the manipulator software to the acquisition window for available software packages.

Spyder Technical Design:

The development of a system to meet all of these requirements at once required an overall design approach for modularity, which was implemented in stages as the project development took place.

Actuator Components

During the initial phases of conceptual design, it was determined that "commercial-off-the-shelf" (COTS) components provided the most cost effective and rugged method of actuating the proposed manipulator arm. The very nature of this particular segment of the nuclear market does not easily support highly custom individual piece axis system, since it is difficult to efficiently make high-tolerance parts on a small production scale. Other factors in the axis selection were accuracy, torque capacity, and integral bearing load capacity to reduce the complexity of the required housing. After a thorough selection process, a high ratio, zero backlash gearing system with low voltage windings (24 VDC), a high-resolution incremental quadrature encoder, and a hollow shaft configuration was chosen. Two different sizes were targeted as applicable to the market, obtained, and then tested.

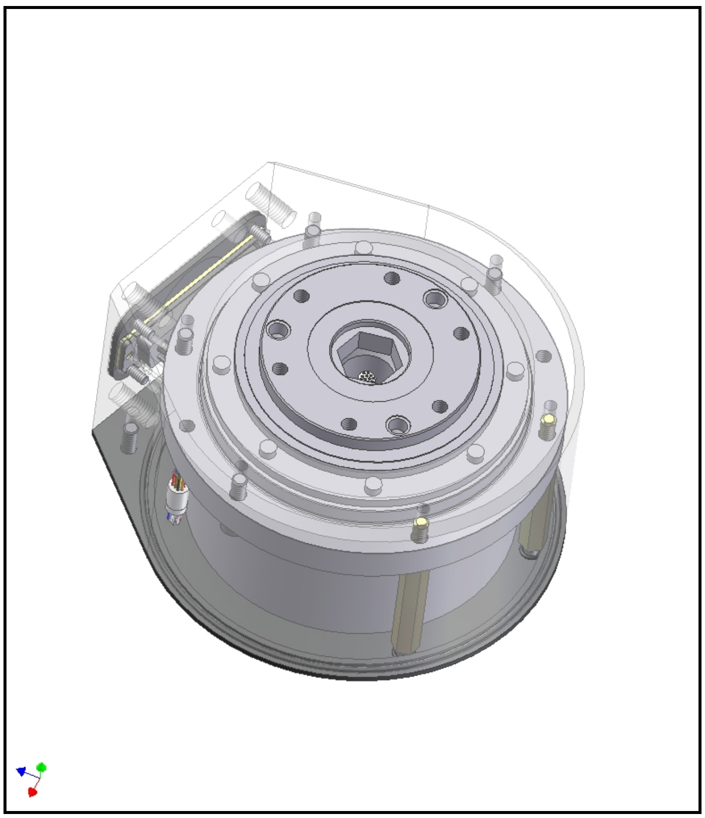

Figure 1: Configuration of the actuator system

Modular Axis Driver

Since it was clear that different BOP component arrangements would necessitate a variety of axes in various configurations and numbers, modular COTS axis drive units that used a Controller-Area Network (CAN) interconnect were considered. The advantage to this system, originally developed for automotive use, was that the bus was specifically designed to allow seamless splicing of components and sensors. The proposed network topology for this system is outlined below:

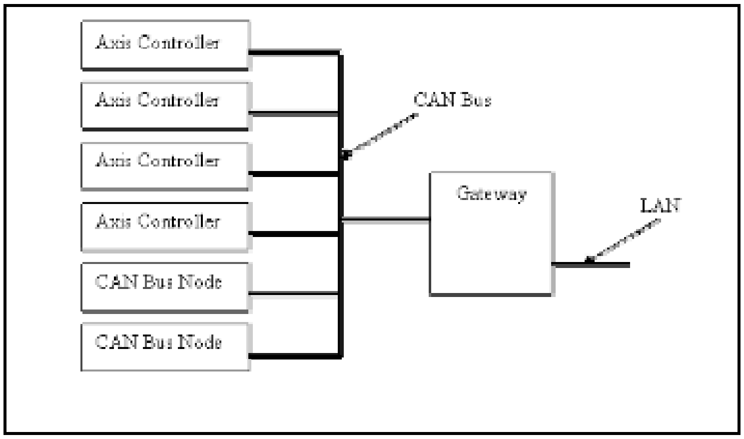

Figure 2: Axis drive modularity layout

Each node on the CAN bus can be linked to the other nodes controlling the axes, so that the overall system can be commanded to perform a certain motion as a coordinated linkage. Axis control loop parameters and position information are locally stored on the individual linked axis drive, and accessed remotely through the LAN network and the control software. The properties of the CAN network allowed scalability of not only control software code, but also of control box design.

Field Component Modularity

One of the major weaknesses of comparable S/G Manipulators is that each axis component is embedded into the arm as a whole. If the part is damaged in use or becomes inoperable, removal is not a trivial matter. The BOP manipulator design needed to address this issue so that downtime would be reduced to a minimum, and easy replacement of axes would be facilitated. Further, having a modular axis unit was critical to the success of the reconfiguration goals previously stated, since the effort expended in the design for one project would be used without modification in the next system. Finally, modular axis components supported the overall goal of developing a single manipulator system that could be reconfigured and deployed to both BOP and S/G applications.

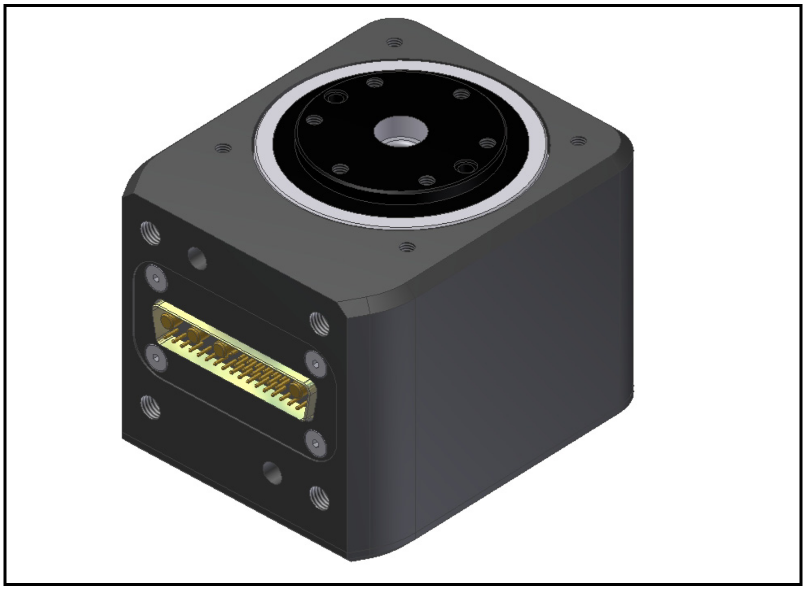

Figure 3: Axis Hotshoe Connection system

While the actuator components met many design requirements based on accuracy and compact dimensions, they were not originally designed for the rough field conditions usually experienced in BOP inspections. A rugged housing was developed to protect the unit from damage, prevent water entry into the axis, and provide a common-style electrical interconnection hotshoe system. This latter feature enables reuse of this component in a variety of different arrangements, and facilitates axis changeout, if required.

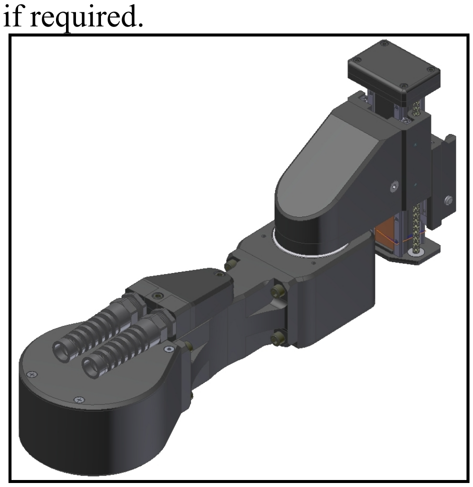

Figure 4: Basic Arm Unit

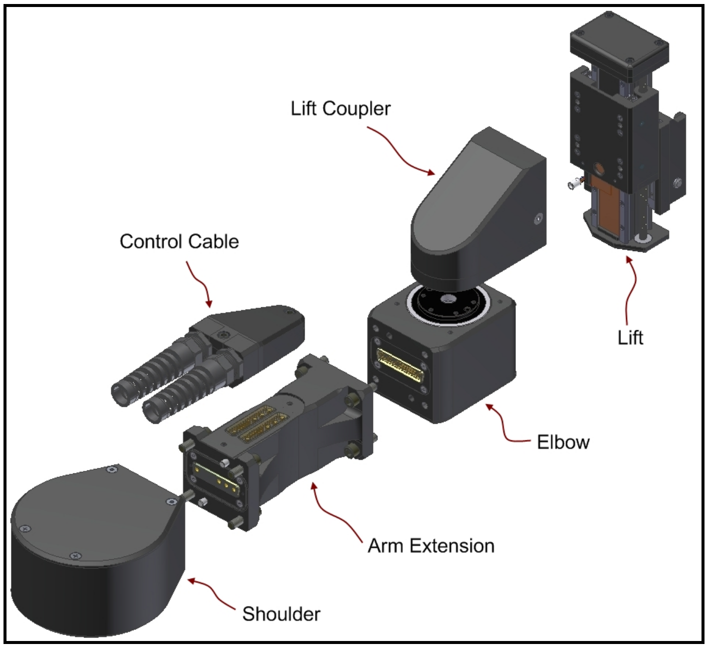

Figure 5: Modular Component Exploded Diagram

As shown in Figure 5, the basic arm component is comprised of a shoulder axis, control cable connection, arm extension, elbow axis, a lift coupler, and the high-speed lift unit. Each is interconnected using the fewest exposed fasteners possible, resulting in low parts count and fewer FME issues in the field. The arm design was also developed with the dovetail tooling interconnection standard, which enabled eddy current inspections as well as remote plugging, inspection and verification tooling currently developed by Intech.

Rugged Control Cable Connection System

Control cables have posed a problem in many manipulators used in the harsh environments encountered in nuclear facilities. The extreme working conditions mean that equipment is often ill-treated causing shearing of connector shells or damage to cables. In order to ruggedize this aspect of the Spyder, a custom aluminum back shell was created with integrated D shell connections. With the incorporated strain reliefs, this creates a very rigid connection as well as the low profile geometry critical in some component arrangements.

Figure 6: A prototype of the control cable interface.

Mounting Configurations

The various tasks that the Spyder has been required to perform have lead to the development of unique mounting configurations. To cover the spectrum of potential configurations that the manipulator may be required, three specific mounting systems have been developed.

Tubesheet Mount System

Due to the considerable variability of potential tube pitch and diameter, the goal of the tube sheet mount was to produce a mounting system that would conform to a broad range of tube sheets. The adaptive base plate design allows the gripper pitch spacing to be varied and locked in order to adapt to any spacing that may be encountered without removing any parts from the system. A gear rack system integral to the base plate ensures that the shoulder axis is precisely in the center of the two outboard grippers.

Figure 8: The tubesheet mount system.

The base plate is gripped into the tubesheet using a pair of polyurethane expanding grippers, currently designed from 1/2" to 1 5/16" component tubing with various wall thicknesses. The polyurethane design gives excellent gripping power without the concern of damaging the tube internal diameter.

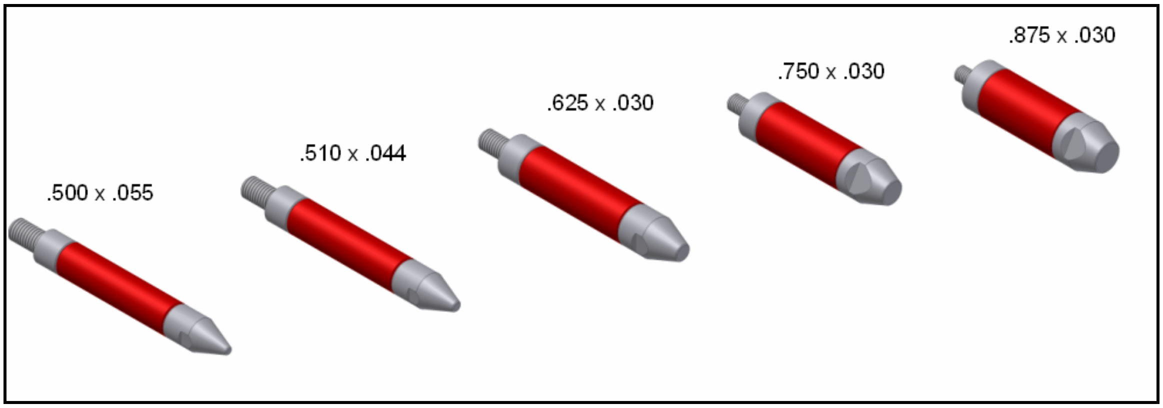

Figure 9: Sample Polyurethane Grippers

Flange Mount System

Many smaller low-pressure BOP components have an integrated waterbox attached to the tubesheet face, which is often difficult or impossible to remove based on access conditions, as well as local dose fields. In these cases, the tubesheet mounting system is removed, and a new baseplate is installed capable of mounting directly to the flange of these systems. Extended guide tube systems are used to reach down to the tubesheet face to guide the eddy current probe to the appropriate tube.

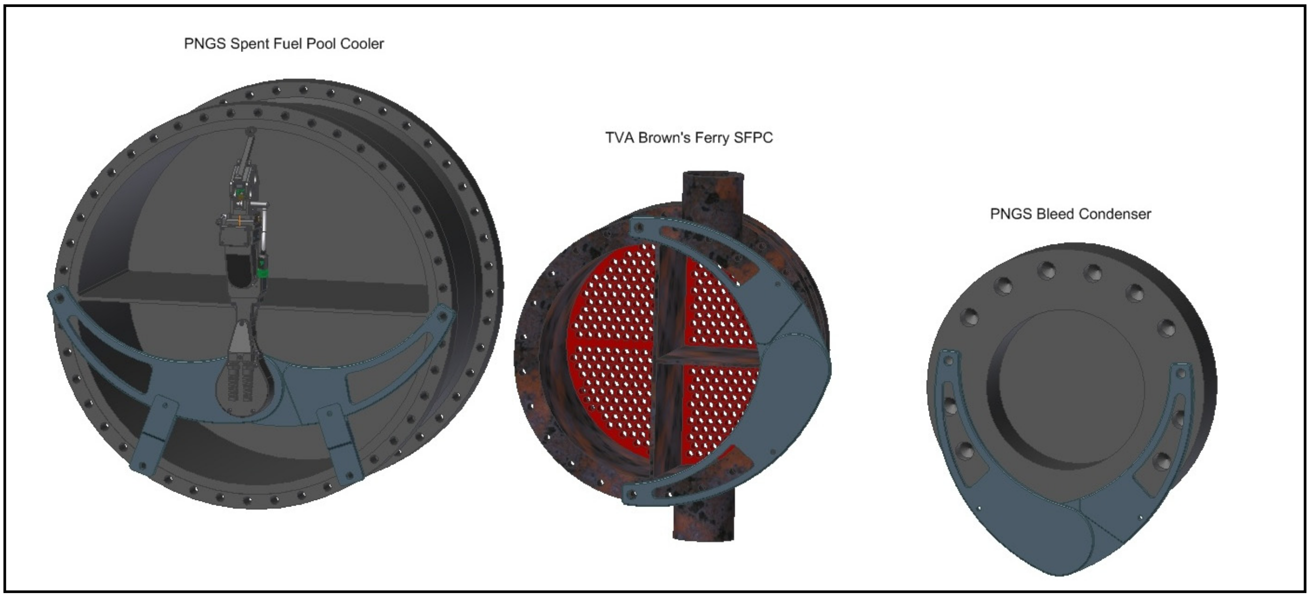

Figure 10: The flange mount system shown on largest and smallest components

Manway Mount System

In some circumstances, due to inaccessibility or high hazardous conditions, it is necessary that the manipulator be mounted to the manway of the vessel. Since these components vary greatly in diameter, depth to the tubesheet and manway configuration, this design is generally more specialized than the former options. However, it still uses the same modular arm components that allow easy repairs and reconfiguration to other applications.

Figure 11: A Manway mounted Spyder Manipulator with manual third axis

Software and Control

The control software for the manipulator is a windows-based DirectX 3d system designed to display near real-time response from encode feedback on manipulator. It features an intuitive user interface for control commands and setup using a simple point and click interface. The software also displays reachable range, plugs, stays, obstructions, bowl features, and any distinctive features of importance to the manipulator operator. Various tubesheets can be loaded via .csv file format.

The manipulator control software is currently integrated with Corestar's Acquisition systems for a seamless eddy current workstation. Position encodes reported by the manipulator are automatically forwarded to the test list in the Corestar system. Further, Corestar plan files can be imported into the Intech software to visually display the testing patterm. Continuing development on this project will enable an automatic acquisition system that will only require monitoring by the manipulator operator as it sweeps the predefined testing path.

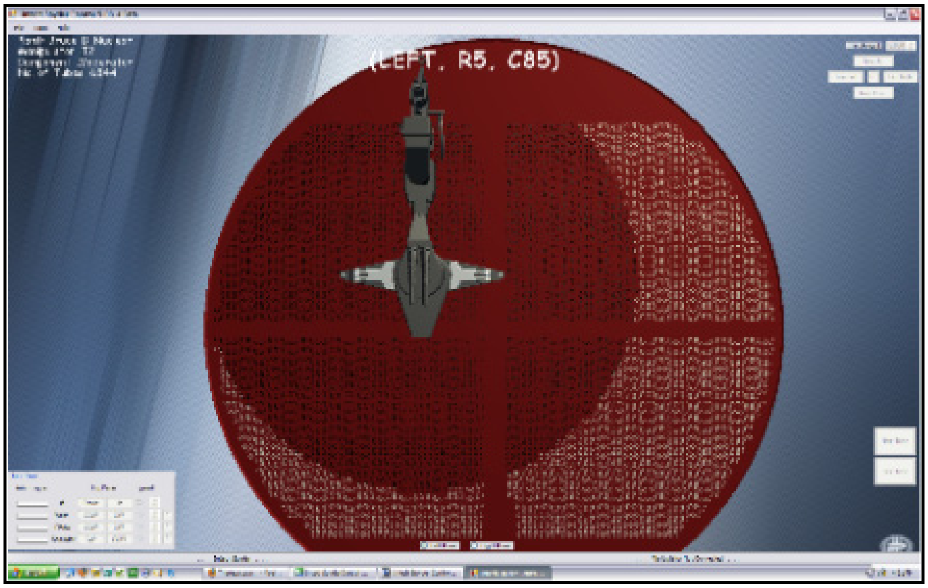

Figure 12: The manipulator control software with the BNGS Moderator Tubesheet loaded.

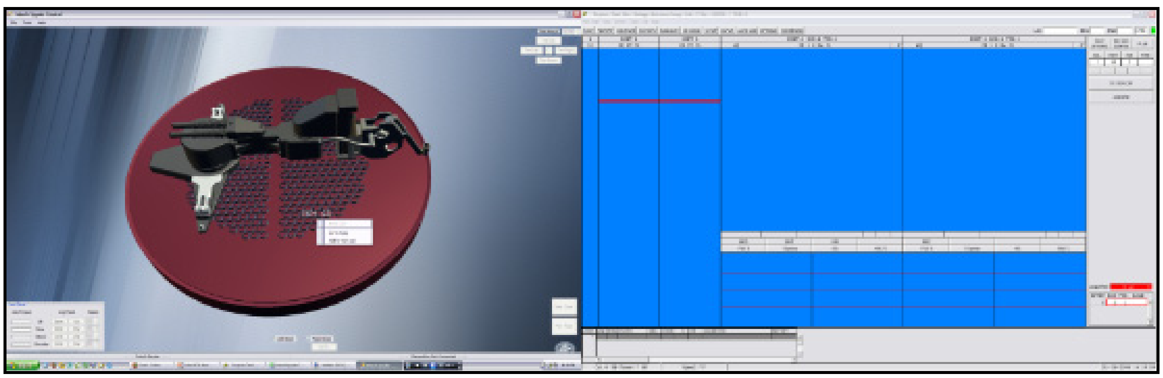

Figure 13: The manipulator control software and Corestar's EddyVISION running side-by-side.

Field Applications

The Spyder series robot has been deployed to a number of work scopes deemed too hazardous and results too critical for human manipulators. These include inspection and maintenance scopes at nuclear power plants and research facilities across North America. In some instances the Spyder performed work in areas too small and radioactive for human occupancy. In each case the resulting robot configuration has been adapted from the modular base design to meet the requirements of each unique BOP component.

Idaho National Laboratory Advanced Test Reactor Heat Exchanger (HX). The M1 robot was the first of the series prototyped to mitigate these risks for use at Idaho National Laboratory's Advanced Test Reactor Heat Exchangers in the Fall of 2006.

Designed to enter and mount 8" diameter hand hole access ports in five heat exchangers, the M1 robot was configured to span 5' to the tubesheet face while navigating two support rods at the bowl transition. M1 delivered eddy current probes to complete 100% inspection of 1600 tubes in each of the HXs over the course of two outages. This first evolution manway mount system proved successful in its installation and operation while highlighting key areas of improvement and lessons learned for subsequent software, hardware, and technique design iterations.

These components had never been inspected in their 40 year service life. The ability of the manipulator system to perform the work without removing the lower head saved dose, potential contamination events, and a large amount of labor.

Figure 14: Spyder M1 in INL HX

Tennessee Valley Authority Brown's Ferry Spent Fuel Pool Cooler (SFPC). Following the Advanced Test Reactor HX inspections, a modified flange mount manipulator, F1, was reconfigured for the Tennessee Valley Authority Brown's Ferry Spent Fuel Pool Cooler HXs. As part of Brown's Ferry heat exchanger predictive maintenance program, eddy current data was historically acquired by manually pulling the data. High radiation fields, contamination levels, and heat stressed environment resulted in personnel exposure to a variety of hazardous conditions, frequent contamination events and continuous coverage from Health Physics. Deployment of the F1 manipulator positioned eddy current personnel away from the heat exchanger during data acquisition of 440 tube ends in each of six Spent Fuel Pool Coolers and as a result reduced total man hours from 793 to 706, radiation exposure from 6.57 Rem to 1.65 Rem, and reduced related personnel contamination events to zero over its previous outage.

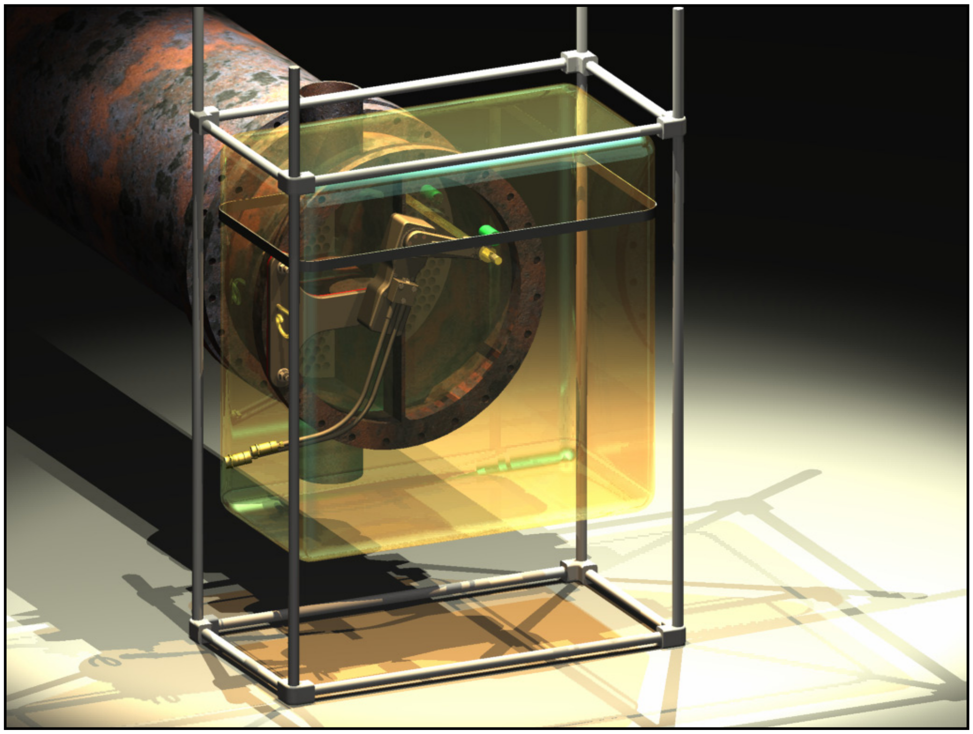

Figure 15: Spyder F1 in Brown's Ferry SFPC

Bruce Power Bruce Nuclear Generating Station Preheaters (PH). During the 2007 Fall outage campaign, Bruce Power successfully realized the first of the tubesheet mount manipulators, T1, which was designed for eddy current and plugging operations in its separate feedwater Preheaters. The T1 robot arm was integrated into the Babcock and Wilcox Canada Prima robot. Remote welded plugging was accomplished from this interface. Integration with Zetec's MIZ-80 iD probe pusher systems was made possible by a special provision with Zetec.

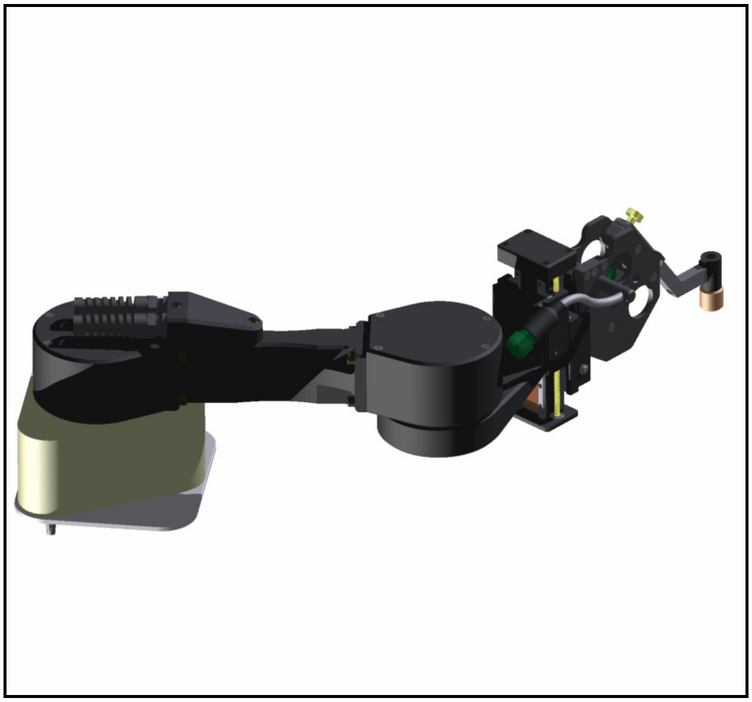

Figure 16: Spyder T1

Ontario Power Generation Pickering Nuclear Generating Station Heat Exchangers (HXs). Faced with the challenge of inspecting a large assortment of nuclear HXs, the Inspection Maintenance and Commercial Service Division of Ontario Power Generation implemented an adaptable design to fit all BOP components including the Spent Fuel Bay HX, Bleed Condenser, Bleed Cooler, Moderator, Recirculating Cooling Water System HX, etc.

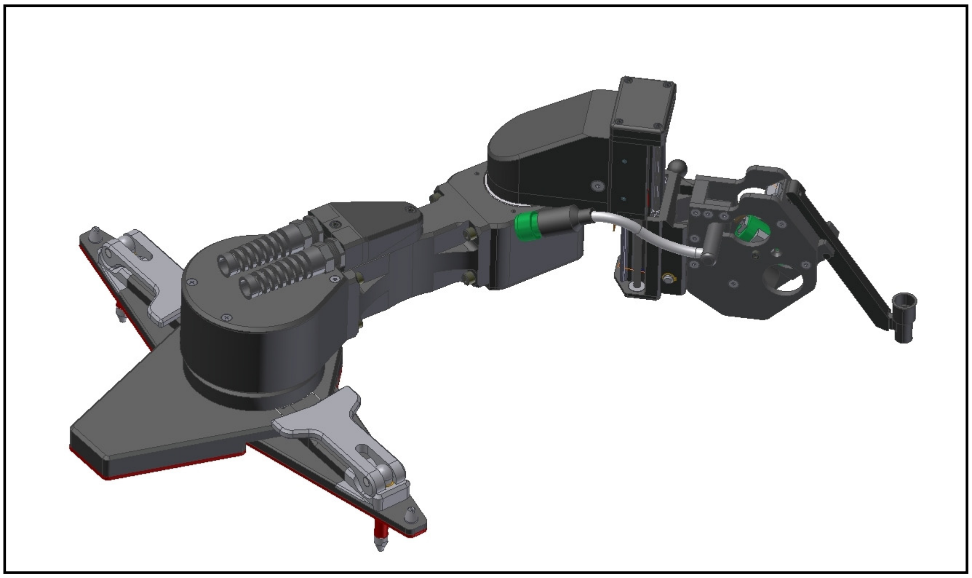

Figure 17: Spyder T2

Arizona Power Systems Low Pressure Feedwater Heaters (LPFWH). Arizona Power Systems most recently completed there second successful campaign performing high-back pressure plug removal from 750 tubes in 5 LPFWH with manway mount system, M2, configured to resist explosive removal forces.

Figure 18: Spyder M2 at APS LPFWH

Conclusion

The design progression of the Spyder series manipulator provides a flexible basis for continued development. Current development models include a combination crawler/arm system capable of auto-repositioning with an added axis for dual/quad inspection capability. Current owners can upgrade easily for rapid inspection and rolled plugging applications. An R1, lightweight rail type system is also at the conceptual design stage for high density plugging applications requiring frequent trips to the manway end effector changes.

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