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Deployment of Sensor Technologies and Supporting Systems for Enhancement of the Commercial Explorer™

[a series of robotic platforms for the Inspection of Un-Piggable Transmission Pipelines]

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Background

NYSEARCH is a voluntary research, development and demonstration organization that serves (20) members in North America and is administered by the Northeast Gas Association (NGA). The NYSEARCH mission is to address members' technology needs and to produce, through contract R & D and technology transfer, viable products that provide quantifiable benefits in terms of improvements to safety and efficiency. NYSEARCH serves primarily the N. American Local Distribution Companies, many of whom also own transmission pipeline. NYSEARCH/NGA hires contractors and experts from around the world as partners in designing, developing, testing and implementing products.

In the early 2000s, NYSEARCH and its members were motivated to seek technology that could provide direct inspection of pipelines that are configured differently from traditional interstate pipelines. These high pressure pipelines, owned by local distribution companies, who operate many lower and medium pressure pipelines in customer networks, have unique characteristics in that they could not be inspected with standard in-line pigging equipment and the cost to render those pipelines "piggable" or the impact to the customer was prohibitive. Thus, with additional motivation from the U.S. Department of Transportation and their agency known as PHMSA (Pipeline Hazardous Material Safety Agency), who published a pipeline integrity rulemaking in 2001, NYSEARCH/NGA embarked on a multi-faceted, long range product development program to produce inspection platforms for pipe sizes ranging from 6" in diameter to 36" in diameter.

InvoDane Engineering is a contractor that NYSEARCH has worked with for years focusing initially on sensor development. InvoDane Engineering is a company that specializes in the design, research, and development of intelligent pipeline inspection tools who had early expertise in complex sensing systems but through this and related programs has grown to a multi-dimensional inspection and robotics technology company. Since 2008, NYSEARCH/NGA has licensed InvoDane for the Explorer family of robotic inspection products and related sensor and supporting technologies.

In late 2010, InvoDane's sister and commercial services company, Pipetel Technologies Inc. introduced the Explorer technology to North America by unveiling Explorer 6/8, an in-line inspection robot designed for 6"–8" un-piggable pipelines using a remote field eddy current sensor. The robot is operator controlled without a tether, powered via onboard batteries, and can be launched, operated and retrieved under live pipeline conditions. While inside the pipe, it inspects the wall for metal loss using a remote field eddy current sensor and can negotiate various unpiggable pipeline features such as back-to-back bends, mitered bends and vertical drops.

In 2011, the Explorer 10/14 was commercialized having the same operational characteristics as Explorer 6/8 with a magnetic flux leakage (MFL) sensor onboard for pipe sizes 10"-14". The market introduction of Explorer 20/26, a robot designed for the inspection of 20"–26" un-piggable pipelines also uses an MFL sensor followed in 2013. In addition to the feature navigation capabilities cited for the smaller diameters, robots for pipe diameters 20" and larger can accommodate a particularly challenging constraint found in larger, high pressure pipelines; plug valves. Plug valves have a trapezoidal geometry that greatly reduces the opening width in the pipeline and are impassable to a conventional inspection tool.

In 2015, additional sizes in the range of 16" – 18" and 30" – 36" are being commercially released to cover the entire range of pipeline sizes encountered in North America. Since 2011, the NYSEARCH research and development effort moved to address issues pertaining to increased efficiencies in the deployment of these technologies and for development, testing and implementation of additional sensors for increased application and value to the members and industry. The Explorer family of products is illustrated in Figure 1.

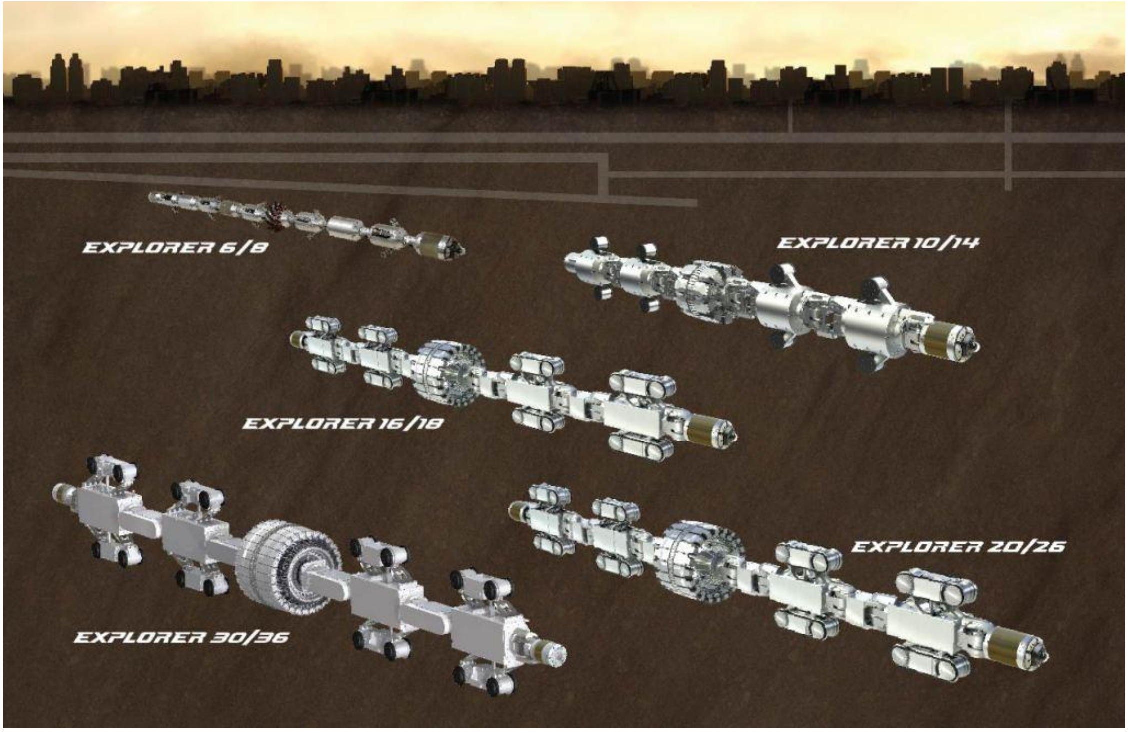

Figure 1: Views of Different Commercial Sizes of Explorer Platform

Aims

While the commercial deployment of Explorer into pipes throughout North America under a wide variety of pipe sizes and operational conditions was successful, there remained areas that would benefit from further development.

First, additional integrity sensing capabilities needed to be introduced in these systems, especially capabilities in detecting and sizing mechanical damage in pipelines, mainly for dents and ovality issues. After corrosion anomalies, mechanical damage/ovality is known to be the most prevalent type of defect encountered in pipelines. In addition, crack detection has become highly desirable because of recent incidents where unsuspected cracks played a role in the compromise of pipeline integrity.

Second, through planning and operational experience, the need to reduce the time required to re-enter the pipeline after replacing batteries was identified as a desired improvement. The proposed solution was to implement a method to safely charge the robot without removing it from the pipe. This in-line charging technology increases operational efficiencies by allowing more distance to be inspected per deployment.

Third, in the unlikely event that the Explorer robot lost battery power while in live pipe, a method to retrieve the robot from the pipe was conceived to address this situation. This rescue robot could be deployed to act as an 'insurance policy' for use in live conditions.

Fourth, for pipeline inspection using in-line sensors, generally cleaner pipe provides higher quality data. Having a configuration of the Explorer tool that would be capable of cleaning the pipe wall prior to inspection ensures better quality data during the inspection.

Finally, and in recent months, to address the need for materials characterization without the need for expensive removal of pipe coupons or hydrotesting, NYSEARCH and InvoDane are investigating the practicality and conformance of a technique for determining the hardness and yield strength of the pipe material from inside the pipe using the Explorer platform. By late 2015, the team will be well into the development of a hardness tester module for the range of platforms.

Methods

Mechanical Damage and Ovality Sensor

Dents and mechanical damage in pipelines can result in stress risers and sometimes cracks; which may in some cases cause leakage or rupture, if the damage is not discovered and addressed in a timely manner. In the in-line inspection industry, sensing and detection of mechanical damage and ovality are achieved through deployment of 'caliper' pigs. These are mechanical devices that rely on displacement measurements to determine deviations from a perfectly circular pipeline cross section. Following a feasibility study, it was determined that the use of a mechanical calliper on Explorer platforms is not the optimal solution. NYSEARCH/InvoDane proceeded to explore the potential capabilities of the on-board cameras that are positioned at the front and rear of the Explorer robotic inspection platforms to detect and size mechanical damage. Evaluation showed that use of supplemental optical equipment and enhancement of the video images was a viable approach. An optical system would provide the detection capabilities and accuracy of a mechanical calliper without the large size of a caliper system. All work during the feasibility study was performed on the Explorer 20/26 size platform but the product concept was designed with the vision of applying the mechanical damage sensor on all size platforms. The work was broken down into three segments: video analysis, image enhancement and laser (optical) analysis methods.

It was determined that while the shadows and coloration changes of the existing video images could provide qualitative dent detection for large dents, that sizing of length, width and depth of the dent would not be possible without enhancements. Figure 2 shows a view of the measurement of the dent width by attempting to measure the swept angle of the shadowing presented by the dent from the standard video. This method exhibited the need for corrections to distortions and offsets. Also, using the existing video capability, the axial measurement (length) was attempted by driving the platform tool past the feature of interest and noting the odometer reading as the feature comes into view and then passes by. Repeatability of the measurement was not evident and precision of the odometer readings

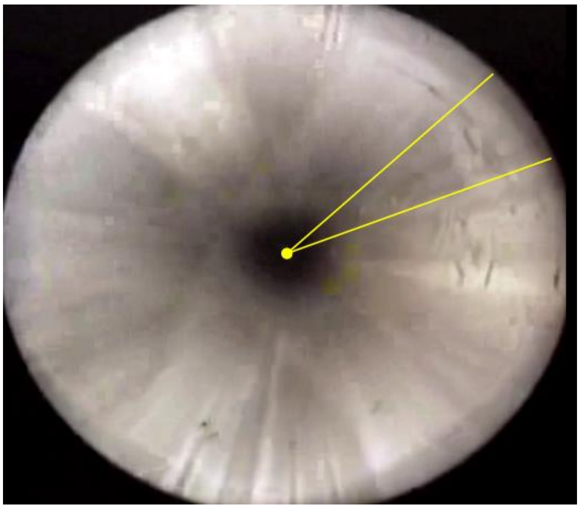

Figure 2: Width Measurement from Video

were generally overestimated while the width (circumferential) of the dent was found to be underestimated. Depth measurement was not possible with this approach.

Furthermore, while dents usually only cover a short axial distance, changes in ovality are typically occurring over longer axial distances. Dents can be differentiated by comparing to the immediate surroundings of the pipe. Changes in ovality require an accurate absolute measurement of the pipe. The existing video technology on the Explorer platform was not sufficient to measure total overall ovality.

InvoDane then investigated ways to enhance the same video imagery to accentuate the presence of dent features in the recorded video. Various parameters could be changed to enhance the video such as control of the image contrast, camera sample rate, and choice of camera lens. From the parametric study, it was determined that the video image could be enhanced and that enhancement during post-processing could aid in dimensioning. However, even with video enhancements, the threshold of detectability was for dent heights greater than 3% (of the OD). Since the reporting minimums are at 2% or better, this method was abandoned.

During the video analysis, it was observed that proper marking of the extents of the dent could be achieved by applying specialized lighting to the pipe surface, including using lasers. InvoDane used analysis methods and investigated various configurations and orientations for applying a laser beam from the Explorer tool head onto the internal surface of the pipe. In general, this optical method projects a laser line onto the surface of the pipe. See Figure 3.

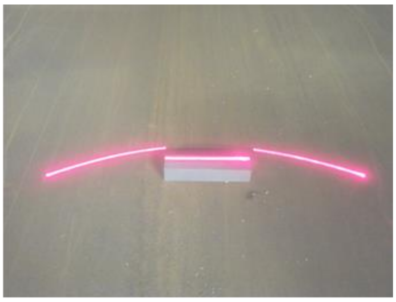

Figure 3: Laser Line projected at angle on surface of the pipe

With the laser fixed to the robot, any deviation in the pipe surface height can be measured. This measurement allows the analyst to determine the depth, width and length of the features that protrude from the interior wall of the pipe. From this work and the camera image work, InvoDane was able to specify the best combination of hardware and post-processing software to minimize power consumption while optimizing the sizing capabilities of the mechanical damage/ovality sensor.

In-Line Charging Tool

For improved operational efficiency, NYSEARCH and InvoDane developed an in-line re-charging system with the goal of charging Explorer's batteries without removing the system from the pipeline and in live operating conditions. This system is intended to be applicable to all sizes of the Explorer series of platforms.

The in-line charging system consists of the insertion module and the power module. The insertion module is attached to the pipe and contains an actuator for connecting the charge plug to the robot. The insertion tool was designed to mount to a 2" hot tap fitting on any live pipeline from 6"-36" in diameter. Off-the-shelf components were explored for the various sub-systems but it was determined that the insertion tool and the battery charging device needed specific design for the use in the Explorer charging situation.

The power module supplies regulated power for charging to the insertion module. The power module can be implemented as a battery bank in a pressurized canister. The considerable weight of the batteries was factored into the layout and designed to be kept above ground during the installation and use of the in-line charging tool. The resulting

Figure 4: In-line Charging Tool in Live Setup

product can be seen in Figure 4.

Rescue Tool

The rescue tool, first created for the Explorer 20/26 platform but also adapted for platforms as small as the Explorer 6/8, was designed to be deployed through a standard hot tap fitting like the one used to launch the Explorer robot. Once in the pipeline, the rescue tool is designed to connect with a disabled robot and to carry out basic diagnostics to determine the cause of failure to the system. The rescue tool has the capability built into it to restore power and communications to the robot in some cases and in others, to tow the disabled robot to a section of pipe that where the robot can be recovered, all under live conditions.

Figure 5: Rescue Tool approaching nose of EXP

The rescue tool has a configuration very similar to the Explorer platform; see Figure 5. Given its mission to potentially tow an Explorer robot, its mechanical components and electric motors are upgraded. The nose module at one end, the end to connect and grasp the incapacitated robot, is modified to include a mechanism that can grab the disabled robot and establish electrical and wireless connection with it. Diagnostics can be run to determine reason of failure of Explorer. Also, the batteries of the disabled Explorer can be recharged using the battery power stored on the rescue tool. Finally, the rescue tool can communicate with the various subsystems of Explorer and transmit wirelessly information and commands to and from the operator.

Crack Sensor

Cracks which are grooved or slotted can be open or closed. With respect to pipeline integrity and the concerns of the NYSEARCH funders, the axial cracks in seam welds are of concern because cracks that grow in this way can be stressed by internal pressure.

Starting with a feasibility study, InvoDane first worked with NYSEARCH on the general requirements of crack detection on unpiggable pipe and then came up with a wide list of potential technologies (including a range of technologies such as radiographic measurement, eddy current measurement, ultrasonic transducers, etc). Then, they narrowed their evaluation by looking at the stringent sensor requirements for this robot and what was needed for the funders' priorities of crack types. The potential options were further narrowed down by considering from those technologies that could potentially meet the sensor requirements, the constraints that are imposed by the necessary integration into the Explorer series of robotic platforms.

The standard axial MFL tool which is used on the Explorer platforms for wall loss measurement (corrosion assessment) could not be used for the primary crack of interest on seam welds because these are narrow axially oriented anomalies that are not oriented properly to be measured by axial MFL. Shifting the orientation of the magnets, a Transverse Magnetic Flux Leakage (TMFL) sensor was explored. The sensors used in this system are hall sensors and the magnetic field is biased in the circumferential direction. For TMFL, the magnetic field from one magnet is not bounded by the adjacent magnet like for in the case of an axial MFL setup. Thus, a stronger magnet is required. Both the orientation and the strength of the magnet were evaluated because of concerns about data coverage and accuracy as well as power consumption due to sensor drag and weight. After performing a number of tests on slotted and cracked plates, it was determined that hall sensor spacing and orientation are very important for detection in this magnetic design.

Seam weld simulated defects that were tested with the TMFL included toe cracks, root cracks and lack of penetration. From the various tests and analysis of sensor spacing as well as flux leakage from the sensors, very specific information became available as to the number of sensors required and the amount of magnetization needed to acquire signals with high resolution. TMFL tests were able to confirm the ability of this approach to detection of axial open cracks/slots in base and weld materials.

The Electromagnetic Acoustic Transducer Technology (EMAT) was also selected to be combined with the TMFL sensor because of its applicability to different types of cracks; particularly those with shallow profile. The transducer consists of a magnetic field applied to a coil placed as close as possible to the surface of the material. The coil is subjected to a strong electric pulse which creates an ultrasonic wave in the pipe wall. These waves can be analyzed when there are anomalies in the material. In the tests that followed, InvoDane was able to demonstrate that both the TMFL and EMAT technologies could detect certain types of cracks but there were trade-offs for each. The designers then needed to concern themselves with how to apply both sensors in the limited space and the rigorous operational conditions experienced by the Explorer platform.

With input from the NYSEARCH funders, InvoDane did a thorough analysis of the configuration of the sensors, their performance and whether they could be arranged and used as probes from a platform sensor module or as an array of sensors on a platform sensor module. Because of a primary driver to collect the full circumference of the pipe data in one pipe, it was finally determined that the combined sensor would be developed with the array configuration. An illustration of the crack sensor configuration is shown in Figure 6.

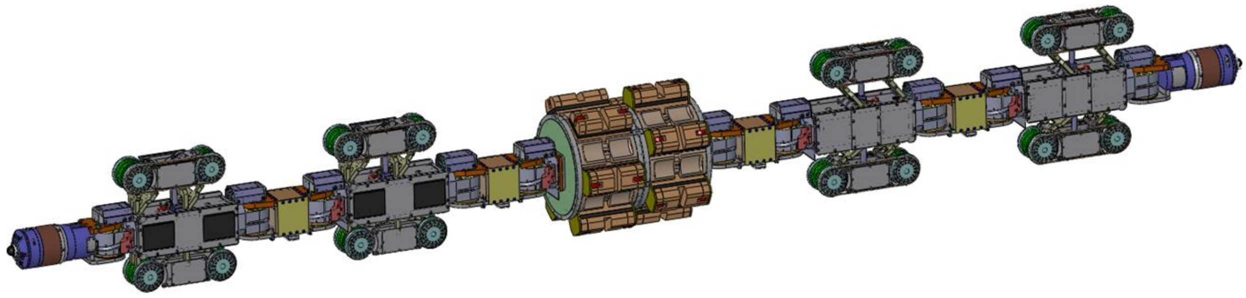

Figure 6: Combined TMFL/EMAT Crack Sensor in center module of Explorer

Cleaning Tool

The starting point for the development of a cleaning module was to use several of the same Explorer platform modules without the sensor module but with a cleaning head and other special features. The project requirements were the same as in the Explorer inspection projects where the pipeline must remain fully pressurized/live, various features for the unpiggable lines must be navigated, and wireless communication must be used.

The major design considerations for the cleaning module implementation were to achieve enough debris removal to be effective for the energy spent but not so much that the resulting debris cannot be removed from the pipe and causes operational issues. The cleaning robot will be implemented as an attachment onto Explorer and will enter through a dedicated hot tap. A second hot tap will be setup with the flow diverted to extract the debris from the gas flow.

Operationally, the main concerns were how to deploy the tool and what type of cleaning head was needed. Further, the team wanted to select the most effective methodology for scraping and suspending debris and then getting it into a separator without any loss of operation.

In the final configuration, an operational scenario involving two hot taps of the pipeline to be cleaned and inspected was adopted, as shown in Figure 7. One hot tap is to be used for launching and retrieving the cleaning tool and the inspection robot, while the other one will be used to attach the separator, introduce the gas/debris to the separator and reintroduce cleaned gas to the pipeline.

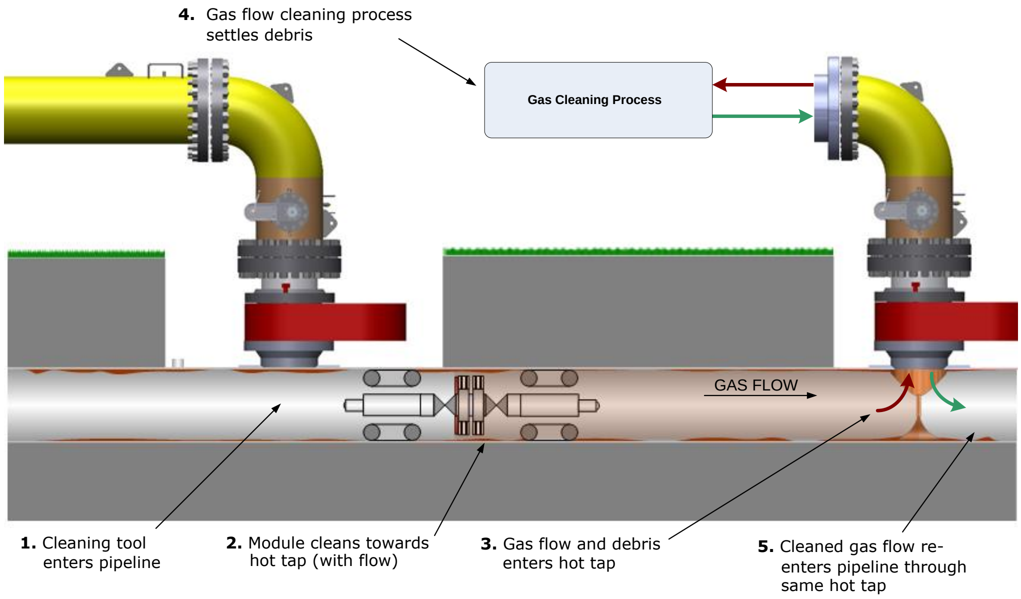

Figure 7: Cleaning Tool Configuration for full operation

Hardness Tester

In the summer of 2013, PHMSA published the draft integrity verification process (IVP) that requires the establishment of a materials documentation process by all pipeline operators in the U.S. The reason for this process is to document the basis used by each operator for establishing a pipeline's MAOP. In the absence of proper material documentation, tests need to be carried out to establish the pipeline's MAOP. Hydro-testing could be used, but such a test is expensive, generates a lot of waste water and provides only pass/fail information. In situ non-destructive tests could be carried out on the exterior of the pipeline using portable hardness testers. This solution requires the excavation of the pipeline in multiple locations and the removal of the coating thus, making it expensive and inefficient. Finally, cut-outs could be obtained for non-destructive or destructive tests in the laboratory, this method depending on the rather difficult and limited option of obtaining the cut-out samples.

An in-line tool that would be able to carry a non-destructive test from the inside of the pipe would be the optimal and preferred solution in many if not most cases. The availability of the Explorer family of robots provides us with the basic technology capability for such a test. A module could be added to the existing robots that would be able to carry out such a test.

It is envisioned that the internal pipeline hardness tester will be based on the portable hardness testers that have been developed in the past for in-situ external testing of pipeline materials. The method outlined in ASME CRTD Vol. 57 correlates hardness data to yield strength. To collect hardness data from the pipe material requires selection of a measurement method. Many measurement methods exist to evaluate hardness including Leeb ball rebound, Brinell, Rockwell, Ultrasonic Contact Impedance (UCI), and automated ball indentation. According to CRTD Vol. 91, portable measurement devices using these techniques are considered sufficient and equivalent to a laboratory instrument, if they are within 96-102% of the values obtained by the laboratory instrument.

The feasibility study was broken down into several steps. The steps included determining a method to prepare the internal surface for measurement, identifying and testing the surface preparation method, determining the method of sensor mounting onto the Explorer and establishing and proposing the hardness test qualification method.

The current and ongoing work is focused on implementing the selected method by designing, building and testing an Explorer module for the 20/26 platform that is able to carry out such a test in a live pipeline.

Results

Mechanical Damage/Ovality Sensor

After both a feasibility study and a development program, NYSEARCH and InvoDane have successfully developed and introduced an optical sensor for detecting and sizing mechanical damage, dents and ovality in pipelines. This optical sensor offers the detection capabilities of state-of-the-art mechanical calipers, while requiring a fraction of the power to operate at a much smaller size.

InvoDane/Pipetel commercialized the resulting mechanical damage/ovality sensor in 2013. The sensor, known as the LDS (Laser Deformation Sensor), has been used for most commercial jobs since then and has been performing well. The LDS system consistently achieves dent measurement specifications of sub 1% accuracy and has been verified in

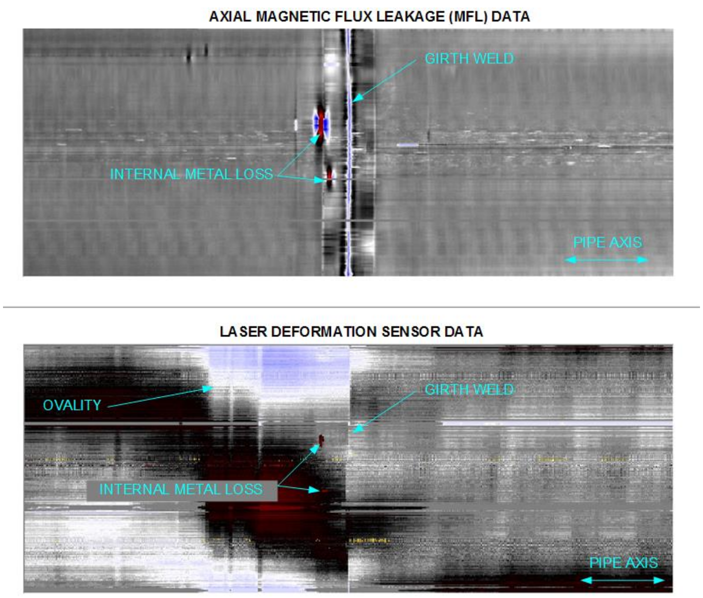

Figure 8: LDS Data from a Live Pipeline

client pipes. The LDS system is typically deployed on all commercial inspections. An example of the image/date obtained from the LDS in live conditions on a 24" pipe inspection is shown in the Figure 9. The dent shows up as the dark blue region at the left of the graphic. Other variations of color are due to round off error, vibration, and positional offsets in the pipe. In addition to the dent measurement, the LDS also can measure some of the larger internal defects found in test pipes. Previous

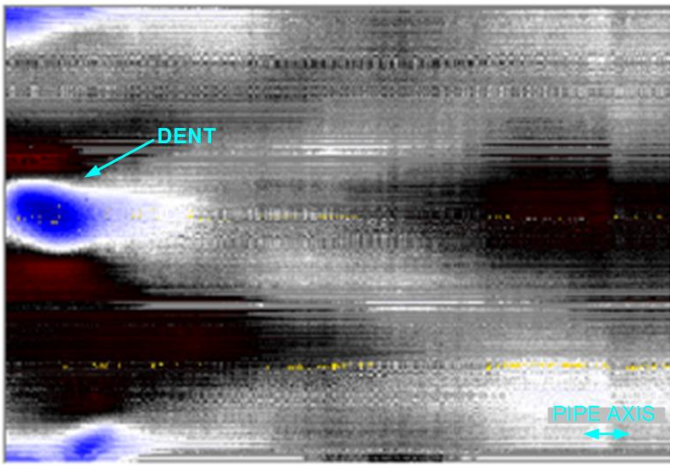

Figure 9: LDS data aboard Explorer showing presence of dent

scans show two defects very close to the girth weld. These defects can be seen in the LDS plot below meaning that they are on the inside of the pipe. This demonstrates the capability of the LDS system to act as an internal/external defect differentiator.

In addition to its use aboard Explorer 20/26, the LDS is also adapted to fit onto the 10/14 and 16/18 and 30/36 robots.

In-Line Charging Tool

In-line charging has provided extended range between full sized hot taps which has both reduced tapping costs as well as increased inspection productivity. The longest length of pipe that has been inspected between full sized hot taps is approximately 4km (2.5 mi) long eliminating the need for two additional full sized hot taps.

Crack Sensor

Data from a test scan is shown in Figure 10. **Error! Reference source not found.**

This data has exceptional quality for both the seam weld and the base material defects. In lab tests on pipes with simulated cracks to date, the TMFL sensor has detected all simulated defects for the priority cracks except those with less than 20% depth. EMAT (combined aboard the TMFL sensor) measurement of the seam weld have also been successful with reduced threshold of detection (50%).

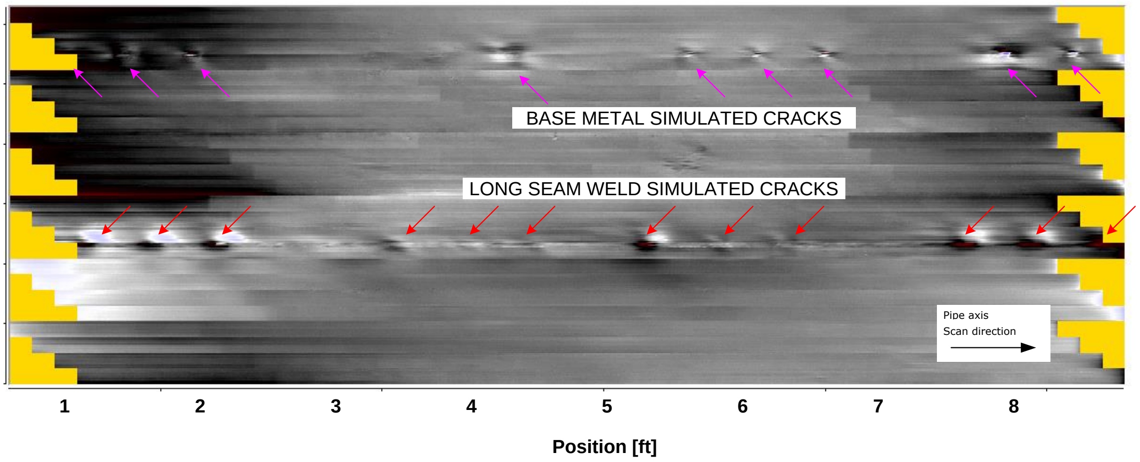

Figure 10: Crack test data

Cleaning Tool

The cleaning module development is now underway with various configurations being evaluated and tested. The team has determined that only two taps are needed for the cleaning tool operation. One tap will be devoted to launch/unlaunch operations for the Explorer cleaning module. In-line charging will likely be required during cleaning operations since the system will require more power consumption than inspecting. A second tap, downstream of the first, will be used to retrieve debris from the gas flow.

Hardness Tester

The hardness tester module has been proven feasible and development is underway. Additional information on the results of this work will not be publicly available until late 2015.

Conclusions

Since initial commercialization in 2010, Pipetel has established itself as a leader in the space of robotic inline inspection of unpiggable natural gas pipelines, having completed over (120) inspections. The company currently has long-term agreements with over (25) natural gas pipeline operators and distributors in Canada and the United States and continues to grow in its capabilities as a service company under Invodane Engineering.

NYSEARCH's program for continued development and testing of supporting technologies is thriving and there are additional efforts that are being discussed or underway that are a subject of further publication. For those sensors described in this paper, the implementation of the LDS sensor, the crack sensor, in line inspection and rescue tools has, as expected, increased operational efficiencies. Like with most R & D, as these tools are put to use successfully, additional challenges and opportunities are being identified.

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