Development of an Inspection Platform and a Suite of Sensors for Assessing Corrosion and Mechanical Damage on Unpiggable Transmission Mains

Quarterly Report

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ABSTRACT

This development program is a joint effort among the Northeast Gas Association (formerly New York Gas Group), Foster-Miller, Inc., and the US Department of Energy (DOE) through the National Energy Technology Laboratory (NETL). The DOE's contribution to this project is $572,525 out of a total of $772,525.

The present report summarizes the accomplishments of the project during its second three-month period (from January 2003 through March 2003). The project was initiated with delay in February 2003 due to contractual issues that emerged between the NGA and Foster-Miller, Inc. The two organizations are working diligently to maintain the program's pace so that it is completed in time

The efforts of the project focused during this period in the assessment of the tether technology that is intended to be used as the means of communication between robot and operator. Preliminary results indicate that tether is a viable option under certain pipeline operating conditions but not all. The exact range of operating conditions that are viable for tether use are being determined as the study progresses. Work was also initiated regarding the design of the robotic platform.

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EXECUTIVE SUMMARY

At the end of this reporting period the project was progressing well with most efforts focused on the assessment of the tether technology to be potentially used as means of communication between robot and operator. Other tasks related to the design of the robot itself were initiated.

The tether assessment portion of the program is in an advanced stage, with a number of tests conducted. A meeting with the NGA program manager was conducted to review Foster-Miller's preliminary findings. A custom made sample (0.9 mm), which is anticipated to provide solutions to some problems identified, is being produced by the manufacturer and will be tested upon arrival. Discussions are also underway with the manufacturer regarding custom fiber coating options.

The agreement between Foster-Miller and PII has been delayed, with final legal issues being worked out now. We expect the agreement to be signed within the next few weeks. In spite of this delay, Foster-Miller has moved forward with the platform design, using sensor drag load information (to size the platform motors) determined during the Phase I NYGAS study. Software modeling of the platform kinematics is being performed. Physical modeling will start within the next few weeks to verify the results of the software modeling, and answer those questions which the software analysis could not. Initial efforts are also underway to develop the camera/illumination system and ovality sensor.

An abstract for a paper describing this work was submitted to the organizers of the Natural Gas Technologies II Conference, organized by GTI and co-sponsored by NETL/DoE, to be held in Phoenix, AZ, in February 2004.

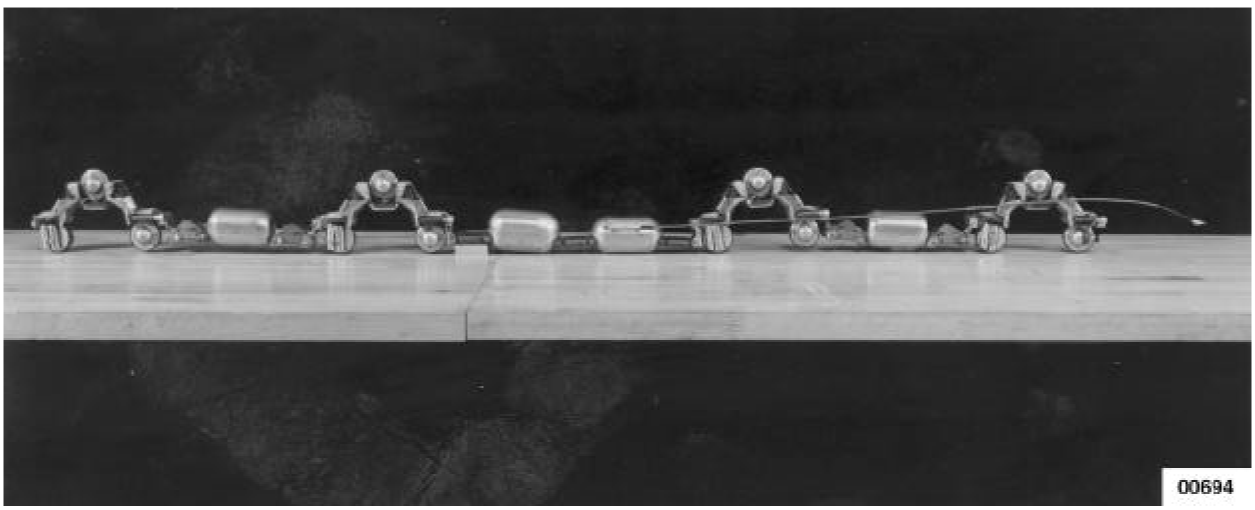
INTRODUCTION

With the recent advances in robotics and sensor technology, and the occurrence a few unfortunate pipeline accidents, the Office of Pipeline Safety (OPS) of the US Department of Transportation has endorsed the concept that all oil and gas transmission pipelines should be capable of 100 percent inspection. This can be accomplished through the elimination of pipeline obstacles that would allow for pigging, or through the development of innovative inspection technologies, hydro testing, or use of direct assessment techniques. Problems arise when the piping network is older and/or constructed without pigging as a design consideration. This is the situation with countless miles of transmission pipelines owned and operated by local gas distribution utilities. There are many physical "obstacles" in the piping network that makes pigging impossible. The most intractable of these obstacles include:

- Bends/elbows with bend radius less than 1.5 D. This is a very common obstruction.
- Mitered joints/elbows greater than 10 deg. This is an obstacle found in older systems.
- Back to back combinations of bends/joints. Commonly found in tightly spaced areas.
- Reduced port valves. This includes valves with ports smaller in diameter than the pipeline. This is also a very common obstacle.
- Reduction/expansion in pipe diameter greater than 2 in.
- Unbarred branch connections. Pigs are not designed to turn down branch lines, and therefore, branch lines must be barred to prevent the nose of the pig from crashing into the lateral and jamming itself in place.

The Gas Research Institute in a report issued in 1995 (entitled "In-Line Inspection of Un-piggable Natural Gas Pipelines") noted that the cost to replace just two of the most common obstacles would be substantial, costing over $3 billion. Therefore, the development of tools to inspect un-piggable transmission and/or distribution pipelines presents a both a formidable technical challenge as well as a significant financial incentive to the gas industry. The adaptation of current pigging technology may not be viable given the geometric challenges of existing interstate and utility owned pipelines. External direct assessment techniques have not been shown to be universally adequate, accurate or cost-effective. Use of an innovative robotic approach would apparently be dictated.

The inspection of un-piggable gas transmission and distribution pipelines requires the innovative marriage of a highly adaptable/agile robotic platform with advanced sensor technologies operating as an autonomous or semi-autonomous inspection system. The work being conducted under this program is based on a robotic platform that is train-like in nature ,as shown in the figure below, and is based on Foster-Miller's Pipeline Inspection System (PipeMouse) developed in early to mid 1990's. Both front and rear tractors propel the train in the forward and reverse directions inside the pipeline. Like a train, the platform includes additional "cars" to carry the required payloads. The cars are used for various purposes including the installation and positioning of sensor modules, the power supply, data acquisition/storage, location/position devices and onboard micro-processors/electronics. The onboard intelligence gives the platform the benefit of an engineer steering the train through complicated pipe geometry. The system includes launching and retrieval stations that are similar to that used for conventional pigging systems, but much simpler in design and operation.



The Pipe Mouse was built to a strict set of performance criteria appropriate for low-pressure gas distribution networks. The Mouse was designed to be highly mobile and agile, had the ability to travel long distances from the entry point and steer down branch line of pipe tees, negotiate mitered (zero degrees) elbows, navigate in both the horizontal and vertical planes, pass through partial section valves, and adapt, by a factor of two, to changes in pipe diameter. These same types of obstacles create problems for inspecting un-piggable transmission mains.

PII North America (a subcontractor for this project) has extensive experience designing and working with sensors based on ultrasonics, electromagnetism, eddy-currents and optical methods. For this program, sensor development will be considerably more challenging than for conventional pigging due to the greater variance of pipe diameter and the more difficult obstacles encountered in un-piggable pipelines. The ability to actively expand and retract the onboard sensor will be needed, not just for obstacle avoidance, but to allow upstream (reverse direction) travel.

The robot will be controlled via a fiberoptic tether system, which will be analyzed, designed, and tested as part of this project. The tether is expected to provide sufficient range for the robot to inspect a substantial length of the pipe without the need of many expensive tapings of the pipeline

To power the computer, sensors, data acquisition and drive wheels, some form of energy storage and electrical power supply is required. Of all the various possibilities (e.g., batteries, fuel cells, ultra-capacitors, flywheels, etc.), the battery approach is clearly the simplest, safest and most reliable. To minimize the number of launch and retrieval stations, the batteries should have maximum energy density. The modular platform concept has an advantage in that battery "cars" can be added as needed, up to the length of the launch tube. Certain obstacles (e.g., mitered corners) also impose a length constraint. Different battery and charging modules may also be swapped in and out based on the range requirement, power and availability of recharging stations.

The anticipated benefits derived from the use of this platform include the following:

- Ability to inspect otherwise inaccessible pipelines (transmission and distribution).
- Cost savings from not having to remove pipeline obstacles for conventional pigs.
- Inspection cost much lower ($/mile) than direct assessment or hydro testing.
- A more versatile platform capable of performing a variety of inspection services.

EXPERIMENTAL

During the period of January 1, 2003 to March 31, 2003 work on the project was initiated.

Task 1: Program Management

A Research Management Plan, detailing the tasks and subtasks of this program, was developed and submitted to DoE. Also, a Technology Assessment document, describing the present state-of-the-art in In-Line Inspections Technologies, was developed and submitted to DoE.

Task 2: Mechanical Design: Robotic Design and Sensor Module

Task 2.1. Robotic Platform

Task 2.1.1 System Engineering

Task 2.1.1.1 Kinematic Analysis

Design Drivers

The purpose of the kinematic analysis is to determine the degrees of freedom required for the robotic platform to negotiate the obstacles encountered in unpiggable pipelines, as stated in the requirements of this program. In order to pass through these obstacles, complex articulations, beyond the capabilities of the previously developed Pipe Mouse, are required. Foster-Miller's approach is to utilize the functionality previously proven on the earlier robot, augmenting the system's functionality where required to address the additional maneuverability requirements imposed by unpiggable pipelines. Various techniques are being employed, including software modeling, pencil and paper analysis, and the development of a physical model. For the initial analysis, the models were designed around a nominal pipe size of 18" diameter, with the capability to expand/contract to +/- 1 pipe size. The steps taken to accomplish this goal are detailed below.

Before modeling could begin, a rough size envelope was established based on all the obstacles that need to be traversed. Considering these obstacles and the +/- 1 pipe size requirement, design drivers were established.

Software Modeling

Kinematic analysis through software modeling was initiated with the construction of a two-dimensional model of a single triad. Rough dimensions for the triad were chosen based on the results of the analysis outlined above. This analysis provided a size envelope to work within, that would theoretically allow passage through all 2D obstacles. The next step was to constrain the 2D model to renderings of the various obstacles. Once the proper relationship was established between the triad model and the obstacle model, we were able to 'drive' the triad through the obstacle, observing the motions required to pass through it completely. Following the two-dimensional model design and analysis, a second model was created. The second model, created in 3D, was developed with the intentions of defining the requirements for the robot to travel in 3 dimensions, particularly back-to-back, out of plane bends (the most difficult to model). During the modeling process for this portion of the analysis, we reached the limits of the 3D modeling software, and realized that accurate conclusions could not be drawn from this type of modeling for the 3D case.

Task 2.2 Sensor Module

Task 2.1.1 MFL Sensor System Design

Work on the MFL sensor has not been initiated yet, partly due to the lack of contract between Foster-Miller and PII North America. This contract is expected to be signed in the next few weeks.

Task 2.2.3 Ovality Sensor Design

Specification of the pipeline ovality measurement system for the inspection platform has begun. The following questions/issues need to be addressed:

- Resolution Requirements
  - Depth resolution.

    - Minimum number of points around circumference.
    - Longitudinal resolution.

Two options were identified. Option 1 is an industrial single point optical displacement sensor and Option 2 is a custom designed structured light sensor. These two options will be explored as the project moves forward.

Task 2.3 Camera/Illumination Design

Specification of the camera and lighting system for the inspection platform has begun. The following questions/issues need to be addressed:

- What is the required spatial resolution?
- Color or monochrome?
- Sidewall inspection capability?
    - Pan and tilt system with remote control required
    - Motorized focus and zoom control on the lens probably required
    - Ring light needed for wall inspection
- High pressure will require housing
- Lighting system
    - Dual or triple redundancy required?
    - Lights must be pressure sealed.

If the camera is used only for navigation, relatively low resolution monochrome video should be more than sufficient. However, if the images are to be used for pipe inspection, examining corrosion, cracks, weld condition, etc. higher spatial resolution and color images may be required. Color provides a capability for examining corrosion or deposits on the walls.

For navigation and cursory inspection the camera may be aimed straight down the pipe. If close wall inspection is desired, the camera must be mounted on a pan and tilt mechanism so the walls may be directly examined. A lighting source, such a diode ring light must be mounted on the pan and tilt mechanism to provide illumination. Also a motorized zoom lens or motorized focus control will be needed for the close inspection. Control of the gimbals and the lens must be included in the optical fiber link system.

A higher power lighting system will be required to illuminate the pipe for navigation and longer range observation. This source should have an adjustable power lever to adjust for different pipe diameters and surface conditions, minimizing the drain on the batteries. Also, because the robot will depend upon these lights for navigation of plug valves and other restrictions, redundancy must be included. The appropriate level of redundancy in the lights (dual, triple, etc.) as well as any necessary redundancy in other critical control electronics must be determined.

Any components that cannot directly withstand the high pressures within the pipe must be housed in pressure vessels. It may be possible to slowly pressurize and depressurize some electronic components to permit their used under ambient conditions. Video cameras and lights for deep sea applications have been identified that can be used at pressures over 1000 psi. Some of these systems are of compact size and could be used in this application. Attention must be paid to thermal dissipation, particularly for the lights to prove they can be safely operated. Many high powered lights for undersea applications cannot be operated in air.

Task 4: Communication

Task 4.1 Tether Assessment

An analysis of the fluid dynamics of the tether (of various diameters) under the minimum, nominal, and maximum pipeline gas flow conditions was conducted. Single mode fibers of 0.2, 0.9, 1.2, 1.8, and 2.9 mm in diameter were evaluated. Laboratory testing was performed to identify any unusual dynamics in the tether when routed through a scaled section of pipeline (including bends and straight sections). Communication tests were conducted to measure the signal degradation of each tether fiber when exposed to the worst case pipeline flutter situation which occurs when the tether crosses the flow stream between two back-to-back bends. A second tether communication test, representing the worst case scenario of a tether under a tensile load (flow induced) being pulled over a mitered corner was conducted.

A varying tensile load was introduced (externally applied under no-flow conditions), with signal loss recorded for each load.

All empirical tests were conducted under flow conditions of ?$V^2/2 = 20$ lb_f/ft^2. The three flow conditions specified for testing by NGA produce ?$V^2/2$ values of 1.14 lb_f/ft^2, 6.28 lb_f/ft^2, and 246 lb_f/ft^2 for the minimum, nominal, and maximum flow conditions respectively. Performing tests at the higher flow conditions was found to be unnecessary due to the fact that the results of the fluid dynamics analysis showed that the tether sizes tested (sizes chosen based on practical packaging considerations for a range of 2.5 miles) would not withstand the stresses at the maximum flow condition.

Foster-Miller has identified the situation of the tether being pulled tight around a zero degree bend (mitered corner) as the limiting factor when specifying a tether for a particular pipeline flow condition. When exposed to a flow-induced tensile load while spanning a mitered bend, the tether is forced to exceed its minimum bend requirement (introducing macro bend losses) and ultimately experiencing micro bend losses if the loads get high enough, reducing signal strength to unworkable levels and possibly failing the tether. It should be noted here that the tensile load required to break the fiber will most likely be 2-3 times that which is experienced by the tether when signal loss occurs. Based on this initial assessment, it appears that signal loss will drive the design of a tether for a given set of pipeline conditions, not the tensile strength of the fiber. One caveat to this assertion is the influence of abrasion (potential for stress risers) on the cable. The glass fiber coating of the fiber has a high modulus and is strong in tension, however surface defects caused by abrasion or foreign particles on the surface may drastically lower the fiber strength. Foster-Miller is currently exploring custom coating options to achieve optimum abrasion resistance.

To avoid tensioning the tether across a mitered bend, tether wall friction must be greater than the fluid drag. Both of these values are a function of gas velocity and pressure, and tether diameter. Unfortunately, as a tether gets smaller (as needed in smaller pipes to maximize winder volume) the tether wall friction gain (friction coefficient times weight) reduces by D^2, while the fluid drag on the tether reduces by D (drag force wins out). Thus it is our conservative recommendation at this early point in the program to keep the ?$V^2/2$ value of the gas flow below the point where tension is introduced into the tether. Of course, the total length of pipe under inspection will determine if a critical tensile load is produced. If only short sections (with tensile forces below the critical level) are being inspected, then this requirement may be adjusted. The bottom line is that tether tests under actual flow conditions in a test pipeline should be performed as part of future workscope to verify these initial results.

In summary, Foster-Miller's preliminary findings to date regarding the applications of a fiber optic tether to a pipeline robotic platform are as follows:

- Tether flutter in pipeline (due to flow of up to $?V^2/2 = 20\ lb_f/ft^2$) does not affect fiber signal transmission
- Based on the limiting design condition identified where fluid drag exceeds tether wall friction (resulting in potential for tether to be pulled around a mitered bend from net tensile forces produced):
  - At minimum conditions (10 ft/s and 250 psig) 1.2, 1.8, and 2.9 mm tethers are acceptable.
  - At nominal conditions (20 ft/s and 350 psig) 1.8 and 2.9 mm tethers are acceptable; 1.2 mm tether does not have enough frictional drag to overcome fluid drag (assuming long enough pipeline lengths).
  - At maximum conditions (75 ft/s and 1000 psig) fluid drag exceeds tether wall friction in all cases – <u>undesirable operating condition.</u>
  - Smallest tethers (0.2 and 0.9 mm) should only be used in flow conditions less than minimum condition ($?V^2/2$ TBD).
- Customized coatings will likely be required (particularly with smaller fiber diameters) as commercially available fibers are not sized for both compactness and abrasion resistance.
- In terms of winder packaging (2.5 miles), max tether diameters for the case of robots able to negotiate plug valve are as follows (note that these values may change based on outcome of winder design):
  - 0.2 mm for 10 inch and 12 inch pipe
  - 0.9 mm for 14 inch pipe
  - 1.2 mm for 16 and 18 inch pipe
  - 1.8 mm for 20, 22, and 24 inch pipe
  - 2.9 mm for 26 inch pipe

PROJECT STATUS BY TASK (*as per March 31, 2003*)[1]

Task 1: Program Management	**On-going**
Task 1.1: Research mangement Plan	Completed
Task 1.1.1: Requirements Document	**Completed**
Task 1.2 Technology Assessment	**Completed**
Task 1.3 Technical Oversight	**On-going**
Task 2: Mechanical Design: Robotic Platform and Sensor Module	**Initiated**
Task 2.1: Robotic Platform	**Initiated**
Task 2.1.1: Systems Engineering	**Initiated**
Task 2.1.1.1: Kinematics Analysis	**Initiated**
Task 2.1.1.2: Brainstorming Session	Not initiated
Task 2.1.1.3: Tractor Design	Not initiated
Task 2.1.1.4: Winder Design	Not Initiated
Task 2.1.1.5: Module Design	Not Initiated
Task 2.1.1.6: Sensor Deployment Mechanism Design	Not initiated
Task 2.1.1.7: System Integration	Not Initiated
Task 2.2: Sensor Module	Not Initiated
Task 2.2.1: MFL Sensor System Design	Not Initiated
Task 2.2.2: Module Design Support	Not Initiated
Task 2.2.3: Specify Ovality Sensor	Not Initiated
Task 2.3: Specify Camera/Illumination	Not Initiated
Task 3: Eletrical/Control Design	Not Initiated
Task 4: Communication	**Initiated**
Task 4.1 Tether Assessment	**Initiated**
Task 4.1.1: Analysis	**Initiated**
Task 4.1.2: Choose/procure candidate materials	**Initiated**
Task 4.1.3: Test Plan	**Initiated**
Task 4.1.4: Lab Test	**Initiated**
Task 4.1.5: Tether Test Report	Not Initiated
Task 4.2 Specify Communication Components	Not Initiated
Task 5: Auxiliary Components	Not Initiated
Task 6: Management and Reporting	**On-going**

[1] Items indicated in bold were initiated during this reporting period

RESULTS AND DISCUSSION

Tether assessment was initiated and progressed significantly. Preliminary results indicate that the tether option is viable in the case of low and moderate transmission pipeline pressures and flows. Additional studies and testing are underway to:

- Perform communication tests on new 0.9 fiber.
- Test all fibers under flow conditions ($?V^2/2=20\ lb_f/ft^2$) when passing through plug valve port (reduced scale test) – look for unusual tether movement (communication and stress).
- Perform single mitered corner pull test (initially performed with 2 mitered bends back-back).

The following are open issues that are to be addressed during the next reporting period:

- Verify effect of abrasion from pipeline flutter at sharp mitered bend – will select abrasion resistant coating (manufacturer's recommendation) and test over period of time (TBD)
- Verify effect of debris/dirt on tether/winder
  - Problems occur if debris enters winder and causes localized fiber strain (micro bends).
  - Will consider sludge mixture of compressor oil and pipe scale.
  - Need to design winder with wiper system to ensure debris doesn't enter.
- Determine maximum length of vertical pipeline sections.
  - Effect of tether weight (self-induced tension on fiber)
  - Tether dynamics if vertical section is "very long"

Tether assessment is expected to be completed during the next reporting period, while module design will intensify. Also, it is anticipated that sensor design will be initiated following the anticipated signing of the collaborative agreement between Foster-Miller and PII.

To clearly understand the mechanical/control requirements of the robot for passage through out-of-plane, back-to-back bends, it was determined that a physical model should be constructed. The physical model will include a tractor (two triads and a center module) and a means for attaching a train of additional modules. A mockup consisting of several obstacles, including back-to-back in and out-of-plane bends and mitered bends will be constructed using the 16" steel pipe provided by KeySpan. Upon completing the fabrication of the physical model, testing will commence in the mockup. The goal of this testing is to establish the controlled motions and degrees of freedom (linkage/coupling designs) required to move the platform, sensor and associated modules through the pipeline.

CONCLUSION

The project was finally initiated during this period and focused on the assessment of the tether technology to be potentially used as means of communication between robot and operator. Also, other tasks related to the kinematics of the robotic platform itself were initiated.

Preliminary results show that the tether option is viable for low and medium pipeline pressures and flows. Advanced tether technologies will be explored that will allow use of tether at higher pressures and flows. Initial efforts are also underway to develop the camera/illumination system and ovality sensor.

The agreement between Foster-Miller and PII has been delayed, the final legal issues being worked out now. We expect the agreement to be signed within the next few weeks.

REFERENCES

None.