Sensor Evaluation for a Robotic In Line Inspection Vehicle for Detection of Natural Gas Pipeline Defects and Leaks

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Submitted by

Michael Hassard and Gerald Stoker
Advanced Diagnostics and Production Testing Department
Sandia National Laboratories
P.O. Box 5800, MS 0555

And

Mark Vaughn and Bob Bickerstaff
Mobile Robotics Department
Sandia National Laboratories
P.O. Box 5800, MS1125
Albuquerque, NM 87185

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ABSTRACT

When examining the condition of a pipeline, In-Line Inspection (ILI) utilizing various Non-Destructive Testing (NDT) methods is an essential tool and a significant factor in establishing a quality management program that ensures safe, cost effective operation of the pipeline. An in-line inspection concept has been developed by Sandia National Laboratories that uses a robotic vehicle rather than a conventional pig for in-line inspection. This vehicle could be capable of negotiating tight bends, obstructions, varying pipe diameter, and out-of -round sections. It could use existing valves for launch and recovery, generate power from the product flow, and not unduly interfere with product flow. Because this vehicle can stop in the pipe, previously unused Non Destructive Testing (NDT) technologies could be utilized for better characterization of pipe defects, corrosion, or damage.

This report describes activities looking at the compatibility of NDT techniques not traditionally used in the pipeline inspection industry with a robotic platform and evaluate if these sensors can be adapted to enhance in-line inspection. Mature and commercial off-the-shelf (COTS) sensor technologies were evaluated that could be applicable to a robotic vehicle. Use of existing or currently utilized sensing technologies and the adaptations / miniaturization required to mount them on a conceptual robotic vehicle were evaluated. We assessed "What can we see? What is the probability of detection? And, How do we make it fit in a robotic vehicle?" This report summarizes those evaluations.

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1. INTRODUCTION

When examining the condition of a pipeline, In-Line Inspection (ILI) utilizing various Non-Destructive Testing (NDT) methods is an essential tool and a significant factor in establishing a quality management program that ensures safe, cost effective operation of the pipeline. No NDT technology or technique is universally applicable. Therefore, pipeline operators and inspection service companies jointly choose the appropriate technology for each particular situation. The level of defect specification needed is matched to the performance of the typical inspection tool.

An in-line inspection concept has been developed by Sandia National Laboratories that uses a robotic vehicle rather than a conventional pig for in-line inspection. Sandia has developed a wide range of un-tethered, autonomously controlled and powered, mobile, robotic platforms for surveillance and testing in many environments. This expertise and capabilities were used to identify and develop potential concepts for robotic inspection systems for in-line inspection of natural gas pipelines. The robotic vehicle concept developed could be capable of negotiating tight bends, obstructions, varying pipe diameter, and out-of -round sections. It could use existing valves for launch and recovery, generate power from the product flow, and not unduly interfere with product flow. The general design concepts for the system are identified in Reference 2 and are shown in Section 3 of this report with ideas of how NDT sensor systems might be incorporated into a robotic inspection vehicle.

The robotic vehicle as designed would be able to regulate its own speed, independent of product speed, and would be able to stop and even reverse motion in the pipe for in-depth, close inspection of detected flaws. Because this vehicle could travel at speeds slower than the gas flow velocity or could stop in the pipe, previously unused Non Destructive Testing (NDT) technologies could potentially be utilized for better characterization of pipeline defects, corrosion, or damage. Further, NDT technologies are constantly being improved and new methods developed in an effort to keep pace with the development of new materials (i.e. composites) and other applications. Advances in the use of lasers and imaging technology (including video and thermography) have made non-contact NDT more viable in many situations.

As part of our effort, Sandia conducted a state-of-the-art review of NDT technologies applicable to defect inspection, and specifically those having the potential for adaptation to in-line pipeline inspection. Sandia developed a report on potential or applicable NDT technologies early in FY02 that has almost 100 references on NDT technologies and discusses applications, uses, and potential strengths and weaknesses.[1]

Also for this effort, Sandia developed an advisory group of pipeline industry representatives to help guide in the selection and evaluation of NDT technologies for application with a robotic in-line inspection system. Several NDT techniques were recommended by this industry panel to review in depth and evaluate for possible use in a robotic in-line inspection system or vehicle. The recommended technologies included Ultrasonic Testing (UT), Eddy Current (EC), Electro Magnetic Acoustic Transducers (EMAT), and Capacitance Sensors.[2] Each of these methods were researched and/or investigated for ability to detect flaws in a natural gas pipeline environment. Their viability, adaptability, strengths and weaknesses were evaluated in this project.[2,3]

This summary report specifically describes activities looking at the compatibility of NDT techniques not traditionally used in the pipeline inspection industry with a robotic platform and evaluate if these sensors can be adapted to enhance in-line inspection. Mature and commercial off-the-shelf (COTS) sensor technologies were evaluated that could be applicable to a robotic vehicle. Use of existing or currently utilized sensing technologies and the adaptations / miniaturization required to mount them on a conceptual robotic vehicle were evaluated. We assessed "What can we see? What is the probability of detection? And, How do we make it fit in a robotic vehicle?" The results of that assessment for each of the major NDT areas identified by the industry panel are presented and discussed in this report.

Through our research we have found that the techniques and technologies in use today are very advanced and industry is intimately acquainted with the challenges, shortcomings, and ability to detect flaws that most of the technologies posses. Much of what is known is often closely guarded and proprietary to pipeline inspection companies. However, we have made progress, and there are some industries that are tremendously excited about robotic in-line inspection system concepts. If a robotic vehicle can be built, some members of the pipeline inspection industry would be agreeable to adapting their developmental inspection hardware to fit within that vehicle.

2. NDT TECHNOLOGY EVALUATION FOR ROBOTIC IN-LINE INSPECTION

As mentioned in the introduction, several NDT technologies were initially identified for evaluation. Detailed information on the technologies evaluated and their capabilities is available in Reference 1. Based on industry input and available information on NDT technology capabilities, several technologies were identified for more detailed evaluation as discussed in Reference 2. A short summary of the detailed evaluation of each of the primary NDT technologies assessed for application to a robotic vehicle are presented below.

Ultrasonic Testing:
Our investigation did not disprove anything to change the currently accepted standard regarding ultrasonic inspection. A liquid or semi-liquid couplant is essential to test sensitivity. Currently, Ultrasonic pigs are used only in liquid filled pipes, or with a liquid couplant slug surrounding the pig. Since a robot designed not to block product flow at the center of the pipe is being considered, it will be impossible to use a couplant slug in conjunction with this type of robotic inspection system.

Advances in roller interface material are not to the point that we can do away with a couplant completely. Too much sensitivity is lost at the transducer to pipe wall interface to detect critical flaw size. In addition, due to the relatively small size of each robotic segment, an adequate supply of couplant cannot be carried on board. For these reasons, a robotic vehicle will not perform detailed ultrasonic testing of extensive sections of dry pipe. Smaller "problem" areas may still be investigated more closely by stopping the vehicle, backing up to the location requiring greater scrutiny, and then dispensing a small amount of couplant and scanning ultrasonically, but UT isn't viable (at this time) for fulltime 100% coverage of a gas pipeline with a robotic vehicle.

As seen below in Figures 1 and 2, UT configurations utilizing dual-element side view transducers or single element forward view transducers could ensure full inspection area coverage. We anticipate the need for a single UT array with one roller probe per robotic section making use of two or three channels of data gathering. The use of dual ultrasonic arrays will not be required (as originally thought) as "side view" pitch catch and pulse echo roller probes are now available from industry leaders such as "Sigmatix."

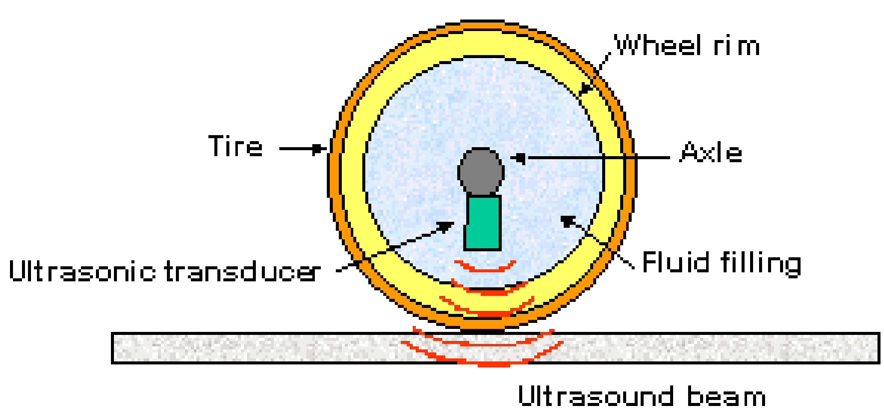


Figure 1. Typical Side View of Ultrasonic Testing Configuration

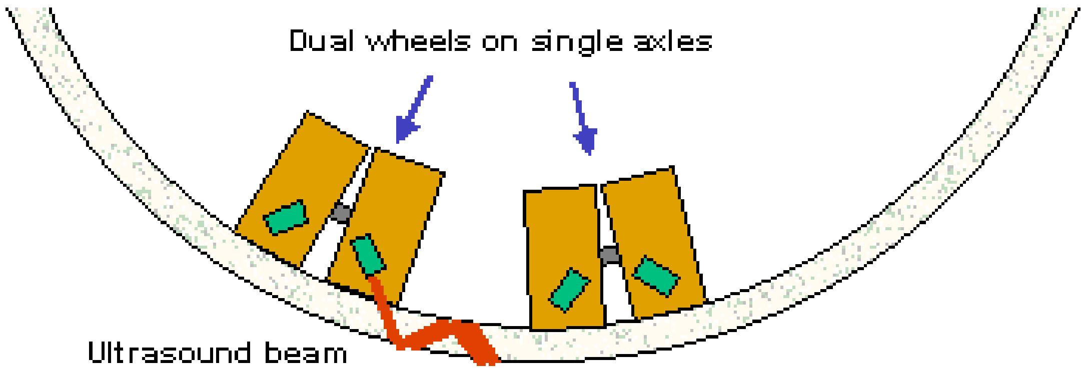


Figure 2. Typical Cross-section of Ultrasonic Testing Configuration

Studies are ongoing with regards to the possibility of using air-coupled ultrasonic transducers. If these prove viable, the need for couplant will be eliminated. Non-contact “air-coupled” transducers can also be oriented in any direction needed. This advanced technology would also greatly reduce the wear and tear, power requirements, and structural requirements to the robotic vehicle.

The avidly expressed interests of those in industry for development of advanced sensor technologies (such as air coupled UT or EMATs) encouraged the authors to focus on these types of technologies instead of pursuing in detail improvements in conventional UT.

Eddy Current:

Eddy Current (EC) sensors may be used in either a stand-alone configuration, or attached to a servomotor and married to a capacitive sensor for maintaining stand off. The stand-alone configuration would be much simpler, more dependable mechanically, and require less energy. Spring loaded dragger arms with sensors imbedded in the tips at fixed standoffs would be recommended. This would also free up all the internal space of each EC robotic segment for signal generation and data storage and analysis. Thus, allowing more channels per robotic segment.

Getting good resolution or adequate depth of penetration at desired scanning speeds of even 1-2 meters per second is problematic. Also, coping with large dynamic variations in sensor lift-off from the pipe surface would be difficult and reduce sensitivity. Therefore, applying EC NDT techniques onto a moving vehicle, even a robotic vehicle moving at relatively slow speeds, could be a difficult data quality and data sensitivity issue.

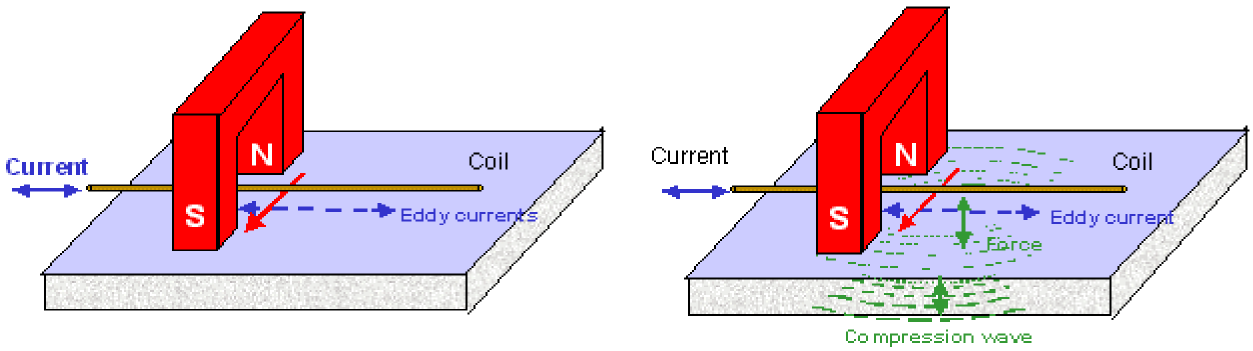
Capacitive Sensors:

Capacitive sensors by themselves would not be capable of interpreting minor flaws or indentions. They may be employed as a rough mapping sensor to determine major damage. However, the relative position of each section of robot could be used to perform the same mapping function. Therefore, the robotic inspection tool could function as a caliper system, probably using much use less energy and data storage capacity than having a series of capacitive sensors around the pipe diameter. For these reasons, capacitive sensors were not determined to be of significant application to a robotic in-line inspection system.

Electro Magnetic Acoustic Transducers:

EMAT sensors are being constantly studied, modified, and improved. In the past, EMAT systems were not employed in the inspection of pipelines because they consumed so much power that a conventional un-tethered pig was not viable. Sensitivity of these systems may have also been lacking in the past. However, if EMATs could be made to work within a pipeline environment with a robotic in-line inspection system, there is a huge potential for this type of sensor. For example, EMATs can mimic the signal results of both UT and EC, while not being limited by either couplant or standoff issues or problems.

Figure 3: Conventional EMAT Technology



- Establish a magnetic field in the pipe wall
- A coil carries AC current at 90° to the magnetic field
- Mirror eddy currents start to flow in the pipe wall

- A force normal to the pipe wall is exerted on the eddy currents
- This force generates ultrasound traveling through the pipe wall

There is a large amount of cutting edge research being performed by various industry groups including EMAT Consulting, PII, and Tuboscope (to name a few). Because of the proprietary nature of this work, much of the developing capabilities are unavailable at this time. These companies though understand the potential for EMAT technology to be a major technique for the future of pipeline inspection.

During the NETL Natural Gas Infrastructure Reliability Industry Forums in September 2002, several representatives were in agreement regarding the best course of action for sensor development for a robotic vehicle. Most participants were impressed with the paradigm shift in in-line inspection vehicle concept a robot provides. Sandia's "Slinky Robot" idea is an aggressive leap forward. However, industry's reaction to the idea of mounting existing and what many consider even obsolete sensor technology on such a progressive robotic platform was met with uniform disappointment. Dr. George Alers of "EMAT Consulting" and NIST led those who expressed their displeasure at the idea of even considering UT roller probes. Dr. Alers is responsible for much of the research and development that resulted in the "smart pigs" that are being used today. "You just build the robot! We will put the sensors on!" Designing, installing, and proving of advanced sensor technologies to be installed on the vehicle can and should be performed through a partnership as well. Dr. Alers has, on numerous occasions, expressed enthusiasm for partnership in this type of project.

3. SENSOR DESIGN COMPATIBILITY WITH A ROBOTIC VEHICLE

Whether it's brand new and cutting edge technology in the form of EMAT sensors, or tried and true Ultrasonic wheel probes (with their limitations), fitting the sensor and it's related electronics into a new robotic type vehicle for in-line inspection, as well as supplying an ample amount of power, are hurdles to overcome. In order to produce a viable robotic in-line inspection vehicle that can support these sensing technologies, additional general system information is needed to evaluate and develop a system. Regardless of the final sensor suite, configuration, space, weight, and power concerns must be met.

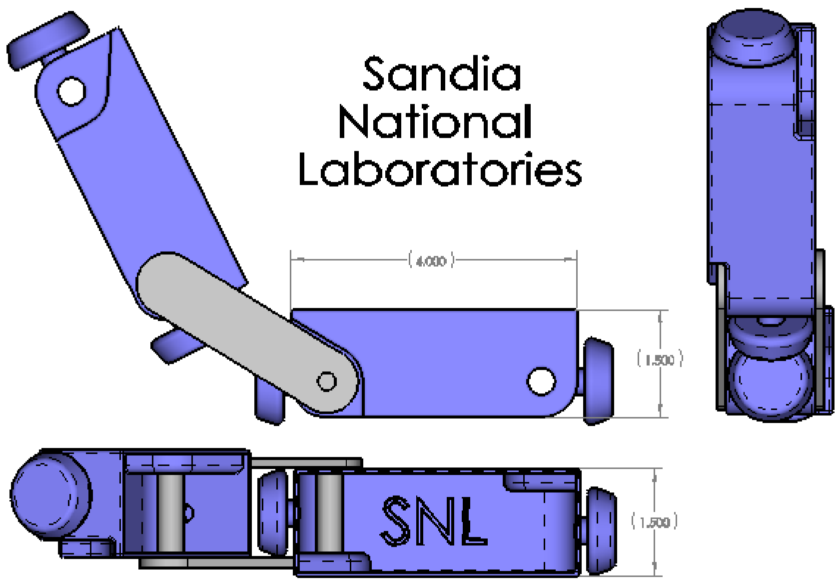


Figure 4: Sandia Robotic In-line Inspection Segmented Vehicle Concept

One robotic design concept, which is shown in Figure 4, is a robotic pipe crawler that has linked sections. Because the sections are articulated and offset, the robot is able to change size as the pipe diameter changes. The ideal shape and size of the sections has yet to be determined but boxes shown enable room for sensors, electronics, batteries, etc. The wheels shown on each section provide the drive to enable the robot to move along a pipe.

This general concept has been considered and modified and upgraded based on the evaluation of the NDT technologies previously discussed. The modified and upgraded version is shown in Figures 5-7. First of all, the sections are individually shaped as airfoils. This allows us to take advantage of the swiftly passing gas flow in several ways. Outward pressure is created, forcing each of the sections against the pipe wall. The result is better traction, more even sensor readings around the entire circumference of the pipe, and more efficient maneuverability within the pipe. The cross sectional profile facing the oncoming gas may not have changed, but the aerodynamic shape will reduce drag, which will prove more enabling when it comes time to stop and back up for a closer look at various section of the pipe.

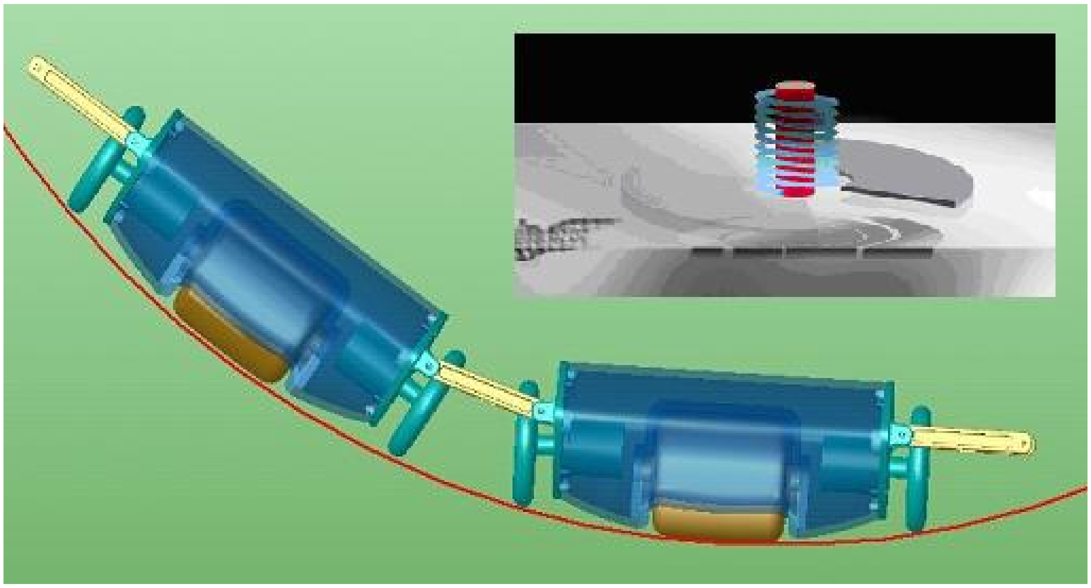
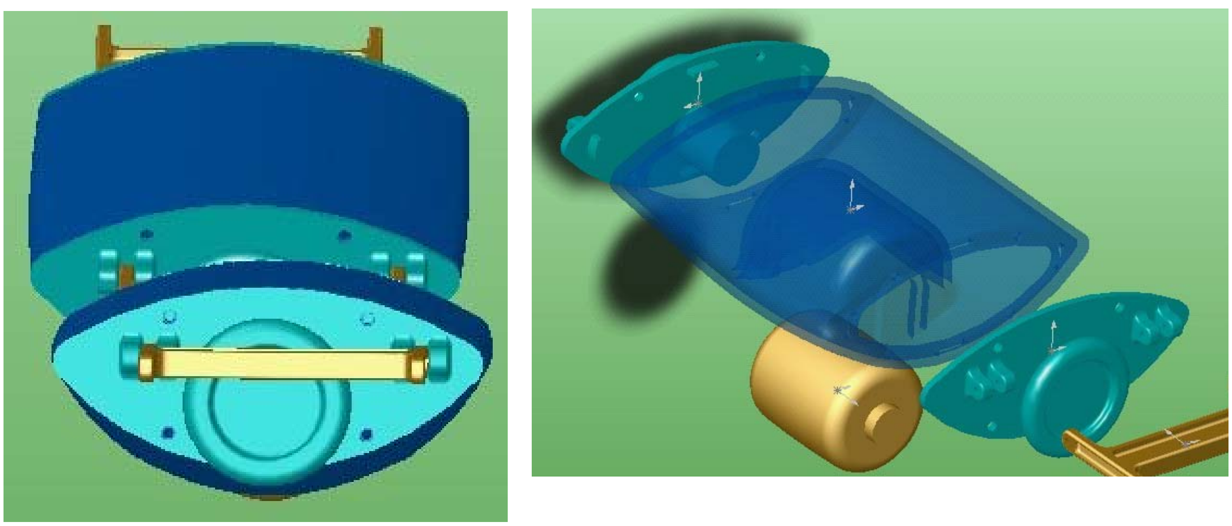


Figure 5. Pipeline Robotic Vehicle Concept Upgraded for Ultrasonic Probes and EC Probe Insert



Figures 6 & 7. Side and Exploded Views of Robotic Vehicle Element with Ultrasonic and EC Sensors

The total cubic inches available to install sensors, motors, and on board signal processing for this type of design is greatly increased. In fact, the interior space is more than doubled. While differing sensor suites and their individual sections will perform vastly differing tasks, one thing will remain the same: Each type of sensor that has been evaluated and it's related electronics can fit in this design. For example, a system layout that includes a direct contact UT fluid coupled wheel is shown. Other sensors would take up differing space.   EMAT would probably take up more space, while EC would take up a significantly smaller space.   Some techniques take up little enough space that there will be room to run multiple channels from each robotic section.

Data assessment and defect evaluation:

Signal evaluation must be performed on board the robotic vehicle in order to make data storage practical. In addition, if data transmission is to be performed at regular intervals, rather than real time, extensive programming will be required in order to capture the repeated scans performed by the robot when it backs up to a questionable area in order to re-inspect more closely. Another option would be a second vehicle passing through the pipeline to perform a detailed analysis of the locations identified by the first pass vehicle. Recommended data transmission would take place utilizing a system similar to the "Gasnet" described by Dr. Hagen Schempf of Automatika at the NETL "Natural Gas Infrastructure Reliability Industry Forums".

Weight:

A robotic system is needed that is hefty enough to offer adequate control within the pipeline environment. Too light and the unit could be literally blown away, too heavy and it cannot negotiate obstacles or reverse it's course under limited power. The propulsion concept to enable the robotic vehicle to go both backward and forward and go at below the velocity of the gas is to use magnetic drive wheels. The weight of a robotic type inspection system, though much less than a standard inspection pig, is expected to control the overall weight of the system. Based on the type and number of sensors required for an inspection, we do not expect any of the sensors discussed to unduly affect or govern the overall system weight. For example, Eddy Current coils weigh as little as a few grams while UT roller probes may weigh as much as half a pound each. With similar electronics on board, the weight of different sensor systems should not vary very much.

Power:

The power required for each of the different types of sensors evaluated is actually quite similar. But until the basic requirements for the electronics system such as the number of transducers, the pulse repetition frequency, operating frequency, extent of onboard data analysis, and the amount of on-board storage are defined, good estimates are difficult. However, we can propose a likely range that power consumption will fall into by considering multiple channel systems that we have previously assembled and tested. We estimate that each transducer channel will require between 0.2 and 1.0 watts of power. This is significantly smaller that the power estimated for the system propulsion, data evaluation, and data communication elements. Therefore, the sensors system power requirements should not be a major driver for the power system for a robotic vehicle.

4. CONCLUSIONS

Challenges facing the creation of a robotic in-line inspection system include both developing the robotic vehicle and getting the correct sensors to work with the robotic vehicle. This combination will provide the improved pipeline inspection capabilities needed to cost-effectively address in-line inspection of pipelines that are presently unpiggable. The final sensor suite needed and proof of viability will ultimately have to be coordinated with a prototype robotic in-line inspection vehicle. At this stage, application of a sensor suite that can be adapted to a robotic vehicle for pipeline inspection needs appears feasible. Power, size, and weight restrictions do not appear to be controlling factors for the appropriate NDT sensors identified.

Based on input from the pipeline industry, several NDT techniques were particularly evaluated for possible use with the robotic in-line inspection system suggested by Sandia. The technologies evaluated included Ultrasonic Testing (UT), Eddy Current (EC), Electro Magnetic Acoustic Transducers (EMAT), and Capacitance Sensors. Each of these methods were researched and/or investigated for ability to detect flaws in a natural gas pipeline environment and their viability, adaptability, strengths and weaknesses for application with a robotic system.

The summary our findings suggest that for a robotic in-line inspection system:

- UT isn't viable (at this time) for fulltime 100% coverage,
- EC and Capacitance sensors are problematic for this purpose and application,
- EMAT appears to be the best technology and Sandia recommends and supports its use, and
- Industry appears willing to help develop a robotic vehicle compatible with EMAT technology.

The overall sensitivity and utility of these sensors though must still be developed. Many of the existing NDT technologies have limitations that suggest that they would not perform as well as some of the newer NDT sensor technology, such as EMAT. Why build old and proven-to-be-limited technology into an advanced inspection platform? Sandia suggests that a robotic in-line inspection vehicle be designed to be compatible with emerging EMAT technology. This appears to be a technology with the promise of providing the best overall sensor performance and sensitivity without severely restricting the design, operation, or performance of a robotic pipeline in-line inspection system.

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