CMU Biorobotics Lab
Deployment Report

EVN Zwentendorf Nuclear Power Plant
Zwentendorf, Austria

May 13-14, 2013

1 Executive Summary

Nuclear power plants are essentially networks of pipes that require constant attention and therefore must be inspected on a regular basis. Unfortunately, conventional inspection technology such as the commonly used borescope cannot reach all required areas in a power plant because of the scope's limited ability to navigate multiple turns and inability to climb. This means that the piping network either remains uninspected or sections of pipe must be disassembled to ensure proper inspection can take place. Snake robots have potential to perform lower cost and more effective power plant inspections because these highly articulated mechanism can use their many internal joints to thread through tightly packed spaces to access locations that people and conventional machinery otherwise cannot. Along these lines, we had the opportunity to test and demonstrate our snake robots at the never-commissioned nuclear power plant AKW Zwentendforf in Austria.

Over the course of 2 days, the snake robots were deployed in 3 different parts of the plant, and demonstrated a wide range of inspection and locomotion capabilities. Highlights include improved:

- [Access] In multiple situations, the snake robots were able to reach locations that would not have been accessible by other robots or borescopes.
- [Visibility] During the deployments, the robots enabled the operator to manipulate the camera to get the best possible views of the pipes and equipment, in ways that could not have been done with a borescope.
- [Situational Awareness] The robot provided real-time self-righted video ("right-side up") and other sensory feedback that provided better situational awareness than is available from a borescope. This allowed the operator to more easily drive the robot and more easily assess the pipes and confined spaces that the robot was inspecting.

The above listed improvements, which go above and beyond the capabilities of today's commercially available existing borescope and robotic technologies, were a result of our newly developed inspection technologies for the snake robot. Some include:

- [Right-Side up] Gravity-compensated video that always displays "right-side-up", based on the robots internal sensors.

- [Head-look] A new “head-look” that enables the operator to precisely control the head of the robot to attain different vantage points of locations of interest.

- [Pose Display] An accurate and intuitive robot pose display for the operator, based on the robot’s internal sensors; this displays the current shape of the robot and allows the operator to understand where the robot is with respect to the inspection site, i.e., pipes. This allows the user to better understand the remote environment.

Figure 1: (Left) snake robot on control panel for Zwentendorf plant. (Right) CMU team in front of plant.

2 Background

The Carnegie Mellon University Biorobotics Lab, under Professor Howie Choset, has been developing snake robots for over 17 years. The robots have the potential to excel at navigating inside of pipe networks and within confined spaces, and our lab has recently developed our snake robots to the point where they can be reliable deployed in the field. Previous work with the Electric Power Research Institute (EPRI) studied the snake robots' suitability for performing inspections or work inside of conventional fossil fuel power plants (specifically Heat Recovery Steam Generator inspection).

Prior to the deployment at Zwentendorf, our prior work had not directly considered potential applications for the robots inside of nuclear power plants. Similar to fossil plants, nuclear plants contain significant lengths of piping and much complex equipment which is difficult to inspect or access. In addition, nuclear plants may benefit even more from robotic inspection technologies since the presence of radiation makes certain areas of the plant impossible for a human to safely access for an extended period of time.

The Zwentendorf Nuclear Power Plant is unique in that the plant was fully constructed, but never actually used for nuclear power generation. This provides a radiation-free environment that the snake robots could be tested in. The goals of the deployment were to:

1. Identify potential applications where the snake robots can be of use performing inspections or work inside of operational nuclear power plants.

2. Learn more about those potential applications such that future development of the robots and their capabilities can be best targeted.

3. Test the robots in a real world nuclear plant environment to generally assess their robustness and readiness level for deploying, locomoting, and performing inspections outside of the lab.

Lastly, this deployment represented the first opportunity to test various newly-developed capabilities outside of the lab, including the capability for the operator to view the video in a “rotated” fashion such that the images are always aligned with gravity, and a more intuitive control scheme to enable the operator to control the head of the robot like a 6-DOF pan-tilt-zoom camera with simple controls.

3 Details: May 13, 2013

Day 1 consisted of a tour of the nuclear plant, focusing on (1) areas where problems occurred in similar plants, (2) areas where the CMU team was interested in testing locomotive capabilities, and (3) areas that a TV news crew could film the robots in action. The team demonstrated the robots for reporters during that day in the control rod motor room and in the control room itself, and then proceeded to test the robots in a few areas of steam piping near the turbine.

Figure 2: Demonstrating the robot’s climbing capabilities in the control rod room under the reactor core.)Left) the robot climbing into the control rod bores. (Right) the robot inspecting the control motor exteriors.

The first day began with a tour of the nuclear power plant to identify locations within the power plant that would be valuable to access and to plan deployment trials. After the tour, EVN Group, the power company that owns and oversees the plant, invited Austrian TV and newspaper reporters to film our robots and see the way that the Zwentendorf plant was useful for robotics testing and training. The control rod room provided an ideal location to perform initial demonstrations for the EVN team and the reporters, since the robots could demonstrate their ability to climb inside of pipes and outside of tubes in a location where they could be viewed and filmed. For this demonstration, the snake robot was inserted into a nuclear fuel rod bore (approx 4” diameter) and vertically climbed the entire 8-10 foot height of the bore.
The robot also was positioned against a control rod motor, wrapped itself around the motor, climbed the exterior of the motor, and looked into several control rod bores while anchored from the motor (Fig. 2). Lastly, the robot climbed the outside of a 1” machinery cord to demonstrate the robustness of the robot’s climbing capabilities to the TV crew. These demonstrations were primarily for media purposes and to provide the EVN Group with an understanding of the robot’s capabilities; it is unlikely that performing such inspections in other plants would be feasible or useful.

3.2 Turbine Steam Piping

After the media deployments, the team and the robots proceeded to the Zwentendorf plant's turbine room. The turbines capture energy from the generated steam to turn a generator and create electricity. There were originally four stages of turbines, but only three remain at the plant, and the generator has also been removed. The covers have been removed from turbines 1 and 3, exposing the internal structure of the turbines and their blades. There is a great deal of steam piping of various diameters that transports different temperatures and qualities of steam to the different turbine stages. Additionally, steam piping directs steam into a pair of moisture separator reheater vessels, which remove moisture and increase the temperature of the steam between turbine stages. This moisture removal is important to lengthen the life of the turbine blades, and the reheating of the steam increases the plant's overall efficiency. Fig. 3 shows an overview of the turbine room in the plant with the described components labeled.

The piping layout is mirrored along the axes of the turbines. In Zwentendorf, one of the two sides of piping has had several areas of insulation removed and various access points have been exposed through the removal of covers, valves, and in some cases through cutting open the steam

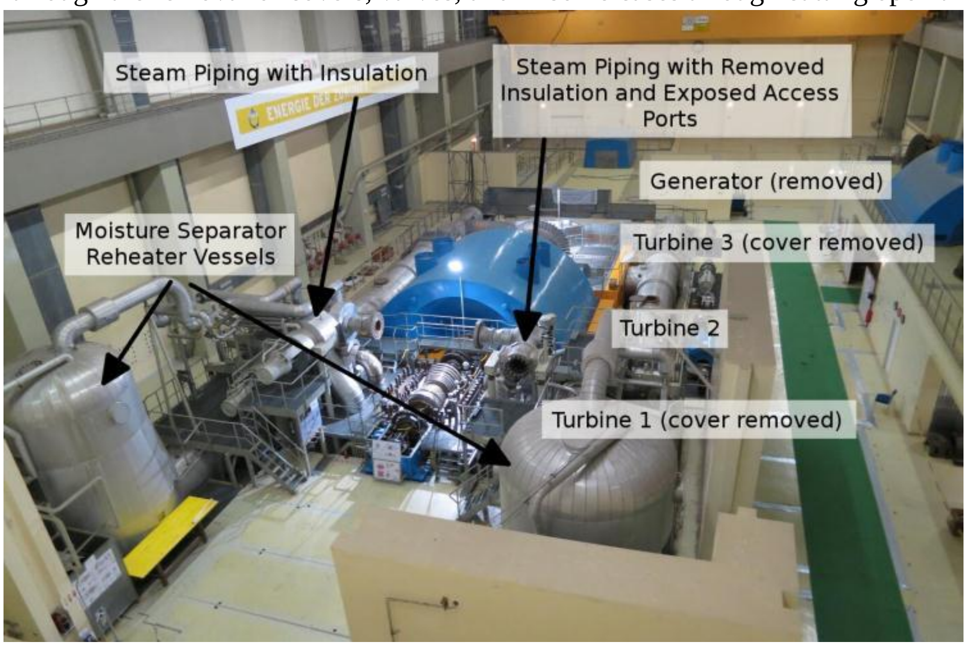

Figure 3: Overview of the turbine room. A fourth turbine stage was removed between turbine 3 and the generator. Also, a mirrored set of turbines and generator originally led into the foreground of this image, but have since been removed from the Zwentendorf plant.

piping. Additionally, one of the two moisture separator reheater vessels had areas of insulation removed and an access panel created. The CMU team inserted the robot into the piping with removed insulation and exposed access points, although after each robot insertion the team carefully studied the mirrored unmodified and uncut piping to see what would need to be removed, opened, or cut open to enable access in an operating plant environment.

3.3 18” Steam Pipe Deployment

The first insertion of the robot into the turbine room steam piping was through a spherical junction vessel (Fig. 4(b)). In an operable power plant of similar design, this location could be accessed through removal of some insulation and unbolting a cover. After inserting the robot into the opening, the robot exited the vessel through an 18” ID steam line which required the robot to turn 90-degrees to the left and drop approximately 60 degrees towards vertical. After a few feet, the pipe turned the remaining 30-degrees to become completely vertical (Fig. 4(a)). The 18” pipe was much larger diameter than the robot can currently climb, so the robot was primarily lowered down this steam pipe using the tether.

As the robot was lowered, the operator controlled the camera to observe points of interest. A sensor probe (believed to be a pressure sensor) was encountered and the robot’s camera head was commanded to investigate the sensor probe from all sides (Fig. 5(a) shows the robot’s view of the pressure sensor after it was lowered past the probe and curled its head to look back at the probe from below). The robot’s on-board sensing enabled the video feed to always be “self-righting” even as the robot’s joints were curled up and as the robot rotated as it hung from the tether, providing a stable and intuitive view. The robot also encountered several smaller steam pipes intersecting the larger 18” line. The robot was able to insert its head into these pipes through commands from the operator, but was not able to transition to locomoting inside them. Enabling the robot to perform such transitions while hanging from the tether is an area for future investigation.

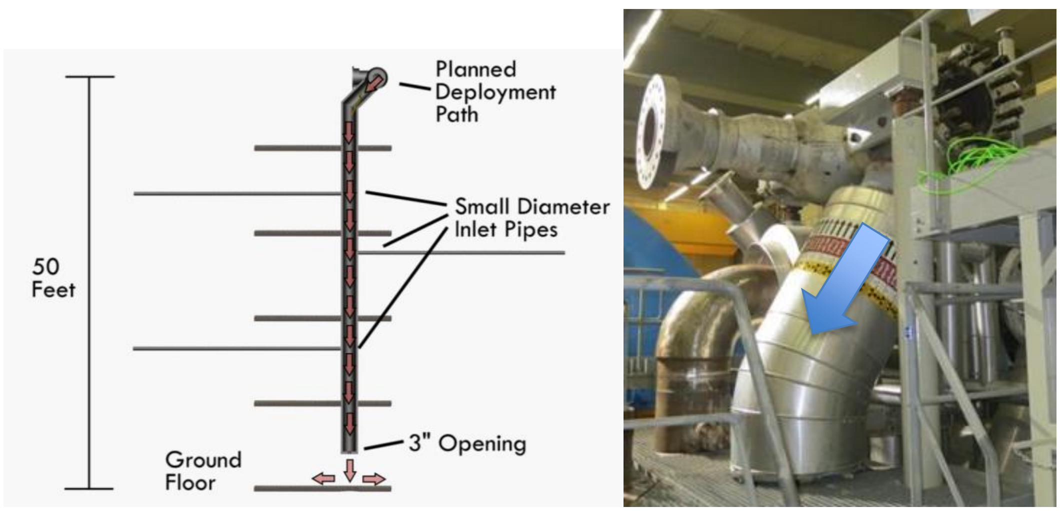

Figure 4: The robot was deployed into an 18” steam pipe through a spherical junction and lowered 50 feet before exiting.

After lowering the robot approximately 50 feet down the entire length of the 18” steam line, the pipe ended with a small opening approximately 3” diameter (Fig. 5(b)). This is presumably a removed valve or a removed drain line. The robot was able to insert its head through the drain line (Fig. 4(d)), perform an investigation of the drain, and then it was lowered a few feet further until it was entirely on the ground. The robot was then pulled by its tether back up through the drain and through the 50 foot steam line where it was retrieved by the operators at its initial insertion point.

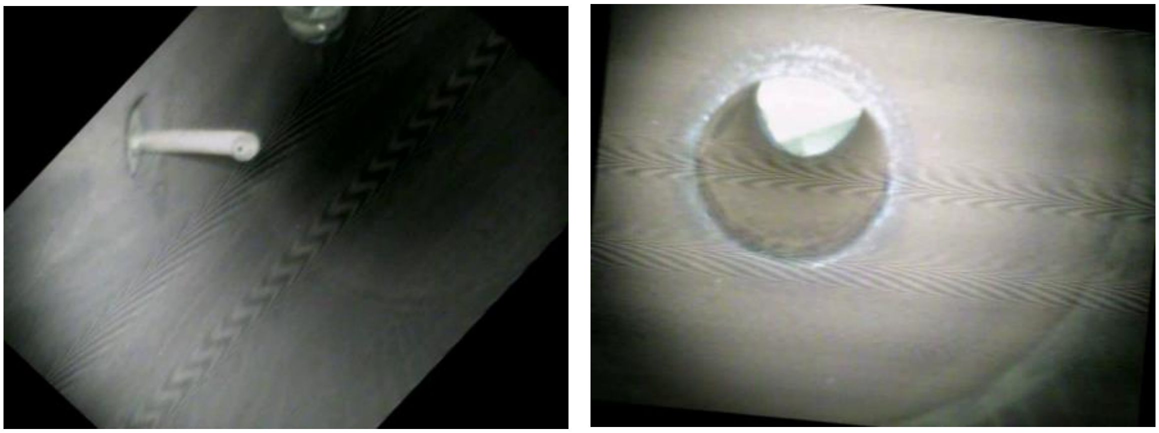

Figure 5: Objects of interest seen by the robot as it was lowered down the vertical 18” steam pipe. Left, the robot’s view of a sensor probe encountered as the robot was lowered down the vertical pipe. Right, the robot’s view of the 3” opening at the bottom of the 18” steam pipe.

While a borescope could be similarly lowered through this 50 foot piping section, the snake robot demonstrated several advantages over the borescope approach. First, the robot’s many degrees of freedom enable the operator to investigate features such as the pressure sensor or inlet pipes in a more complete way. Additionally, the self-rotating video provided a more intuitive view to the operator of what was occurring. With further development, it is likely that the robot will be able to transition from a hanging position into a horizontal pipe, which would enable it to explore other parts of the steam pipe network that would not be accessible with a borescope.

3.4 6” Steam Pipe Leading to Moisture Separator Reheater Vessel

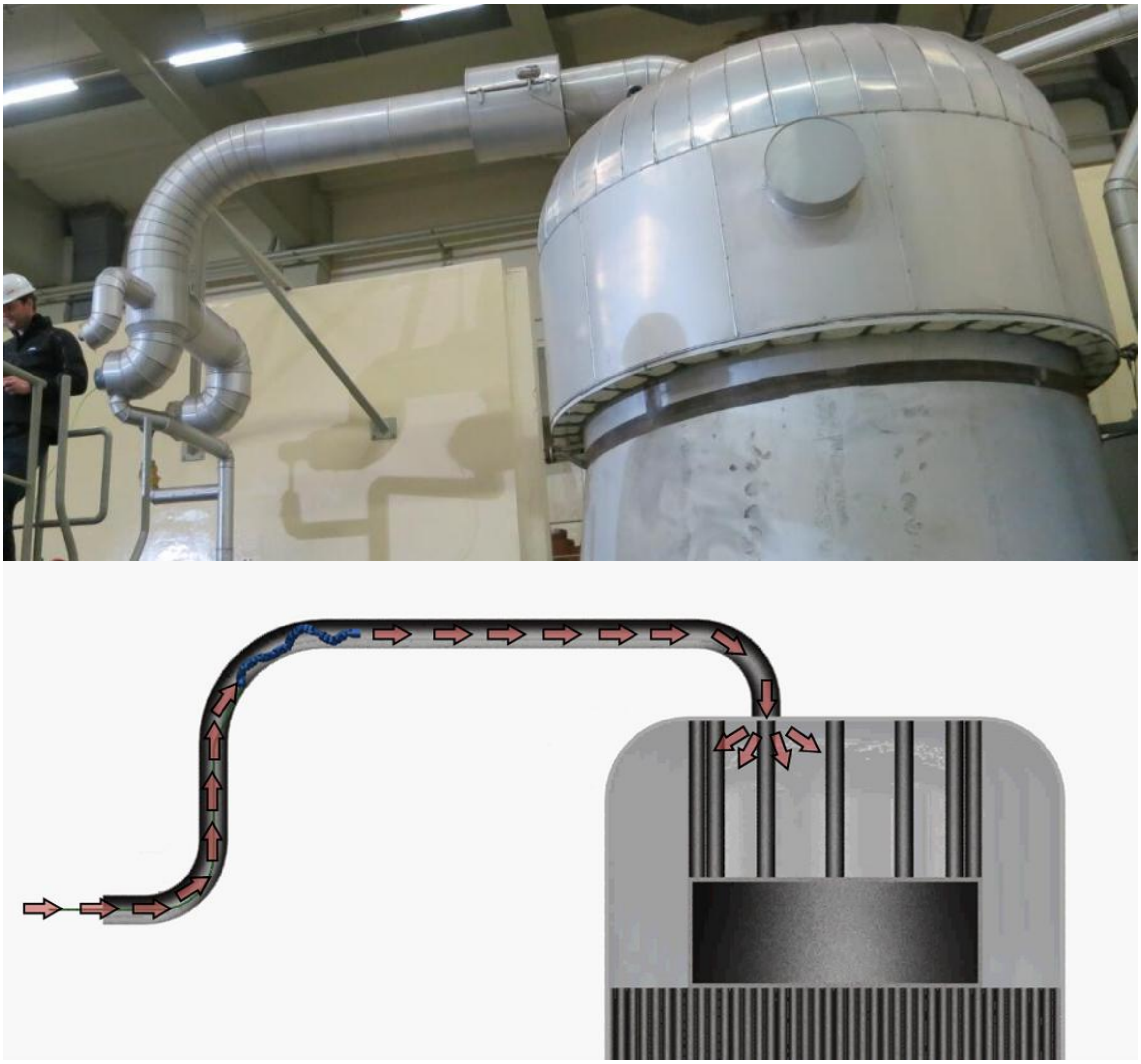

Figure 6: 6” Steam Piping Leading to Moisture Separator Reheater Vessel

The next demonstration involved inserting the robot into a 6” steam line that connects the turbine to the moisture separator reheater vessel. This particular steam line was cut open approximately 15 feet away from the vessel. The steam line begins horizontally oriented immediately following the open cut, and then contains a 90 degree bend to vertical, followed by two junctions coming into the vertical section of the pipe, and then levels off to horizontal. Once horizontal, the pipe proceeds approximately 12 feet where it drops vertically into the top of the moisture separator reheater vessel (see Fig. 6). The robot was inserted into the open cut, climbed through the pipe’s bends, and then proceeded along the horizontal portion of the line. While the robots have previously demonstrated their ability to climb inside of pipes and navigate around bends, this deployment was complicated by the fact that several other inlet pipes and junctions were present in the vertical portion of the piping. Despite these complications to the interior surface of the pipe, the robot was able to climb and navigate the bends using the helical rolling gait.

During the inspection, the robot encountered a sensor probe protruding substantially into the horizontal portion of the pipe close to the vessel (Fig. 7). The robot was able to slither under this obstacle. Once the robot reached the vertical drop into the condenser vessel, it slithered forward until it hung by its tether. The robot was lowered by its tether deeper into the moisture separator reheater vessel, while the head was steered by the operator to look inside of the vessel from multiple vantage points (Fig. 8). The robot could have proceeded deeper into the vessel's void space, but the team opted to be conservative and ensure that the robot could be pulled back with the tether. The robot was then pulled back with the tether out of the vessel, into the 6" steam line, and back around the line's bends where it was retrieved at the open cut access point.

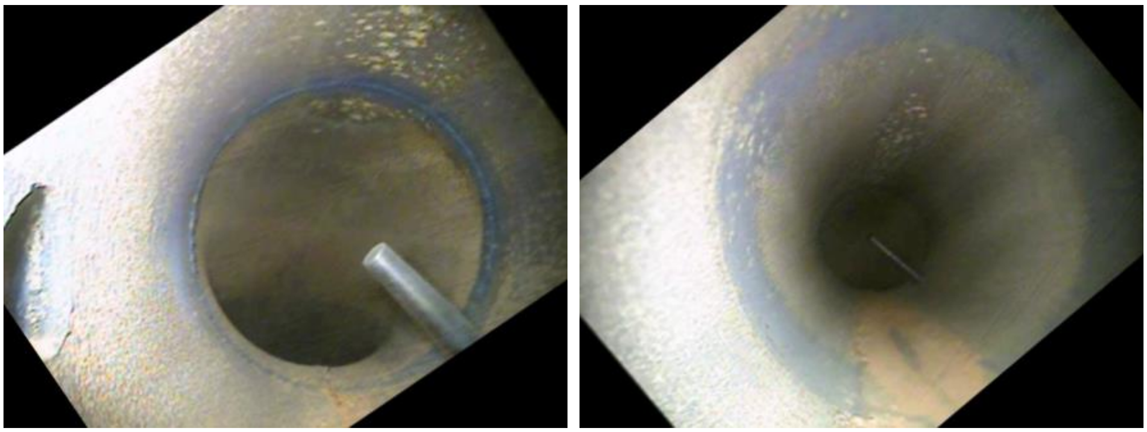

Figure 8: To images from the robot traversing the horizontal segment of pipe on the way to the moisture separator.

During the inspection, the robot provided clear, well-lit, and in-focus video which always rotated the view so that the image was "upright" regardless of the robot's orientation. This represents a major improvement over prior field deployments. To our knowledge, the snake robot is the only robot in the world currently capable of climbing through this pipe, avoiding the difficulties presented by the junctions, navigating under the probe, and then entering the top of the condenser

Figure 7: An image of the inside of the moisture separator. The robot is suspending itself from the pipe entering at the top of the vessel

vessel. A flexible borescope likely would not have been able to proceed vertically and around the pipe's bends into the vessel. Lastly, while the open cut that was used to insert the robot would not be present in an operating nuclear power plant, the team was able to trace the undisturbed mirror of the 6" steam line that entered the other moisture separator reheater vessel and determined that viable access points existed elsewhere in the same line. Additional work is required to quantify the maximum distance and the maximum number of bends that the robot can currently propel itself through in similar 6” piping to determine how far back an access point can be to still allow the robot to locomote to its end target.

4 Details: May 14th, 2013

Day 2 began with a tour of a separate power plant in Theiss (heavy oil fired), before returning to Zwentendorf for more deployments. These deployments were located at the top of the reactor and included the inspection of more steam piping. The robot locomoted through the steam pipe until a closed valve was reached. The valve was opened and the robot continued through the steam pipe. The robot was also inserted into a ring of 6” piping believed to be a fire suppression system.

4.1 Plant Visit in Theiss

On the second day, the CMU team toured a different nearby plant in Theiss (heavy oil fired), also owned and operated by EVN Group. The team saw the boiler setup and the tour guide described in detail the various ways that the boiler tubes and headers are currently inspected and the types of problems they have. The team demonstrated the robot in a break room for many of the plant personnel, who were impressed especially with the self-righting video feature. No deployments were performed in any of the Theiss plant’s piping or equipment since access into the piping or headers would have needed to be cut, which was infeasible given the time constraints

4.2 Steam Piping at Top of Reactor

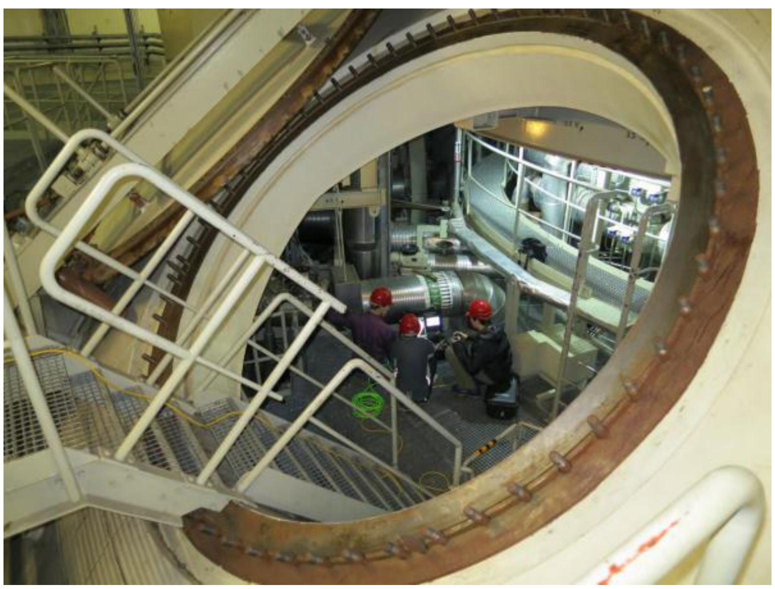

Figure 9: Deploying in the upper area of the reactor.

The CMU Team returned to the Zwentendorf Nuclear Plant for the remainder of the day and performed some more inspections of various sizes of steam lines that travel between the reactor, the condenser, and the turbine. The team entered the reactor core containment vessel, above the reactor, and identified many 18” steam pipes leading towards the reactor or exiting the containment vessel (Fig 9). One such steam line had a large valve removed, which provided a suitable access port through which the robot could be inserted into the steam line to travel in either direction (Fig. 10).

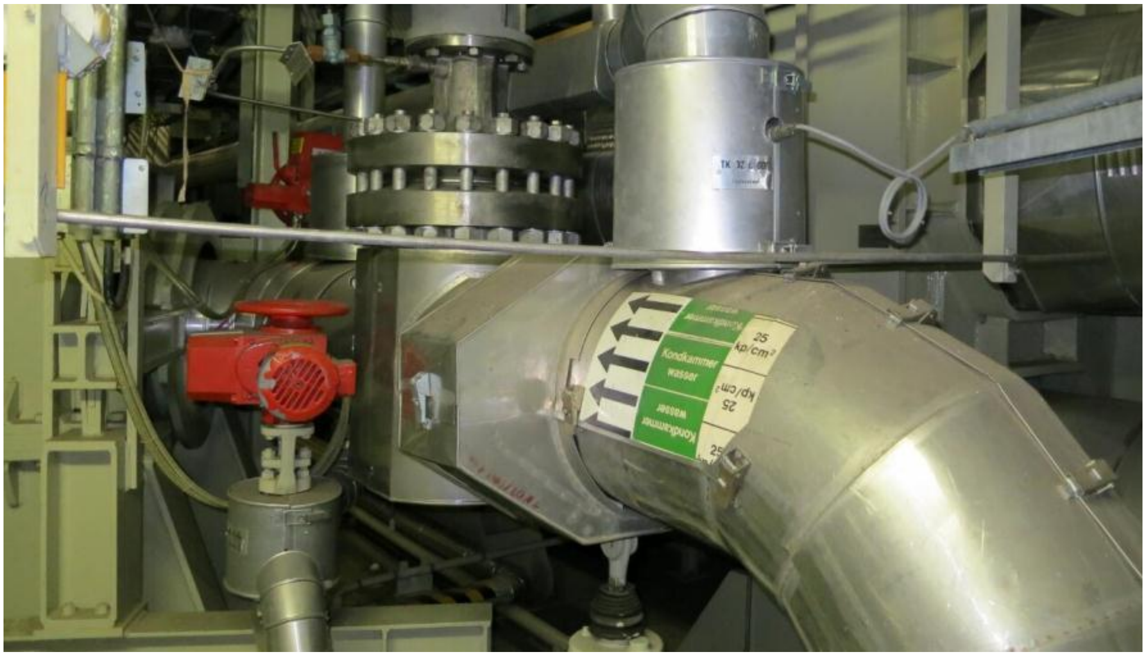

Figure 10: External view of the valve and steam piping that the robot traversed.

First, the robot was driven into the steam pipe away from the reactor. The 18” line horizontally exited the reactor containment vessel, bent 45-degrees to the right, contained a valve capable of completely closing the pipe, and then proceeded vertically down below the floor and into lower portions of the power plant (the team could not fully trace the pipe to its origin). Once the robot was inserted, it slithered along the pipe and maneuvered around the 45-degree bend. The robot encountered a loose bolt and washer that had somehow settled inside the steam pipe (Fig. 11). When the robot reached the valve, it was found to be about 90% closed and did not leave the robot enough space to continue. The team found the control override for the valve and slowly raised the valve while the robot recorded the operation from inside the pipe. Once the valve was sufficiently raised, the robot slithered through the opening. A smaller diameter pipe entered the 18” steam line from the top, just past the valve (Fig. 11), and the robot was able to lift its head up and into this pipe. However, the robot was not able to transition from the bottom of the 18” steam line to climbing vertically into the intersecting line, which suggests an area for future development to enable the robots to inspect as much of the piping network as possible. After lowering the head back into the main 18” steam line, the robot proceeded forward until the pipe transitioned to a vertical drop. Since the robot had already passed through a valve and several bends, the team opted to not lower the robot down the drop. The robot then slithered backwards through the valve it had passed and was retrieved by the team.

Figure 11: Views from inside the steam pipe in the upper reactor area. Top left, a partially open valve. Top right, a nut and bolt. Bottom, a 90-deg bend in the pipe with a smaller pipe junction.

A second deployment was conducted sending the robot into the same 18” steam pipe, but this time in the opposite direction from the access point toward the reactor core, but again the robot encountered a precipitous vertical drop that could potentially jeopardize the team’s ability to retrieve the robot with the tether.

4.3 Nitrogen Line at Top of Reactor

Figure 11: Left, inserting the snake into the nitrogen line. Right, a view down the nitrogen line during the inspection.

At the top of the reactor within the containment vessel, close to the steam line previously inspected, a ring of 6” pipe with regularly spaced 2” openings at the bottom surrounds the reactor’s perimeter. This line holds nitrogen and is believed to be an emergency cooling system or fire suppression system. The regularly spaced 2” openings are believed to normally contain valves or nozzles to distribute the nitrogen if needed, but in this case, the nozzles were removed and the openings were mostly plugged, except for a few covered only with duct tape (Fig. 12). To surround the reactor, this piping consisted of largely straight, horizontal sections with occasional bends to route the pipe around the reactor perimeter.

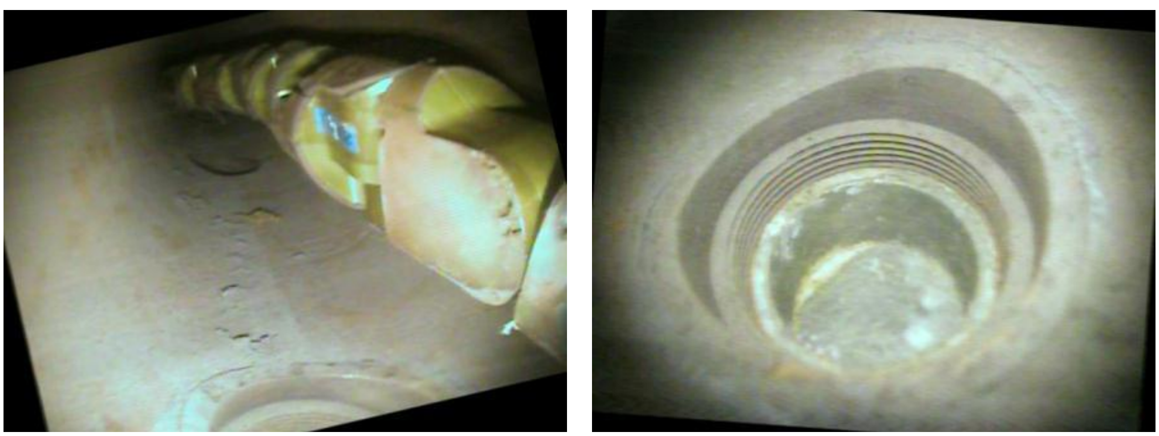

Figure 12: Views from the robot inside the nitrogen line. Left, looking back behind the robot. This view demonstrates the articulation of the camera head in very tight spaces. Right, looking down at one of the 2” plugs.

The team found an unplugged 2” opening through which the snake robot was inserted into the 6” line. Since the robot’s OD is approximately 2”, the robot had to be carefully inserted into the 2” openings.

Additionally, the 2” openings were positioned at a right angle to the main 6” line. A coordinated effort between the robot operator and the individual inserting the robot into the 2” opening was required to insert the robot. A few modules at a time were pushed up through the opening and into the 6” line, and then the operator would command those portions of the robot to bend sharply so that they did not hit the top of the 6” line. This procedure was repeated until the entirety of the snake robot was through the 2” opening, around the tight right angle bend, and into the 6” line. From here, the robot slithered forward through the 6” line, including through one of the horizontal bends. The robot was then removed through the initial insertion port.

5 Conclusions

The robots performed very well during the trip and did not fail once during the two days of deployment. The new features that were deployed for the first time (including video rotation, pose estimation, and intuitive camera controls that allow for easy steering of the head in 6-DOF) worked well and made a tremendous difference to the operator in terms of providing enhanced situational awareness when the robot was not within line-of-sight. The plant workers, many of whom had extensive experience with borescopes, were impressed with the self-rotating video and the context that this feature provides when performing inspections. More so than prior power plant deployments, the robot’s camera images were clear, generally well-lit, and in focus.

The robots demonstrated the ability to locomote within a variety of steam pipes and into several vessels. Especially with the snake robots’ ability to climb vertically, navigate around bends, and navigate past valves and sensor probes, they may hold potential as a useful inspection tool to inspect the steam pipes themselves or to reach locations in the plant such as the moisture separator reheater through the steam pipes. This inspection capability could give plant operators a more complete understanding of the plant’s condition during scheduled outages, reduce the need for access ports to be cut or opened to accommodate conventional equipment, or could permit faster and more efficient inspections of critical plant locations during downtime. Lastly, the robot’s locomotion capability could be useful in the event that foreign material may need to be removed from the plant; it is expected that various tools (or advanced sensors) can be added to the robot in ways that a borescope could not accommodate.

In addition to the steam piping and vessel inspection applications, our discussions and tour also indicated that there were several underwater inspection or maintenance tasks that could be aided with snake robot technology. The next-generation snake robot will be waterproof and could be useful towards these submerged nuclear applications.

The deployment also led to brainstorming and suggested several improvements that will make the robots even more capable. Such improvements include enhancements to the hardware, software, and accessories. A specific focus is to enable the robot to navigate various geometries and orientations of pipe junctions; this will enable the robot to inspect a large percentage of a steam pipe network from a single access point. Additionally, this deployment suggested additional research into the robot’s retrievability after navigating past multiple bends or down vertical drops; there were several times where the robot could have proceeded deeper into the piping or vessel but the team was unsure if it could be retrieved after doing so. One brainstormed concept to alleviate this problem was a ”tether-runner” device that could locomote along the snake robot’s tether to position itself around bends, at which point the tether- runner mechanism could anchor in place using an air-bag or other mechanism and assist with steering the tether around the bend with minimal friction.

Lastly, the team took advantage of this opportunity to learn about nuclear plants in general and the various ways that they are inspected and maintained. Through continued research and development, and future deployments to Zwentendorf and other nuclear plants, the CMU team is hopeful that the snake robots and their unique capabilities can be a useful and valuable technology for inspectors and operators of nuclear power plants in the future.