Advanced Inspection Robot for Unpiggable Pipelines

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The National Energy Technology Laboratory of the US Department of Energy, under Award DE-FC26-02NT41645, and the NYSEARCH Committee of the Northeast Gas Association (previously the New York Gas Group), sponsored research to develop a robotic pipeline inspection system capable of navigation through the typical obstacles that make transmission and distribution pipelines unpiggable. The research contractors, Foster-Miller and GE Energy performed an engineering study and developed a conceptual design that met all the requirements for navigating and inspecting unpiggable transmission pipelines. Building on Foster-Miller’s previous efforts developing the Pipe Mouse robot, the RoboScan inspection robot (Figure-1) meets the navigational challenges of unpiggable pipelines by utilizing four, self-adjusting locomotive units, integrating an innovative segmented MFL inspection module, and incorporating auto-correcting inter-module couplings.

![Figure-1 RoboScan Inspection Robot for Unpiggable Pipelines](image)

The platform performance specifications were developed as part of an earlier research effort and reflect the needs as expressed by the pipeline owners and operators. Table 1 summarizes the design requirements that have been factored into the RoboScan robot.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Primary Criteria</th>
<th>Secondary Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Size Range</td>
<td>12 to 24-in (18” nominal)</td>
<td></td>
</tr>
<tr>
<td>Pipe Wall (in.)</td>
<td>Up to .50-in</td>
<td></td>
</tr>
<tr>
<td>Inspection Distance (miles)</td>
<td>5 (target), ±2.5 each direction</td>
<td></td>
</tr>
<tr>
<td>Pipeline Velocity (fps) &amp; Pressure (psig)</td>
<td>Nominal: 20 fps &amp; 350 psig</td>
<td>Min: 10 fps &amp; 250 psig</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max: 75 fps &amp; 1000 psig</td>
</tr>
<tr>
<td>Obstacles to Negotiate</td>
<td>• Plug Valves (Nordstrom drawing no. C-50710)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Min Bend R&lt;1.5D (miter bend worst case)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Compound 90° bends (in &amp; out of plane)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Diameter Reduction (2 pipe sizes up or down)</td>
<td></td>
</tr>
<tr>
<td>Defects to be Detected</td>
<td>External Corrosion</td>
<td>Ovality, Gouges, Internal Corrosion</td>
</tr>
<tr>
<td>Contaminants</td>
<td>Loose debris on invert</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge deposits, oil, water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corrosion deposits</td>
<td></td>
</tr>
<tr>
<td>Pipeline Corrosives</td>
<td>Mercaptan</td>
<td></td>
</tr>
<tr>
<td>Platform Launch Capabilities</td>
<td>Live launch</td>
<td></td>
</tr>
<tr>
<td>Pipeline Cleaning Requirements</td>
<td>None</td>
<td>Investigate Further</td>
</tr>
<tr>
<td>Nominal Inspection Velocity (ft/min)</td>
<td>30</td>
<td>55 platform speed (no inspection)</td>
</tr>
<tr>
<td>Drive System</td>
<td>• Bi-directional</td>
<td>Maximum allowable pressure drop in pipeline obstacles (valves, bends, etc) - needs to be defined</td>
</tr>
<tr>
<td>Platform Size (cross-section)</td>
<td>• Maximum allowable pressure drop in smallest diameter within range (needs to be defined)</td>
<td></td>
</tr>
<tr>
<td>Communications</td>
<td>• Bi-directional data link (tether) – control and inspection data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Camera</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Electromagnetic sonde (emergency location)</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>• Remote control (tether) through base station (base station design not included)</td>
<td>Full autonomous in future – “learn” with tether</td>
</tr>
<tr>
<td></td>
<td>• Semi-autonomous (tether break return)</td>
<td></td>
</tr>
<tr>
<td>Modular Design</td>
<td>Expandable and repairable by modular changeout</td>
<td></td>
</tr>
</tbody>
</table>

The Roboscan platform consists of front and rear locomotion tractors each comprised of two triads that propel the entire train of modules through the pipe. Referring to Figure 2, the overall platform is comprised of several modules, each with an assigned function:

- Tractor/Triad systems - provides platform locomotion.
- Curling links – provides lifting moment to assists triad through bends.
- Electronics modules – packages electronics for various systems.
- Rotary couplings – provides relative rotation capability between triads for back-to-back and out-of-plane bends.
- Flexible couplings – allows modules to bend in all planes relative to each other while providing sufficient axial and torsional rigidity.
- Battery modules – provide power, power management and remote charging interface.
- Winder module (optional) – houses fiber optic tether, contains communications interface and manages tether payout and take-up.
- Centering coupling – positions MFL sensor/ovality module on the pipe centerline.
- MFL sensors – records and maps internal and external pipe wall corrosion.
Description of Problem

North America is crisscrossed with an extensive system of gas transmission and distribution infrastructure including underground pipelines. There are hundreds of thousands of miles of high-pressure gas transmission lines that cross the country and are owned and operated by a large number of interstate pipeline operators. There are 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, the commercial operations of many industries and the continuous delivery of fuel to millions of residential customers. Inspection, maintenance and repair of these pipelines are necessary elements of a pipeline integrity program. When access is practical, internal pipe inspection, maintenance and repair can offer a cost-effective approach to providing the services needed to ensure the safe and efficient operation of the infrastructure. However, difficulties in gaining physical access to and through these pipelines can present a potentially staggering economic burden on the owners/operators.

Unpiggable Pipelines

*Physical Obstacles:* There are many physical “obstacles” in the piping network that makes pigging impossible. The most intractable of these obstacles include:
• Bends/elbows (90-deg) with bend radius less than 1.0-D.
• Mitered joints/elbows greater than 10-deg.
• Back to back combinations of bends/joints.
• Reduced port valves, including valves with full ports but smaller in diameter than the pipeline and/or plug valves that have neither full diameter ports nor circular openings.
• Reduction/expansion in pipe diameter greater than 50-mm (2-in).
• Unbarred branch connections.

The elimination of one or more of these physical obstacles is required to make an unpiggable pipeline into one that can use a Smart pig. The Gas Research Institute in a report issued in 1995 entitled “In-Line Inspection of Unpiggable Natural Gas Pipelines” [1] noted that the cost to replace just two of the most common obstacles would be substantial. The cost to replace unpiggable valves and sharp bends was estimated at approximately $1.5 billion. In addition, another $1.5 billion would be needed to install the necessary launch and retrieval stations used to insert and recover the pig from the pipeline. These costs do not include the operating problems associated with the loss of service while these repairs are undertaken.

Flow "Obstacles": The use of pigs is totally dependent on the availability of pressure to "push" the pig through the pipeline. The pressure level must be sufficiently great to accommodate the additional pressure drop across the pig along with the expected pressure drop needed to maintain the flow capacity and its associated pipe friction loss. Typically, this requires several hundred PSI line pressure given the enormous weight of the pig hardware and the large pressure drop required across the elastomeric cups used to seal the pig against the pipe wall. Unfortunately, the operation of many utility owned transmission pipelines is at a pressure too low to support the operation of a conventional pipe pig.

Other Considerations: The cost of pipeline inspection using Smart pigs is expensive and assumes that the launch and retrieval traps are already installed and available to the inspection contractor. Although most interstate pipelines are many miles long, transmission pipelines owned and operated by the local distribution company are usually extremely short by comparison. Some of these pipelines are only one to two miles in length. Essentially none of these pipelines have traps installed and, thus, have no access for robotic devices.

Regulatory Requirements

The U.S. Department of Transportation through its Office of Pipeline Safety (OPS) has long held the position that all transmission lines must be inspected on a regular basis to ensure the safety of the public. In the past, this requirement was only applied to liquid pipelines, and not to the unpiggable portions of those pipelines. However, with the advances in robotics and sensor technology, OPS has recently endorsed the concept that all transmission pipelines (both liquid and natural gas) should ultimately be capable of 100 percent inspection. This can be accomplished through the elimination of pipeline obstacles for pigging, through the development of innovative inspection technologies, hydrostatic testing, or using a direct assessment technique.

Congress passed legislation (Pipe Line Safety Improvement Act 2002) to require that the Department of Transportation's Office of Pipeline Safety institute rulemaking on a testing program for natural gas pipelines in high consequence areas. The rulemaking includes a 10-year baseline inspection of all piping in high consequence areas followed by a seven-year re-inspection period. This applies to the use of hydrostatic testing, direct assessment or an in-line inspection robot. The adaptation of current pigging technology may not be viable given the geometric challenges, flow restrictions and economic drivers of utility owned transmission lines especially in high consequence areas. The external direct assessment
technique is limited to certain pipeline defects and has not been shown to be sufficiently reliable/accurate or cost-effective under all field conditions. Hydrostatic testing, although physically possible, is very expensive and time-consuming with little or no useful pipeline condition data generated after completion of the testing. The application of innovative robotic technology to the inspection of unpiggable pipelines is a natural extension of existing pigging products to this difficult environment.

RoboScan Inspection Platform

The RoboScan® robot is based on Foster-Miller’s previous efforts developing the Pipe Mouse robot [2]. The original Pipe Mouse robot was designed for use in gas distribution lines ranging in diameter from 100 to 150-mm (4 to 6-in). This robot was designed to operate in both forward and reverse directions, as well as navigate through smooth bends (1.5D or greater), mitered bends and tees (both main and branch lines). The Pipe Mouse received its locomotive force from four ‘triads.’ Two triads and an electronics module make up a tractor. One tractor is located at the front and rear of the robot providing the necessary pushing and pulling force to propel itself through the piping system. Figure 1 depicts a conceptual representation of the RoboScan triad/tractor arrangement.

A fundamental feature of each triad is the ability to contract and extend within the pipe. Onboard drive motors actuate four bar linkages causing each triad to independently contract or extent by shortening the triad wheelbase. This motion is controlled via a force feedback loop based on load cells located in each of the three wheels on each triad. The feedback loop measures the force that the pipe wall exerts on each of the three wheels, and then either contracts or extends the linkages to maintain a preset force level. This control system provides each triad with the capability to autonomously expand or contract upon the encounter of a change in pipe diameter (either larger or smaller). This capability is also particularly useful when the robot encounters small obstacles such as weld beads, displaced joints or debris. The robot can easily change shape to accommodate these types of obstacles and continue its passage through the piping system.

Another key feature of the triad design is the curling link. The curling link connects each triad to its corresponding electronics module, and exerts a curling force that assists the robot when it enters and exits a bend or the branch line of a tee. Each curling link is designed to exert a downward force on either a module or triad creating a tendency for the robot to curl inward upon itself. This force is called preferential curl.

Tractor steering is accomplished by means of rotating the drive wheels on each triad such that the robot may roll (in either direction) along the pipe wall. The preferential direction of curl can be aligned with the oncoming bend by rotating and appropriately orienting the centerline of the robot within the pipe. This orientation process will allow the robot to automatically enter any bend or tee that intersects the pipe.

Platform Kinematics

**Bi-Directional Motion:** The platform can travel within the pipe in both the forward and reverse directions. This motion is achieved by the use of bi-directional drive motors at each wheel on the four triads. Through constant engagement of the triads with the pipe wall and through use of the force feedback loop, the platform is capable of traveling both the downstream and upstream directions (as well as vertically upwards and downwards) regardless of the flow velocity.
**Pipe Ingress/Egress:** The RoboScan platform will be capable of entering and exiting pipelines at a 90-deg angle utilizing a field-installed hot tap fitting. By orienting the robot such that the direction of curl is aligned with the desired direction of travel, the constant curling force exerted by the curling links will direct the robot towards the chosen path.

**Smooth Bends (<1.0 D):** A typical bend installed in a transmission line can have a tight bend radius less than 1.0 times that of the pipe diameter. This type of obstacle is easily traversed using the basic functionality of the RoboScan platform. When the robot is properly aligned with the orientation of the bend, the curling force provided by the curling links will self-direct the platform through the bend. During all maneuvers, any one of the four triads can provide all of the necessary locomotion force should any of the other triad wheels momentarily lose contact with the pipe wall.

**Plug Valves:** A substantial obstacle for any pipe inspection robot is the plug valve. In most cases, the plug valve restricts approximately 70 percent of the available pipe width and 20 percent of the available height. As shown in Figure 3, the plug valve presents multiple obstacles to overcome. Beyond the severe restriction in available cross-sectional area, any reduction in height will create a ‘step’ for the robot to roll over. Based on the particular severity of this step, a combination of large diameter wheels and the autonomous contraction and expansion of the triad allow each tractor to pass through the valve. Clearly, both the tractors and the modules must maintain a slim aspect ratio or profile in order to pass through the narrow confines of the plug valve. Since the valve significantly reduces the working cross-sectional area of the pipe, and is a severe deviation from the standard geometry of a pipe wall, NDE sensing capabilities are curtailed during passage through plug valves.

![Figure 3 RoboScan Passing Through Plug Valve](image)

**Defect Detection: Magnetic Flux Leakage (MFL) Sensor**

The principles of magnetic flux leakage are well established and the technique has been used for the detection of defects in ferritic components for a number of years. The basic technique relies on applying a magnetic field across the pipe wall, and mapping the flux density at the surface. The presence of a defect (internal or surface breaking) essentially changes the cross section of the pipe wall under examination. This causes a redistribution of the magnetic flux and localized changes in the magnetic permeability of the material. As a result, some of the magnetic flux leaks out of the surface and the presence of the defect can be detected by a hall-effect sensor. Even defects on the far side of the pipe wall to the measuring sensor can be detected. The technique is robust, fairly insensitive to dirt and pipe surface condition, and particularly suited to those defects that constitute a loss in volume of ferritic material.
A segmented sensor concept with deployment mechanism was developed for passing through the many unpiggable obstacles. Generally, magnetizers of a MFL-based sensor create large attraction forces against the pipe wall. The attractive force is detrimental because it causes friction, which increases the locomotive power requirement and makes the robot less able to negotiate bends and other obstacles. Conventional MFL pigs are rotationally symmetrical and flux the full circumference of the pipe at one time. Based on geometric studies, it has been determined that a single MFL sensor will not be able to carry enough magnetic material through the plug valve and still have sufficient capacity to flux the full pipe circumference. Therefore, a number of magnetizer segments will be required for the full circumference with two segments mounted on each module. One of the sensor concepts currently being evaluated is shown in Figure 4. Each sensor segments carries a “simple-hinged” arrangement of three magnetizers with approximately 55-deg of circumferential coverage.

![Figure 4: Conceptual Design of MFL Sensor Module](image)

To get the requisite coverage, a single sensor segment can be utilized, but will require multiple passes up and down the pipe. More sensor segments/modules can be added to the train until there is a sufficient number so that the entire circumference can be examined in a single pass down the pipeline. However, each additional module increases the length of the platform. There is a limitation on the overall length of the platform, and a compromise solution is required depending on the mission objective. The optimized solution for shorter inspection runs is the inclusion of two sensor modules (4 MFL segments) with inspection of the pipe wall on the outward and return legs of the run. This approach simplifies the mission to a single launch and retrieval station while achieving full circumferential coverage.
Command, Control, and Communication

The control architecture of the RoboScan system will be based on a network of embedded microcontrollers. Each module in the overall platform will contain its own micro-controller. The couplings between the modules will function as physical, power, and communications connectors. When a module is physically coupled to the system, that module will also be powered and its micro-controller becomes part of the overall control network. In an emergency, any module (micro-controller) can become master of the network, directing the other system functions. This aspect of the system serves two purposes. First, sensor or task modules can take control of the operation of the RoboScan, dictating speed, position and direction as needed by that particular task. Second, each controller can monitor the functional "health" of the other controllers. If a problem is diagnosed in part of the control network, the problem can be isolated. Once identified, another controller can assume the operation of the problem controller in the system.

Battery Technologies

To power the computer, sensors, data acquisition and the drive wheels, some form of energy storage and electrical power supply is required. Of all the various possibilities (e.g., batteries, heat engines, fuel cells, ultra-capacitors, etc.), the battery approach is clearly the simplest, safest and most reliable. To minimize the number of launch and retrieval stations on long duration missions, the batteries will have the maximum energy density available. The modular platform approach has the advantage that battery “cars” may be added as needed, up to the length of the launch tube. However, certain obstacles (e.g., mitered corners) also impose a length constraint that must also be taken into consideration. Different battery and charging modules may also be swapped in and out based on the range requirement, power and availability of in situ recharging stations.

Platform Operations: Launch and Retrieval

The RoboScan platform has several advantages that simplify the launch and retrieval hardware compared to conventional pigging. First, the robot can be "driven" into the main line rather than having to be pressurized and "blown" in from behind. This greatly reduces the complexity of the plumbing and operation of the launch and retrieval traps. Second, RoboScan can be launch in its smallest configuration and can (depending on the pipeline size) result in a launch station that is half the diameter of the receiving pipeline. This advantage will result in significantly lower capital and construction cost for the launch and retrieval traps.

Unlike conventional pigs, the RoboScan can be launched (and retrieved) in a variety of positions. Smart pigs need the in-line launch and retrieval tube orientation to be horizontal which necessitates a major reconfiguration of the existing pipeline. In contrast, the RoboScan launch tube can be installed at a right angle (either vertically or horizontally) to the pipeline through a hot-tap saddle arrangement. This permits the launch station to be located almost anywhere along the pipeline. Because the RoboScan can be inserted vertically into the pipeline, many of the construction and pipeline reorientation problems and cost associated with conventional pigging traps are eliminated.

The retrieval station is also greatly simplified. Instead of having to catch the pig, slow it down and divert the flow, RoboScan can be programmed to stop and crawl into a simple 90-deg branch-line. In fact, the launch tube can also act as a retrieval tube should the RoboScan platform return to the launch location at the end of the pipeline survey. To further simplify launch and retrieval operations, the launch and retrieval traps can be outfitted with wireless antennae to permit local control during these maneuvers. By switching over to manual control, the operator can ensure that the RoboScan platform is properly
positioned inside the pipeline before initiating the autonomous inspection operations, and/or the extraction process.

Conclusions

The geometric complexities of older pipelines make it difficult to utilize inspection robots in these piping networks. Although Smart pigs and other robotic technologies have been deployed within oil and gas pipelines, there remain many obstacles within the unpiggable portions of these networks that prevent the use of robots. The GRI Pipe Mouse and other robotic platforms have validated the basic premise that basic pipeline obstacles can be navigated through without jamming. The RoboScan platform has been designed to navigate through the physical and operational obstacles found within unpiggable gas transmission and distribution systems.

Acknowledgments

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References

(1) In-Line Inspection of Unpiggable Natural Gas Pipelines, Southwest Research Institute, San Antonio, TX, Gas Research Institute, Chicago, IL, May 1995.