FINAL Technology Status Assessment Report

Instrumented Pipeline Initiative

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19 February 2009	T.J. Piro	Added Long Range Ultra Sonic Testing System for Buried, Unpiggable Pipelines.	Revision 1
25 February 2010	T.J. Piro	Added Disclaimer Statement	Revision 2

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1.0 INTRODUCTION

Concurrent Technologies Corporation (*CTC*) and subcontractor, Carnegie Mellon University (CMU), have performed a Technology Status Assessment and developed a report summarizing the state-of-the-art sensor technology for applications in a natural gas pipeline. This report will include both positive and negative aspects of each existing technology. This assessment involved communication with various gas pipeline manufacturers and industry representatives to obtain input on sensor needs and future testing applications and opportunities.

2.0 CURRENT STATE OF TECHNOLOGY

The team communicated with various natural gas pipeline utilities and industry representatives, in particular those from Pennsylvania, and collected public information from government agencies, research institutions, and the industry. The report presents the benefits and shortcomings of existing technology and compares each sensor system to the low-cost, in-situ, time-reversal based, continuous monitoring of distributed pipelines proposed by this project. The report also outlines opportunities for the development of future sensor technologies for pipeline monitoring applications.

The goal of Instrumented Pipeline Initiative (IPI) Project is to develop a distributed autonomous sensor system capable of continuously and automatically monitoring natural gas pipelines. The IPI distributed sensor system differs substantially from many existing systems and technologies that primarily focus on pipeline inspection. The IPI monitoring system uses an integrated, ubiquitous active acoustic sensing device network to detect, locate, and assess incipient defects, leaks, and failures for natural gas pipeline safety and integrity.

2.1 Summary of Existing Industry/Sector

Natural gas pipelines are critical infrastructures that gather, transport, and distribute natural gas for many of our day-to-day needs and activities. Natural gas pipeline companies monitor, control, and manage the natural gas that enters the pipeline from the producers and processors and delivers this gas to the consumers via the local distribution companies. The United States natural gas pipeline network is a highly integrated transmission and distribution grid. A recent report in 2007 by the Energy Information Administration (EIA) of the Department of Energy (DOE) shows that there are more than 302,000 miles of large diameter (61% exceeding 16" diameter) natural gas pipelines in the United States [1]. There are three major types of pipelines: the gathering pipelines, the transmission pipelines, and the distribution pipelines. The gathering pipelines transport raw natural gas from the wellhead to the processing plant, often operating under significantly lower pressure than the transmission lines and using pipes with diameters of 4 inches to 12 inches. The transmission system consists of interstate and intrastate pipelines with diameters ranging from 6 inches to 48 inches at pressures anywhere from 200 to 1500 pounds per square inch (psi). The distribution pipelines deliver natural gas to retail customers. The diameter of most distribution pipelines are small, ranging in size from 1 to 6 inches in diameter. The majority of pipes in service are made of bare steel or coated steel. In addition to steel pipes, more than 500,000 miles of buried polyethylene (PE) plastic natural gas pipelines have been installed over the past 40 years in the United States [2]. The corrosion resistance properties and ease of installation have significantly stimulated demand for PE pipes.

The vast nationwide pipeline network imposes a major challenge to the natural gas companies: how to routinely inspect pipelines for corrosion and defects to ensure the efficient and safe operation of the pipeline systems. The United States pipeline industry is regulated by the Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA). Statistics data collected from 1986 to 2008 show that distribution pipelines and transmission pipelines accounted for a significant portion of pipeline incidents at the cost of more than $1 billion for each of the two types of pipelines [3]. The data make clear the necessity for a proactive, continuous, automatic monitoring system that can provide early detection and early warning of incipient defects, leaks, and failures before they reach catastrophic failure.

2.2 Technologies/Tools Used

Pipeline defects consist of corrosions (internal or external), stress corrosion cracking, outside force damage, weld and fabrication defects, etc. Over the years, engineers have developed many pipeline inspection tools and the technologies for inspection of pipeline safety and integrity. There are three types of basic tools or platforms for pipeline inspection: (1) intelligent mobile sensing devices, (2) standalone inspection systems, instruments, and (3) resident pipeline sensors.

2.2.1 Intelligent Mobile Sensing Devices

Intelligent mobile sensing devices are pigs, crawlers, and the Explorer [4] type robots. Pigs, also called pipeline inspection gauges, are intelligent robotic devices that are propelled down pipelines to inspect the interior part of pipes. Pigs can inspect the conditions of the pipeline wall and perform pipeline internal cleaning. Although pigs are standard inspection tools for large diameter pipelines, they are limited by unpiggable pipelines due to over- or under-sized valves, radius or mitered bends.

2.2.2 Standalone inspection and systems and instruments

Standalone inspection systems and instruments, for example, GE's automated sensor systems utilizing phased array ultrasonic technology are mounted on the outer surface of pipelines and use ultrasonic or electromagnetic waves to detect corrosion and defects at a given point in time and space.

2.2.3 Resident Pipeline Sensors

Limited research has been conducted on using a distributed network system of sensors, deployed along pipelines, for inspection and monitoring. This technology is the focus of our proposed research.

2.3 Benefits and Inadequacies of Current Technology

Each tool or platform can utilize various techniques to achieve the goal of inspection and monitoring. This technology survey, although not exhaustive, summarizes the following four major technologies: (a) magnetic flux leakage (MFL), (b) remote field eddy current, (c) ultrasonic guided wave technologies, and (d) remote sensing techniques. The benefits and inadequacies of the four inspection technologies are listed in Table 2.1.

Table 2-1. Inspection Technologies Benefits and Inadequacies

Technologies	Basic Principles	Benefits	Inadequacies
Magnetic Flux Leakage (MFL) [4]	MFL uses a powerful magnet to magnetize the steel pipe. At areas where there is corrosion or missing metal, the magnetic field that "leaks" from the pipe is detected.	MFL can detect metal-loss defects in pipelines with good confidence. An MFL tool can characterize the depth, shape, and length of a metal-loss region.	Many MFL inspection systems use extremely high magnetic intensities. Very narrow axially oriented defects, such as cracks and seam corrosion are rarely detected using current MFL technology and only work on metal pipe.
Remote Field Eddy Current (RFET) [5]	Eddy-current testing uses electromagnetic induction to detect flaws in conductive metal pipelines.	Can operate at large lift-off distance from the pipe surface. Reasonable wall thickness measurements. Sensitive to many pipeline defects.	It works only for metal pipes. Depth of penetration is limited. Signal levels are small. Significant excitation power is needed.
Ultrasonic Guided Wave [7]	Acoustic waves travel long distancees on the surface of pipelines, detect and locate corrosion or defects by measuring the elapsed time between the reflections.	No need for a liquid couplant; Ability to traverse valves and other internal pipe obstructions; can use piezoelectric sensors or magnetostrictive sensors. Most accurate technology for wall thickness	It is not able to scan a long range axial distance of a pipe from a single transducer position.
Remote Sensing Technologies [8]	Uses aerial and satellite remote sensing integrated with GIS technologies to assist pipeline risk assessment and inspection.	Capable of wide area pipeline infrastructure change mapping and inspection and pipeline emergency assessment and management.	This technology is not adequate for detection and inspection of corrosion defects. Does not detect before a substantial leak.

In addition to the aforementioned four major technologies, there are many variations of such inspection methodologies and sensing techniques, for example, electromagnetic acoustic transducer (EMAT) [9], permanent magnet eddy current [10], multi-purpose deformation sensor [11], dual magnetization MFL [12], magnetostrictive sensor technique [13], etc. Furthermore, natural gas companies and research institutions aspire to develop inspection techniques for plastic pipelines [14-15]. In this technology assessment, we focus on the monitoring and inspection technologies for steel pipes.

3.0 DEVELOPMENT STRATEGIES

3.1 New Technology and Research Requirements

Governmental regulatory bodies demand continuous improvement of pipeline inspection tools and technologies [16-19]. New pipeline integrity regulations require that operators assess pipeline sections that were not previously inspected by conventional methods, such as smart pigs. For example, currently, there is no method for inspecting most distributed cased pipelines under roadways, rivers, and streams. New federal regulations require the inspection of these pipelines by 2012. In the next 15 years, a large amount of aging natural gas pipeline will be replaced by pipelines that are manufactured and constructed using modern technologies. New technology advancements make it possible to integrate new sensing materials and instruments into the pipeline manufacturing and construction process; new inspection technologies, devices, and methods will be developed to enhance the current pipeline monitoring techniques.

Government regulations and technology developments motivate innovative solutions for natural gas pipeline safety, integrity, and reliability. The work proposed by this team focuses on distributed active network sensing technologies and aims to develop state-of-the-art pipeline monitoring and inspection technologies to safeguard strategic natural gas pipeline systems in the United States.

3.2 Problems Areas Addressed

In this research project, the team will investigate and develop a proof of concept ubiquitous network platform of acoustic sensors and controllers that provides a continuous, time-reversal based, automatic real-time monitoring and sensing methodology and system for the integrity and safety of distributed pipeline systems. The IPI research differs substantially from existing technologies available on the market and other research supported by past DOE awards. The challenge is to develop a monitoring system that utilizes an integrated active acoustic sensing device network using ultrasonic guided wave technology specifically for pipelines to detect, locate, and assess corrosions (internal or external), stress corrosion cracking, outside force damage, weld and fabrication defects, etc.

This team proposes to address three issues: (1) development of an acoustic sensor network using guided wave technologies; (2) development of state-of-the-art, distributed, time-reversal-based data processing algorithms and methods; and (3) system integration, communication, and control of the developed sensor networks.

Long-range guided-wave inspection is an emerging technology for direct examination of piping for time-dependent internal and external corrosion defects. The proposed technique uses piezoelectric microfiber composite (MFC) actuators/sensors that can be mounted on the surface of cylindrical pipes with great flexibility in terms of excitation angles, deploying topography, sensor patch size, and pipeline coating conditions. Numerical simulations will be performed for characterization of the guided wave propagation along cylindrical pipes in addition and laboratory experiments will be conducted on both bare and coated steel pipes.

A unique feature of the proposed data processing method is the state-of-the-art time-reversal based nondestructive monitoring techniques. Time reversal is a novel signal processing method for detecting, locating, and measuring defects and damages, such as third party damage and corrosion in pipeline systems. Time reversal is a robust method that is reference-free and adapts to varying operational and environmental conditions, which could be expected in field applications. In this research, the team hopes to develop a time-reversal-based distributed sensing and detection schemes for pipeline inspection and damage monitoring.

The active acoustic sensing network technologies provide integrated and comprehensive methodologies to detect, locate, and assess pipeline defects and damage. Cost effective communication and control protocols that are suitable for natural gas pipelines will be investigated. The proposed sensor network system will provide automatic, continuous monitoring of the state of the pipelines and the pipeline infrastructure. Further, the proposed sensing and monitoring solution can be used to detect defects in areas where conventional inspection technologies cannot be implemented. Section 2.2 can be referenced for examples.

4.0 COMPARISON TO STATE-OF-THE-ART SENSOR TECHNOLOGY RESEARCH

A survey was completed of past Department of Energy (DOE) National Energy Technology Laboratory (NETL) and Department of Transportation (DOT) awards focusing specifically on inspection and remote sensing technologies for pipelines. The information was provided by the DOE website, DOT awards for pipeline safety research through the Pipeline Research Council International (PRCI) website, commercial monitoring products for threats and impacts on pipelines including GE's ThreatScan™ and UltraScan™, and other vendor's ultrasonic solutions, as well as many other available references on pipeline inspection and monitoring.

This survey, although not exhaustive, compares and contrasts this approach. Table 4-1 details similarities and differences to previously awarded projects.

Table 4-1. Existing Pipeline Monitoring and Inspection Technologies

Project	Sponsor	Similarities	Differences
Inspection Technologies			
DTRS56-02-T-0007 Long Range Ultra Sonic Testing System for Buried, Unpiggable Pipelines.	DOT/DOE	Both projects develop a system to detect cracks and corrosion using acoustic sensors.	This DOT/DOE project developed a portable inspection system known as Teletest®, for detecting defects in inaccessible pipelines [20]. The system utilizes a single sensor location and requires the operator to relocate the sensor to perform each inspection. Teletest® is an inspection-only system incapable of monitoring pipeline continuously. The IPI proposes to use a network of sensors to continuously monitor and inspect the integrity of pipelines.
FWP05FE03 Multi-purpose Sensor for Detecting Pipeline Defects	DOE	Both projects develop acoustics technologies to detect pipeline defects.	This DOE project developed a multi-purpose sensor to be run inside a pipeline that can determine ovality of the pipe, structural defects in the pipe, etc. The developed sensor can be integrated into a mobile robot platform. The IPI will study how to use a network of sensors that are mounted on the surface of a pipe to monitor and inspect pipelines.
DE-FC26-04NT42267 Remote Detection of Internal Pipeline Corrosion Using Fluidized Sensors	DOE	Both projects develop a network of sensors to monitor pipeline defects.	This DOE project developed a vast network of fixed and floating sensors combined with a vast and extremely complex communication/decision making system. It focused on wireless transmission for communication. The IPI Team will investigate various technologies for communication between pipelines, including electromagnetic waves and guided acoustic waves. The proposed sensor network can detect, locate and assess pipeline defects and damages.
DE-FC26-04NT42266 Delivery Reliability for Natural Gas-Inspection Technologies	DOE	Both projects can provide value-added functionalities to the Explorer robotic platform.	This DOE project developed coils that can be integrated with the Explorer II robotic platform. It is not suitable for general purpose continuous monitoring and inspection of pipelines.

Project	Sponsor	Similarities	Differences
Inspection Technologies			
FWP-42623 Ultrasonic Measurement of Plastic Strain in Pipelines	DOE	Both projects can detect by a third party or from natural events.	This DOE project utilized electromagnetic acoustic transducers for measuring residual stress and plastic strain distributions in natural gas pipelines. This project did not study how to organize the sensors into a network and to evaluate network performance. The IPI proposes a network of acoustic sensors and using state-of-the-art time reversal technique to monitor, inspect and locate pipeline defects.
FWP04FE12 Power Generation in Natural Gas Pipelines	DOE	Both projects study the sources of power for continuous operation of a sensor or a device.	The DOE project studied the possibility of power generation in a natural gas pipeline due to the flow of the gas itself. It was only one part of the IPI research.
DE-FC26-02NT41320 Gasline Network Sensor System - GASNET	DOE	Both projects try to develop a prototype network sensor system for monitoring and communication.	The DOE project developed an in-pipe natural gas prototype measurement and wireless communication systems for assessing and monitoring pipelines. The IPI proposes to use guided acoustic wave propagation to monitor pipelines and to communicate between acoustic sensors.
DE-FC26-02NT41604 Pipelines as Networked Communication Links	DOE	Both projects investigate how to establish a communication network through pipelines.	This DOE project examined two methods of using natural gas pipe as a communication medium using electromagnetic waves. The IPI will investigate various technologies for communication between pipelines, including electromagnetic waves and guided acoustic waves.
DE-FC26-02NT41645 Development of an Inspection Platform and a Suite of Sensors for Assessing Corrosion and Mechanical Damage on Unpiggable Transmission Mains	DOE	Both projects develop inspection platforms for pipelines.	The DOE project developed a robotic pipeline inspection system capable of navigation through unpiggable pipelines. The IPI will use a network of sensors mounted on pipelines to continuously monitor the integrity of pipelines.
DE-FC26-01NT41156 Development of Nonlinear Harmonic Sensors for Detection of Mechanical Damage	DOE	Both projects develop sensors and associated circuits to detect mechanical damage.	The DOE Project used nonlinear harmonics, an AC magnetic method for detecting local anomalies of stress and plastic deformation. The IPI proposes to use acoustic sensors to detect pipeline defects.
DE-FC26-01NT41154 Development of an EMAT In-Line Inspection System for Detection, Discrimination and Grading of Stress Corrosion Cracking in Pipelines	DOE	Both projects develop platform to detect and monitor cracks using acoustic sensors.	The DOE project focused on detecting and monitoring a particular defect, i.e., Stress Corrosion Cracking using electromagnetic acoustic transducers. The IPI proposes to develop an acoustic sensor network platform for detecting corrosion, cracks and third part damage.

Project	Sponsor	Similarities	Differences
Inspection Technologies			
DE-FC26-02NT41319 Monitoring Technology for Early Detection of Internal Corrosion for Pipeline Integrity	DOE	Both projects use guided waves that propagate along the pipeline in a pulse-echo mode to detect corrosion.	This DOE project used magnetostrictive sensors and is limited to benign and relatively low-attenuation sections of pipelines. The IPI will use piezoelectric sensors. The IPI will also use time reversal techniques to deal with the complex acoustic wave propagation along pipelines.
FEAB209-FEAB210 New Acoustic Wave Pipe Inspection System	DOE	Both projects consider using acoustic sensors to inspect and monitor pipelines.	This DOE project developed a specially designed Electromagnetic Acoustic Transducer (EMAT) sensor, capable of detecting physical flaws of natural gas pipelines. The IPI will use off-the-shelf acoustic sensors to develop a sensor network system to monitor pipelines.
FEW01-01124 Sensor Development for the IPP Robotic Vehicle for Internal Detection of Gas Pipeline Defects	DOE	Both systems can detect pipeline defects.	This DOE project developed a robot vehicle for inline inspection. The developed robotic inspection system can monitor and inspect pipeline defects. The IPI will use a network of acoustic sensors that are mounted on pipes to monitor continuously pipeline defects and third part damage.
DE-FC26-01NT41159 Circumferential MFL IN-Line Inspection for Cracks in Pipelines	DOE	Both projects develop inspection systems for pipelines.	The DOE project uses circumferential magnetic flux leakage (MFL) to detect metal-loss corrosion. This implementation works by orienting the magnetic field around the pipe rather that along the axis. The IPI proposes to develop acoustic sensor networks to monitor and detect corrosion.
Remote Sensing Technologies			
DE-FG02-03ER83688 Low Cost Distributed Sensing for Gas Pipelines	DOE	Both projects use acoustic sensors to monitor pipelines.	This DOE project examines the feasibility of developing acoustic sensor arrays using ordinary communications-grade optical fiber. However, the fiber communication is not workable, and the phase II of the program is not pursed. The IPI proposes to use guided wave propagation as a communication means.
DE-FC26-02NT41324 Acoustic Detecting and Locating Gas Pipeline Infringement	DOE	Both projects develop acoustic technologies to detect and locate pipeline defects.	The DOE project developed a Portable Acoustic Monitoring Package (PAMP) for detecting and locating pipeline defects. The IPI proposes to use a network of small acoustic sensors to monitor pipelines. This technology is not limited to gas pipes.
DE-FC26-01NT41317 Low cost GPR Gas Pipe & Leak Detector	DOE	Both projects develop techniques to locate the defects of pipelines using signal and image processing techniques.	This DOE project developed a light-weight ground penetrating radar (using microwave radiation) system for tracking metal/non-metal pipes and for detecting leaks. The IPI will use acoustics sensors to detect and monitor pipelines.
GE 's ThreatScan	GE	GE's product and our system use acoustic monitoring technologies to detect third party damage.	The GE ThreatScan system uses hydrophones to listen for third party machinery hitting the pipe. It is a passive system with no ability to detect corrosion or actual damage. It can only listen for sounds that suggest potential damage has occurred. The IPI proposes to use a network of acoustic sensors that should actively detect all types of damage and corrosion.

Project	Sponsor	Similarities	Differences
Inspection Technologies			
GE's UltraScan Duo	GE	GE's product and our system use acoustic array technology for automated pipeline inspection.	The GE system goes along the pipe to inspect large diameter pipes, for example 24" to 42" pipelines. The IPI proposes to use acoustic sensor networks to monitor and detect defects for any diameter of pipelines.
DOT Pipeline & Hazardous Materials Safety Administration Benchmarking Emerging Pipeline Inspection Technologies Report	DOT/DOE	Both projects provide inspection technologies for the integrity of pipelines.	This joint work between DOT and DOE reports on various inspection technologies on pipelines. However, none is based on sensor networks. The IPI proposes to use a network of acoustic sensors to monitor pipelines. The project will rely on state-of-the-art time reversal acoustic techniques.

4.1 Unique features of research

4.1.1 Time Reversal Based Technique

Time reversal is a novel signal processing method for detecting, locating, and measuring defects and damages, for example, third party damage and corrosion in pipeline systems. Time reversal is a robust method that is reference-free and adapts to varying operational and environmental conditions, which can be expected in field applications. The survey has concluded no past DOE or DOT awards have explored time reversal based techniques for pipeline inspection and continuous monitoring

4.1.2 Active acoustic sensing for continuous monitoring

Although some past DOE or DOT awards have considered using acoustic sensors for pipeline monitoring and experimenting with guided Lamb wave propagation in the wall of a pipe, they do not fully characterize the guided wave propagation along a pipe nor do they address the problem of how to organize and deploy sensors as a network and validate the network performance; the past use of acoustic sensors has focused mainly on passive sensing, not on active sensing. In contrast with existing technologies, an inspection platform will be developed based on a network of active sensing and actuating devices to continuously monitor pipelines

4.1.3 Continuous Monitoring Methods to Detect, Locate, and Assess Pipeline Defects

The main distinguishing feature of the IPI research and solution is the automatic, continuous monitoring of the state of the pipelines and the pipeline infrastructure. Further, the proposed sensing and monitoring solution can be used to detect defects in areas where conventional inspection technologies cannot be implemented, for example, with unpiggable pipelines. The deployment of active sensors provides the opportunity to localize defects with high accuracy and to characterize their nature and type, improving the detection of real defects and reducing the rate of false alarms. Based on the concept of time reversal acoustics (TRA), the proposed method should detect and localize damage for further assessment.

5.0 FUTURE

5.1 Barriers Overcome by Research

Time reversal based ultrasonic guided wave detection and sensing for pipeline monitoring using sensor networks is an emerging technology. The proposed technology provides a platform that enhances or complements existing pipeline inspection tools and technologies. This research addresses barriers such as (1) multi-mode guided wave propagations along cylindrical pipelines; (2) theoretical and experimental characterization of bonding, sizing, excitation of microfiber composite sensors suitable for pipelines; (3) time reversal acoustic technology for detection, localization, and classification of corrosion and defects under various operational conditions; (4) distributed sensor network for communication, control, and processing.

5.2 Impact on the United States Domestic Gas Supply Industry

There are hundreds of thousands of miles of high pressure gas transmission lines that cross the country and millions of miles of low pressure distribution piping that are owned and operated by hundreds of local gas distribution companies. The safe and efficient function of this infrastructure is vital to the nation's energy security. Therefore, continuous monitoring and management of these pipeline systems is of significant importance for our domestic gas supply industry.

5.3 Deliverables (Tools, Methods, Instrumentation, Products, Etc.)

This project is one of few studies that advances active sensing technologies specifically designed for pipeline systems. A primary outcome of this research will be a better understanding of guided wave propagation in pipeline systems, and integration of active sensors with pipeline systems to advance the proposed monitoring system toward future commercial adaptation. Deliverables include (1) development of a prototype pipeline monitoring system using a network of active sensing devices; (2) state-of-the-art sensor technology suitable for natural gas pipeline inspection; (3) numerical simulation algorithm for guided wave propagations in pipelines; (4) state-of-the-art time-reversal based detection, localization, and classification algorithms for pipeline inspection; (5) experimental investigation of the proposed methodology through full-scale destructive testing.

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