BASELINE STUDY OF ALTERNATIVE IN-LINE INSPECTION VEHICLES

FINAL REPORT
Contract No. DTRS5602T0004
SwRI® Project 14.06170

Prepared for

United States Department of Transportation
Research and Special Programs Administration (RSPA)
Office of Contracts and Procurement, DMA-30
400 7th Street, S.W., Room 7104
Washington, D.C. 20590

Prepared by

Sensor Systems and NDE Technology Department
Applied Physics Division
Southwest Research Institute®

October 2003

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON
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TABLE OF CONTENTS

Page

TABLE OF CONTENTS

Page

LIST OF FIGURES

1. INTRODUCTION

Transmission pipelines were largely uninspected for corrosion and other defects prior to the introduction of in-line inspection technology in the mid-1960s. Hydrostatic testing was common and was generally accepted as a proof test of pipeline integrity. It was well known, however, that there could still be defects in a pipeline even though it passed a hydrotest. In fact, there were even concerns that hydrotesting could result in growth of subcritical crack-type defects. On top of these disadvantages was the growing concern about the environmental impact of disposal of hydrotest water—water that might be contaminated with hydrocarbons and other material in the pipeline. And, for some pipelines, there was a direct economic burden to the hydrotest in that the lines were under constant use delivering product and could not conveniently be taken out of service for as long as the time required for the hydrotest.

So there was a need for an effective way to locate defects in transmission pipelines without the potential side effects of hydrotesting. Internal pipeline devices (pigs) had been pumped through pipelines for cleaning and batching for many years. Kaliper® pig services were being run to map pipeline diameter restrictions. Concurrently, nondestructive testing technology had been developed for inspection of oilfield tubular goods. The most common inspection method for this application was magnetic flux leakage (MFL), a method in which sensors are used to detect the diversion of magnetic flux due to pipe wall anomalies. It was proposed to combine the tubular goods inspection technology and the caliper pig technology to deploy MFL on a pipeline pig and collect data of the pipeline condition inside the pipe. Thus was born the in-line inspection (ILI) business that is the primary method for determining pipeline integrity today.

The earliest full-coverage MFL pigs used a spool-shaped electromagnet energized by direct current from onboard batteries. Data were stored on an onboard tape recorder. The facts that the magnetizer was a spool with a solid central core and the tape recorder was necessarily bulky to provide enough tape for long runs dictated that the pig had a significant length-to-diameter ratio. This would not have been an issue if pipelines were straight, but all pipelines contain bends—either fabricated short-radius bends or more gentle field bends. The requirement to negotiate bends dictated that the pig have a limited length of solid section. Hence, many pigs are made of multiple modules with universal joints to facilitate bending. The minimum bend radius (usually expressed in terms of pipe diameters) that can be negotiated by a specific pig design is a fundamental descriptor of the pig and, in the aggregate, these descriptors set the definition of "piggable" for some pipelines.

As will be discussed below, the bend radius limitation is only one of several characteristics of ILI devices that preclude their use in some pipelines. This report will present statistics of smart pig specifications in a matrix of pig capabilities and pipe sizes. A prospective user will be able to determine whether there is a pig available that can negotiate his pipeline.

Almost all of the in-line inspection done in today's market is performed by tools of the traditional piston-type design. Pipelines that cannot accommodate piston pigs due to configuration or pipeline operating parameters are generally not inspected from the inside. Inspection, in those cases, is performed by hydrotest or some combination of monitoring techniques making up a

Direct Assessment program. But there is reason to believe these pipelines could be inspected internally if only a compatible inspection vehicle were available.

It was a goal of this project to identify and evaluate nonpiston vehicle concepts that could potentially carry inspection sensors and recording apparatus into both piggable and nonpiggable pipelines. It has been suggested that pipeline integrity management in some future time might include the use of autonomous robots that would “live” in a pipeline, taking power from the moving product stream and communicating to the outside of the pipeline, from time to time, information on the condition of the pipeline. The system then would include a vehicle, sensors, data recording, power generation, and communication. Work has been done in various research centers on each of these components. Some mention will be made of the other components, but the thrust of this report is on the vehicle.

2. THE SCOPE OF THE PROBLEM

2.1 Unpiggable Pipelines

2.1.1 Why Some Pipelines Are Unpiggable

Many existing pipelines can support pigging operations, especially the newer ones where that capability was among the design criteria. Unfortunately, not all pipelines are piggable. Several conditions can render a section of pipeline unpiggable, obstacles that obstruct or prevent the passage of a pig through a portion of the pipeline. These are described briefly below.

(1) *Bend Radius <1.5D*. Bends are intentional directional changes in the pipeline and can be either gradual or tight. Newer pipeline designs avoid tight bends as much as possible because of the impact on inspection and cleaning. Pig manufacturers usually list the minimum allowable bend radius on the pig data or specification sheets. This information is included in the pig operational parameters matrix in Section 4. The minimum bend radius is often listed as 1.5D or 3D. Increasingly, the design goal appears to be 1.5D. (D refers to pipe diameter.)

(2) *Miter Bends*. Miter bends are formed when two sections of pipe are cut at an angle and welded together, forming an angle bend rather than a smooth bend. Miter bends were more common in older pipelines than in today's designs. The angles usually were quite small, on the order of 10 degrees or less. In most cases, angles greater than 5 or 10 degrees make the section unpiggable. Fortunately, this is an infrequent occurrence.

(3) *Other Bends*. This category is used to describe bend configurations that prevent pigging, such as back-to-back bends. The term "back-to-back bend" refers to two bends separated by only a very short transition piece or no transition at all. Such combined bends are common where line offsets are required. If a distribution main, for example, must be offset vertically to pass beneath a street, it is common to combine two bends of 90 degrees at each side of the street. Thus, the line is dropped rapidly, passes horizontally under the street, and rises in similar fashion on the other side.

(4) *Unbarred Branch Connections*. Branch connections are encountered where there is a need to divert some of the pipeline flow to an intersecting pipe. When the branch connection (tee) is made, an opening is made in the pipeline. The opening can be made anywhere around the circumference of the pipe, but most occur in a plane horizontal to the pipe and are referred to as side openings. If the opening is too large, pigs can get stuck in the branch connection. This can damage or block the pipeline. Problems can also be avoided by installing bars across the opening when the opening exceeds a certain size—for example, one half the diameter of the primary pipe. Some pig vendors list the largest acceptable diameter of a branch connection without bars (UNBAR T) in their specification or data sheets for individual pigs.

(5) *Reduced Port Valves*. Valves are used for operational control of the pipeline. There are many kinds of valves, but they can be conveniently placed into two groups. The first group is the full bore (through-conduit), where the valve can be opened to the full inner diameter of the pipe. These valves do not interfere with pigging operations. The second is the group of valves that cause partial blockage. This includes reduced diameter valves, plug valves, and check valves, the latter being found almost exclusively in liquid pipelines. Plug valves have a noncircular opening through the valve and prohibit the passage of the pig. While the design of check valves varies, it usually includes a clapper and a bowl of some shape. The change in diameter in the bowl or the location of the clapper can impede passage of pigs.

(6) *Multidiameter Pipe*. This condition is relatively uncommon. It occurs when pipes of different diameters are joined together. Pigs can handle small changes in diameter without problem, but changes greater than 2 inches may prevent the use of the pig. Usually, the manufacturer will list the maximum allowable reduction in the pipe diameter. Normally, changing the pipe diameter to the next size (i.e., going from 24-inch pipe to 22-inch-nominal-OD pipe) will not be a great enough change to interfere with successful pigging activities.

(7) *Physical Damage*. Physical damage, such as a dent caused by heavy equipment, can reduce the ID of the pipe in a localized region enough to interfere with the passage of inspection pigs.

2.1.2 Distribution Line Issues

Federal regulations for pipeline safety are not usually applied to gas distribution networks because such networks do not operate at pipe stress levels above a few percent of specified minimum yield stress (SMYS). Exceptions to this include facility mains, which are very similar to transmission pipelines even though they are part of the municipal distribution system. Many facility mains operate at pressures that qualify them for the pipeline integrity rules. Because of this, local distribution companies (LDCs) are interested in pipeline inspection with internal inspection devices (smart pigs). Many facility mains and other lower pressure distribution lines were installed in municipal environments after other underground services such as water lines, sanitary and storm sewers, and electrical distribution ducts were already in place. In many cases, the gas mains were simply routed around the other lines so that there are many tight bends (even miter connections), back-to-back bends, and other impediments to pig transit. In addition, there are fittings such as drips to contend with. Unpiggable valves such as plug valves abound.

As a result of these impediments to pigging and the increased emphasis on pipeline inspection, LDCs have a need for new vehicle concepts that will let them inspect a greater fraction of their piping systems. Some work has been done to alleviate the problem. The Gas Research Institute funded the development of an MFL inspection system for 4-inch distribution pipes. The inspection head was deployed on the end of a coiled-tubing push-pull rod inserted into the pipe through a weld-on saddle and valve that was left in place after the job was done. Other similar devices with video capability have been offered for several years.

2.2 Value of Alternative Approaches for Piggable Pipelines

The preceding discussion has focused on the problems of unpiggable pipelines. Certainly, a critical need exists for those lines that cannot be internally inspected now. But unpiggable pipelines are not the only pipelines that would benefit from new concepts of internal inspection. Consider the tradeoffs that must be made whenever a piggable pipeline is inspected. Liquid media pipelines cannot move product any faster than the pig transit speed. Most pigging vendors prefer transit speeds on the order of 4 to 7 mph (1.8 to 3.1 m/sec). Pigs that have bypass capability can run gas lines at speeds slower than the gas throughput speed, but the amount of bypass is limited.

The robotic concepts considered in this report would not offer any significant obstruction to the pipeline. They would not require slowing of the throughput. The only flow speed effect might be the dynamic pressure on the vehicle. For example, 24-mph flow would be considered a minor force on the vehicle if the environment were outside the pipeline. However, gas under pressure increases its density to the point that the impact on a vehicle could be the equivalent of a category 5 hurricane. This means that the vehicle would have to make provision for keeping its place in the pipeline during some strong gas flow forces.

What is gained for this tradeoff? If a vehicle stays in the pipeline, taking its power from the flowing medium and sending data out for analysis, it will be in a position to detect corrosion or other defects at the earliest possible opportunity. And if it can send data out of the line before the tool has to be removed from the line, the pipeline operator can take action at the earliest possible moment. One can imagine that the pipeline operator may purchase or lease inspection systems that would stay in his pipeline indefinitely. And if the receiving electronics and software were designed to be easily usable by the operating company maintenance personnel, the inspection function might evolve into just another monitoring component of the SCADA (Supervisory Control and Data Acquisition) system.

3. INSPECTION TECHNOLOGIES

3.1 Magnetic Flux Leakage (MFL)

The most widely used technology for metal loss and crack detection is magnetic flux leakage (MFL). MFL is also one of the oldest methods for testing ferromagnetic materials. Figure 1 is a schematic showing the generation of the magnetic flux and the change caused by the presence of a defect such as wall thinning. As shown in the figure, the MFL method consists of inducing a magnetic field in the material—in this case, the pipe wall—and looking for any flux leakage that is the result of a defect. A defect such as local reduced wall thickness or a volume with different magnetic properties like an inclusion can cause a diversion in the magnetic field. The magnetic field is induced either by permanent magnets or electromagnets, the former being more widely used because they do not require an electrical power supply. Of note is that MFL is an indirect measurement method in that the amount of wall loss or defect size must be inferred from the data.

There are two types of MFL pigs, the conventional MFL pig and the high-resolution MFL pig. The basic differences between the two are the number and size of the sensors and the data processing/analysis. Each can use permanent magnets or electromagnets. Each can use detector array pairs to help determine if the defect is on the outer surface or the inner surface of the pipe. Conventional pigs usually have fewer but larger sensors for a given pipe diameter than a high-resolution pig. The high-resolution pigs acquire more data because they have more sensors, each covering a smaller area to improve the resolution for defect location and sizing.

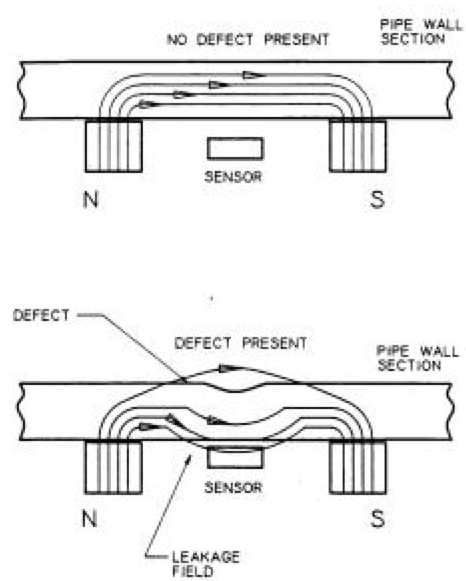


Figure 1. Schematic showing the generation of the magnetic flux and the change caused by the presence of a defect such as wall thinning

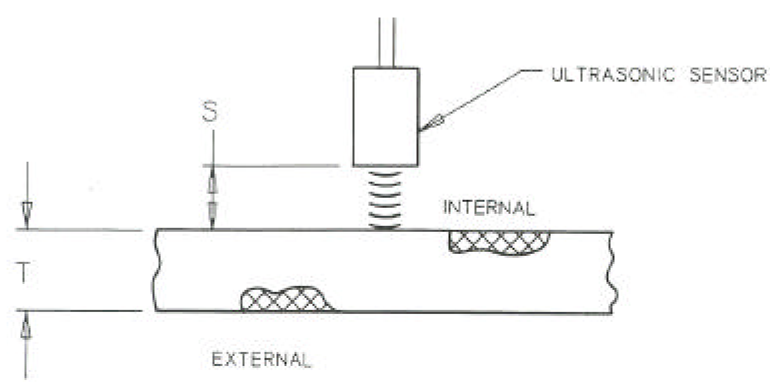
The two MFL pig types have specific uses. The conventional MFL pig is a sensitive metal loss detector and can identify corrosion in a pipeline. It is mostly used for the initial inline inspection (ILI) of a new pipeline. The high-resolution pig, because of its greater number of sensors, can provide a more detailed description of the corroded area, including length, width, and depth. This pig would be used after corrosion has been detected to better assess the extent of the corrosion.

The velocity at which the pig travels in the pipeline is an important factor in the use of MFL pigs. The induced magnetic field is determined by the strength of the magnet and the time needed to induce the magnetic field in the pipe wall. There is a slight delay between when the magnetic field is applied and when it reaches a stable, usable value. A more significant factor in speed limitation is the demagnetizing effect of eddy current reaction fields due to pig speed. When an MFL pig moves through a pipeline, the changing axial magnetic field causes circumferential electrical currents to flow around the periphery of the pipe. This induced current generates a magnetic field that opposes the pig's magnetic excitation. Since the induced currents are proportional to the rate of change of the axial magnetic field, i.e., pig velocity, the reaction field increases with pig speed, leaving a reduced net field to magnetize the pipe. Consequently, there is an upper limit on how fast the pig can travel and still perform effectively. The manufacturers list a recommended velocity range in the pig specification sheet.

3.2 Ultrasonics

The ultrasonic (UT) technique is considered by many NDE specialists as the most direct and accurate way to measure wall thickness. It is widely used in other industries where precise wall thickness measurements are needed. UT is becoming more widely used in pigging, although there are limiting factors that must be considered.

Ultrasound is defined as the sound frequencies higher than the audible range of 20 to 20,000 cycles/second (Hertz or Hz). The frequency range used for inspecting pipe is commonly from 1 to 5 megahertz (MHz). Figure 2 is a schematic representation of an ultrasonic sensor used in metal loss detection. The ultrasonic sensor (transducer) shown in the figure both transmits ultrasound and receives the returned ultrasound from the pipe wall.



S=standoff, the distance between the sensor and the internal wall; T=thickness, the distance between inside and outside surfaces of the pipe wall

Figure 2. Schematic representation of an ultrasonic sensor used in metal loss detection

Ultrasonic measurement devices use transducers to transmit ultrasound into the pipe material. Ultrasound will be returned as an echo from the front surface of the pipe (ID), the pipe backwall (OD-surrounding medium interface), and from any reflectors located within the pipe wall. Cracks, laminar defects, inclusions, and metallurgical changes are examples of such reflectors. The velocity of sound in various metals is known, and the time of flight from the back wall or reflector can be precisely measured and converted into a distance measurement that corresponds to the wall thickness. The position of the transducer with respect to the front surface is a critical factor because the amplitude of the returned signal can be reduced if the ultrasound is not transmitted normal to the surface, as shown in the figure. The amplitude will be affected by the angle (deviation from normal) and the condition of the front surface. Conditions like corrosion can scatter the ultrasound, which, in turn, lowers the amplitude of the returned signal. The UT technique for wall-thickness measurement is not amplitude dependent but is time dependent since the thickness is based on a time-of-flight measurement. Measurements can still be made if signals of sufficient amplitude can be obtained.

The UT technique is capable of producing more accurate wall-thickness measurements as compared to those from magnetic methods. The greater accuracy is a result of the uniformity of the velocity of ultrasound in the material being examined. The velocity in steel is independent of the metallurgical properties of the steel and has been accurately measured. The time of flight of the signal reflected off the backwall can be very precisely measured to produce thickness measurements. Ultrasonic measurement is essentially independent of the metallurgical properties of the pipe and less sensitive to variations in the magnetic properties of the steel. Further, it is a direct measurement of the time of flight rather than an inferred measurement based upon signal amplitude as with MFL-thickness measurements. Accurate time-measurement devices have been available for decades.

Ultrasound is also used for crack detection. Figure 3 is a schematic representation of UT crack detection. Whereas in wall thickness measurement the ultrasonic beam is directed perpendicular (0 degree) to the pipe wall, the transducer is positioned so that the beam enters the metal at an angle, as shown in Figure 3. The angle of the UT beam in the pipe wall material makes it possible to detect axial cracks that would not be seen by a 0-degree beam.

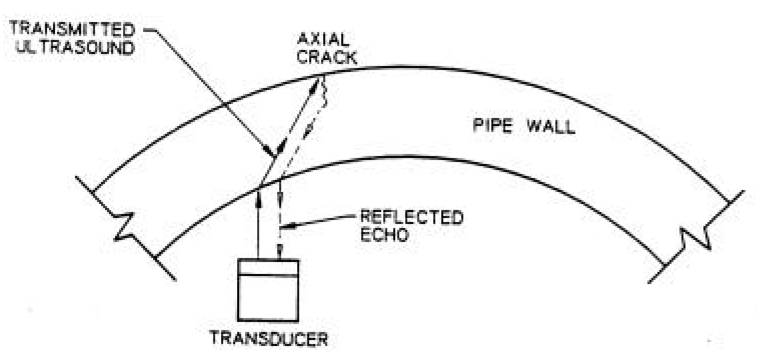


Figure 3. Illustration of ultrasonic crack detection

A factor that must be considered in the use of UT is effective transmission of ultrasound from the transducer into the material being examined. In the optimal case, the transducer is in direct contact with the material and transmission is achieved by use of a couplant, often a liquid couplant like glycerin, that allows the transmission of ultrasound from the transducer into the material. Conversely, air highly attenuates ultrasound so that very little ultrasound is transmitted from the transducer through air to the material. So a method to couple the transducer to the pipe wall must be in place in order to obtain a sufficient level of ultrasound. Liquid product can serve as an effective couplant in liquid lines. Gas pipelines can be inspected with UT if the pig is configured to carry a volume of couplant such as water along with the device. This can be accomplished by using batching pigs to carry the necessary volume of water. Use of the batching pigs is reasonably successful if the line does not contain branch connections that would bleed off the water. Work has been done on gas-coupled UT, but it is still in the developmental state.

At the present time, UT pigs carry arrays of transducers, each with the ability to examine roughly 0.5 inch of the pipe circumference. The number of transducers needed for full coverage rises quickly to the point that hundreds are needed for large-diameter pipe. The number of transducers adds to the complexity of the data acquisition hardware and software and the volume of data. It is possible to perform some preprocessing of the data to reduce the volume of data and increase the range of the device.

The term “dry coupling” is used to describe ultrasonic coupling without the use of a liquid couplant. Several “dry-coupling” techniques are being investigated, but none are commercially available. The techniques include electromagnetic acoustic transducers (EMATs), laser acoustic couplers, and dry wheel couplers. The EMAT is a device using the magneto effect to generate and receive ultrasonic signals for UT. It does not require a liquid couplant but does not produce strong signals. The laser acoustic technique uses a laser to produce sound in the material and optical interferometry to detect the emitted sound. The dry wheel coupler consists of transducers mounted in a rim with a “tire” on the rim that is composed of a material that allows the transmission of ultrasound into the material being examined, essentially coupling the transducer to the wall surface.

EMAT applications have been used for years in laboratory environments but have not been successfully applied to pipeline inspection. As mentioned above, one factor is the weak signal as compared to conventional ultrasonic transducers. Consequently, significant amplification is needed to obtain usable signals, which, in turn, increases the complexity of the data acquisition system hardware. Another factor is that the EMAT must be positioned very close to the surface being inspected. This proximity to the pipe wall increases the risk of damage to the EMAT. Engineering solutions to these factors are being developed in vendor laboratories.

3.3 Remote-Field Eddy Current (RFEC)

RFEC is based on the use of an excitation coil placed in the pipe with its axis along the pipe axis. The coil is driven with alternating current having a frequency such that the generated magnetic field will penetrate through the pipe wall and not be severely attenuated by the electromagnetic skin effect. Sensors are placed adjacent to the pipe wall at a distance several pipe diameters away from the exciter, as shown in Figure 4. At this “remote-field” location, the

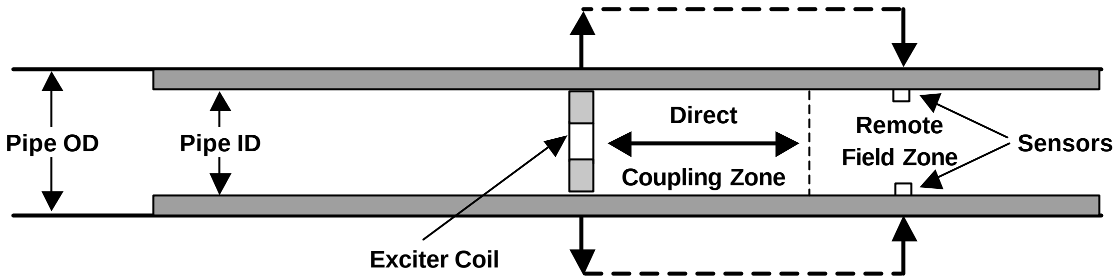


Figure 4. Traditional RFEC probe configuration (cross section)

magnetic field from the excitation coil is very small, and the direct coupling from it into the sensors is minimal. At the sensor location, however, a field component exists that has penetrated through the pipe wall to the OD and then back through the pipe wall to the ID. This component is detected by the sensors and is sensitive to material-loss defects because it has penetrated through the pipe wall.

Typically, RFEC is implemented using an exciter coil that is only slightly smaller than the ID of the pipe; this maximizes coupling with the pipe wall and results in stronger signals received by the sensors. It is possible to use smaller diameter excitation coils, but the sensitivity will be reduced.

3.4 Nonlinear Harmonics

The name nonlinear harmonics comes from the fact that the magnetic characteristic curve for ferromagnetic materials is not a linear relationship between an impressed magnetic field and the resulting magnetic flux density in the material. The well-known B-H curve shows the relationship between magnetizing force, H, and the flux density, B (see Figure 5). If a sinusoidally varying magnetic excitation is applied to a magnetic material such as steel, the resulting magnetic flux varies in the manner of a sinusoid with significant harmonic content. In other words, the flux density curve is distorted by components of frequency multiples of the excitation frequency. It has been demonstrated by work at SwRI that the third harmonic, particularly, carries information about the permeability and responds to changes in the strain state of the steel. NLH sensors are essentially transformers, and if the third harmonic content of the secondary voltage can be detected and recorded with its phase information, information can be produced that is related to previous mechanical damage, regardless whether pipe wall distortion from that damage is evident or not.

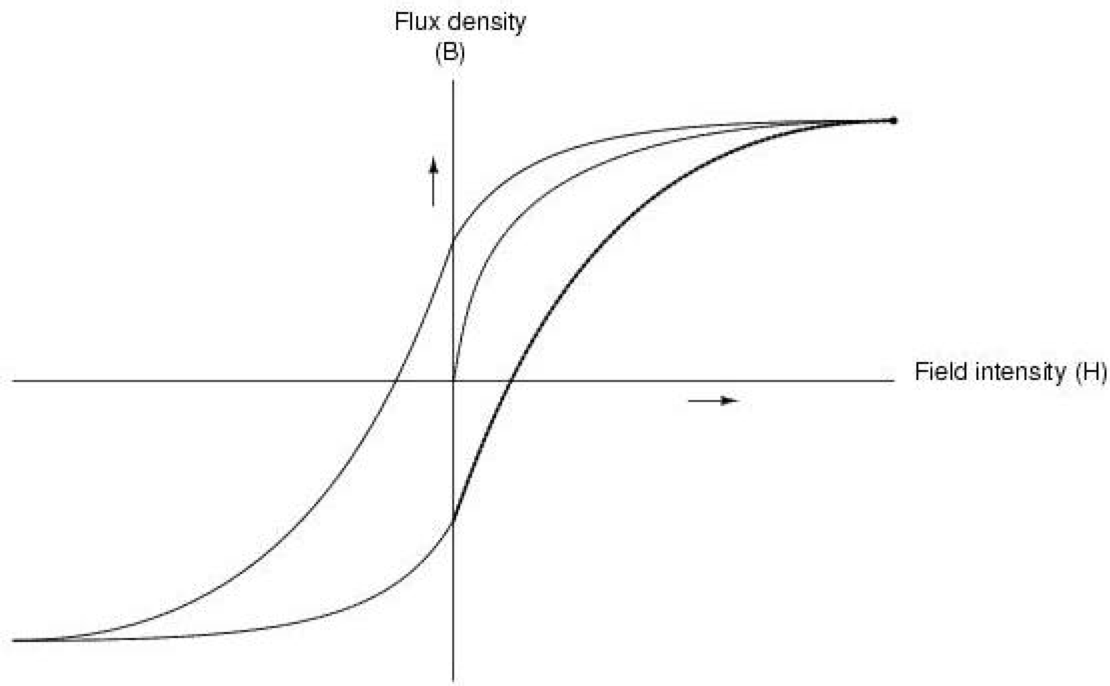


Figure 5. B-H curve showing relationship between magnetizing force, H, and the flux density, B

Under funding from the Gas Technology Institute (GTI) and more recently from both GTI and the Office of Pipeline Safety, SwRI has gathered NLH data from numerous mechanical damage defects. These tests, which were performed in SwRI laboratories, had as their goal the development of an assessment procedure for mechanical damage. There is currently no industry-wide accepted assessment for mechanical damage other than the consideration of the depth of a dent. Analysis and experiments have shown that dent depth alone is insufficient to accurately appraise the severity of a defect that may or may not have an associated gouge and which may or may not have been re-rounded. So, as the only technology that has shown direct response to mechanical damage, NLH is very important for developing a new assessment method.

3.5 Barkhausen Noise

Barkhausen noise refers to the burst of signals produced by moving and expanding magnetic domains in magnetic material as the magnetization increases from zero in either polarity. The amount of Barkhausen noise is influenced by the stress in the magnetic material. Hence, Barkhausen is commonly used to locate stress anomalies. Common implementations of Barkhausen detection rely on periodically varying magnetic excitation, either sinusoidally or sawtooth or ramp waveforms. Work presently under way on a DOT-funded project at SwRI seeks to prove feasibility of detection of Barkhausen noise continuously on an MFL pig by an approach called Continuous Barkhausen Noise (CBN). Early results are very promising. Figure 6 shows the potential deployment of CBN sensors on an MFL pig magnetizer.

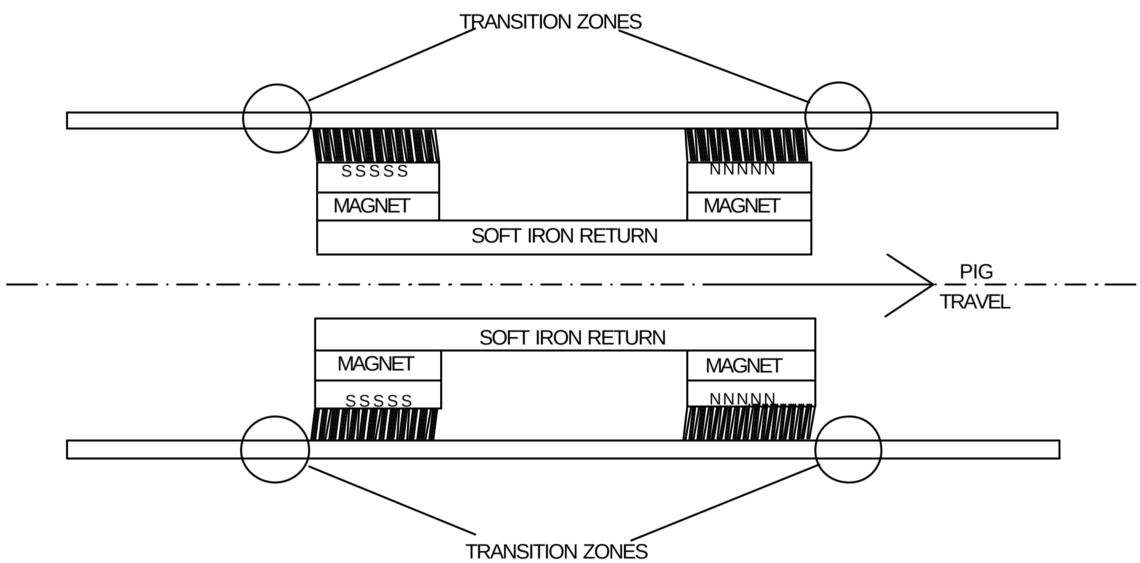


Figure 6. Schematic of MFL magnetizer showing potential zones of Barkhausen noise generation

4. CURRENT STATE OF THE ART IN ILI

4.1 Matrix of Capabilities

One of the objectives of this project is to assess the state of the art of internal inspection vehicle design. Internal inspection vehicles are defined here as smart pigs, devices that perform inspections that involve instrumentation to assess the condition of the pipeline, as opposed to batching pigs, cleaning pigs, mapping pigs, and caliper pigs. The devices considered for this matrix are full-diameter piston-type pigs carrying instrumentation that performs one of several types of nondestructive evaluation (NDE) to look for wall loss, corrosion, and cracking of several varieties. The information was obtained from materials available at pigging conferences, the Internet, and contact with representatives of the service providers.

INSPEC-TION METHOD	PIPE SIZE (INCH)	NO. OF MOD-ULES	MIN P (PSI)	MAX P (PSI)	BEND RADIUS (PIPE DIA)	MAX W.T. (INCH)	MINI-BORE CONT. (INCH)	MINI-BORE DELTA (INCH)	PIG LENGTH (INCH)	UNBAR T (MAX INCH)
MFL	2	3			15D	0.154	1.76		28.5	
MFL/caliper	3	6		2000	10D	0.250	2.90		75.5	
MFL	3	8		1300	5D	0.280	2.83		82.7	
MFL	3	3			12.5D	0.300	2.75		32.5	
MFL	3	4		2000	12D	0.203	3.00		43.0	
MFL/caliper	4	7		2000	9D	0.237	3.87		87.9	
MFL/caliper	4	6		2000	5D	0.250	3.46		70.2	
MFL	4	6		2000	7D	0.250	3.62		78.8	
MFL	4	6		1300	1.5D	0.320	3.70		86.6	
MFL	4	3			10D	0.337	3.70		34.0	
MFL	4	5		1500	3D	0.337	3.63		77.4	
MFL	4	4		2000	5D	0.337	3.60		49.0	
MFL/caliper	6	8		2000	3D	0.312	6.06		106.3	
MFL/caliper	6	6		2000	1.5D	0.312	6.06		79.2	
MFL	6	6		1300	1.5D	0.470	5.35		86.6	
UT	6	9		1740	1.5D	0.870	5.32		158.0	
UT	6	9		1740	3D	0.870	5.32		158.0	
UT	6	9		1740	5D	0.870	5.32		158.0	
MFL	6	3			5D	0.432	5.30		88.1	
MFL	6	4		2000	3D	0.432	5.40		91.0	
MFL	6	4		2000	3D	0.432	5.50		54.0	
MFL	6	4		2000	1.5D	0.432	5.25		56.0	
MFL/caliper	8	7		2000	1.5D	0.375	7.87		110.2	
MFL	8	6		2000	3D	0.375	7.76		129.0	
MFL	8	4		1300	1.5D	0.550	7.48		70.9	
GPS	8	2		2200	3D	0.432	7.20		94.8	
UT	8	9		1740	1.5D	0.870	6.89		171.0	
MFL	8	5		1740	1.5D	0.550	6.47		72.0	
MFL	8	3			5D	0.500	7.11		88.6	
MFL	8	4		2000	3D	0.625	7.20		96.0	
MFL	8	3		2000	3D	0.500	7.25		50.0	
MFL	8	3		2000	1.5D	0.500	6.75		67.0	

INSPEC-TION METHOD	PIPE SIZE (INCH)	NO. OF MOD-ULES	MIN P (PSI)	MAX P (PSI)	BEND RADIUS (PIPE DIA)	MAX W.T. (INCH)	MINI-BORE CONT. (INCH)	MINI-BORE DELTA (INCH)	PIG LENGTH (INCH)	UNBAR T (MAX INCH)
MFL	10	5		2000	1.5D	0.500	9.86		105.0	
MFL	10	3		1300	1.5D	0.710	8.74		82.7	
GPS	10	2		2200	3D				103.2	
UT	10	5		1740	1.5D	0.870	9.06		130.0	
UT	10	5		1740	3D	0.870	9.06		118.0	
MFL	10	5		2176	1.5D	0.500	8.79		114.8	6.45
UT	10	7		1740	3D	0.787			173.2	
UT	10	7		1740	3D	1.970			173.2	
UT	10	3		1233	1.7D	0.925			114.0	
MFL	10	4		1740	1.5D	0.625	9.57		76.0	
MFL	10	3			5D	0.593	9.07		82.8	
MFL	10	4		1232	3D	0.472	9.14		90.6	
UT	10	3		1232	3D	1.180	9.14		123.4	
MFL	10	4		2000	1.5D	0.625	9.00		96.0	
MFL	10	2		2000	1.5D	0.594	9.25		55.0	
MFL	12	6	850		3D	0.625	11.05		149.0	
MFL	12	6	850		3D	0.625	11.05		119.0	
MFL	12	5		1500	1.5D	0.500	11.75		117.0	
MFL	12	3		1300	1.5D	0.630	11.00		82.7	
GPS	12	2		2200	1.5D				117.6	
MFL	12	4	400	2200	1.5D	0.600	11.20		132.0	
MFL	12	5		2176	3D		11.25		210.6	
UT	12	5		1740	1.5D	0.870	10.83		130.0	
UT	12	5		1740	3D	0.870	10.83		118.0	
MFL	12	4		2176	3D	0.760	11.57		170.6	7.65
UT	12	3		1233	1.5D	0.925			112.8	
MFL	12	4		1740	1.5D	0.625	9.57		76.0	
MFL	12	3			5D	0.688	10.97		84.8	
MFL	12	4		2000	1.5D	0.625	10.80		72.0	
MFL	12	2		2000	1.5D	0.688	11.00		68.0	
MFL	14	5		1500	1.5D	0.500	12.95	10.69	118.0	7.65
MFL	14	3		1300	1.5D	0.710	11.97		74.8	
GPS	14	2		2200	1.5D				117.6	
MFL	14	4	400	2200	1.5D	0.600	11.94		138.0	
UT	14	5		1740	1.5D	0.870	12.01		130.0	
UT	14	5		1740	3D	0.870	12.01		118.0	
MFL	14	4		2176	3D	0.870	13.21		174.2	8.40
UT	14	4		1233	3D	0.925			163.2	
MFL	14	4		1740	1.5D	0.750	10.50		62.0	
MFL	14	3			5D	0.593	12.32		84.8	
MFL	14	4		2000	1.5D	0.625	12.60		72.0	
MFL	14	2		2000	1.5D	0.750	12.00		64.0	
MFL	16	4		1500	1.5D	0.500	14.79		120.2	
MFL	16	2		1300	1.5D	0.790	13.70		63.0	
GPS	16	2		2200	1.5D				145.2	
MFL	16	3	400	2200	1.5D	0.744	14.30		114.0	
MFL	16	5		2176	3D		14.58		221.2	9.60
UT	16	4		1740	1.5D	0.870	13.85		177.0	
UT	16	4		1740	3D	0.870	13.85		154.0	

INSPEC-TION METHOD	PIPE SIZE (INCH)	NO. OF MOD-ULES	MIN P (PSI)	MAX P (PSI)	BEND RADIUS (PIPE DIA)	MAX W.T. (INCH)	MINI-BORE CONT. (INCH)	MINI-BORE DELTA (INCH)	PIG LENGTH (INCH)	UNBART (MAX INCH)
UT	16	6		1450	5D		14.96		247.0	
MFL	16	4		2176	3D	0.710	14.90		178.8	8.40
UT	16	4		1233	1.5D	0.925			168.0	
MFL	16	4		1740	1.5D	0.750	12.00		62.0	
MFL	16	4		2000	1.5D	0.750	14.40		40.0	
MFL	16	2		2000	1.5D	0.844	14.00		70.0	
MFL	18	4		1500	1.5D	0.500	16.79		128.3	
MFL	18	6		1500	3D	0.500	16.20		173.0	
MFL	18	2		1300	1.5D	0.790	15.59		72.8	
GPS	18	2		2200	1.5D				141.6	
MFL	18	2	400	2200	3D	0.660	16.00		104.4	
MFL	18	5		2176	3D		16.35		221.4	10.80
UT	18	4		1740	1.5D	0.870	15.36		177.0	
MFL	18	4		2176	1.5D	0.630	16.74		175.7	10.80
UT	18	4		1233	1.5D	0.925			168.0	
MFL	18	4		1740	1.5D	0.750	13.50		62.0	
MFL	18	1		2000	1.5D	0.750	16.20		40.0	
MFL	20	3	550		3D	0.625	17.60		100.0	
MFL	20	3	550		3D	0.625	17.60		115.0	
MFL	20	4		1500	1.5D	0.500	18.64		145.3	
MFL	20	1		1300	1.5D	1.000	17.52		49.2	
GPS	20	2		2200	1.5D				114.0	
MFL	20	2	400	2200	3D	0.660	18.60		123.6	
MFL	20	4		2176	3D		18.71	12.00	215.4	
UT	20	4		1740	1.5D	0.870	16.93		177.0	
UT	20	5		1450	3D		18.50		230.0	
MFL	20	3		2176	3D	0.820	18.71		160.8	12.00
UT	20	4		1233	1.5D	0.925			168.0	
MFL	20	4		1740	1.5D	0.750	15.00		65.0	
MFL	20	3		1232	3D	0.551	17.00		106.3	
UT	20	3		1232	2D	1.180	17.00		124.0	
MFL	20	1		2000	1.5D	1.000	18.00		50.0	
MFL	22	3			3D	1.000	18.50		47.0	
MFL	22	4		1500	1.5D	0.500	20.53		146.0	
MFL	22	4		2176	3D		20.51	13.20	215.8	
MFL	22	3		2176	1.5D	0.710	20.51		156.0	13.20
UT	22	4		1233	1.5D	0.925			168.0	
MFL	22	4		1740	1.5D	0.750	16.50		65.0	
MFL	22	3			3D	1.000	18.50		47.0	
MFL	22	1		2000	1.5D	1.000	19.80		50.0	
MFL	22/24	3	500		3D	0.500	20.74		129.0	
MFL	22/24	3	500		3D	0.500	20.74		144.0	
MFL	24	3	450		1.5D	0.500	22.10		129.0	
MFL	24	3	450		1.5D	0.500	22.10		144.0	
MFL	24	3	450		1.5D	0.500	22.75		128.0	
MFL	24	3	450		1.5D	0.500	22.75		143.0	
MFL	24	3	450		1.5D	0.750	21.75		122.0	
MFL	24	3	450		1.5D	0.750	21.75		137.0	
MFL	24	3		1500	1.5D	0.500	22.55		111.3	

INSPEC-TION METHOD	PIPE SIZE (INCH)	NO. OF MOD-ULES	MIN P (PSI)	MAX P (PSI)	BEND RADIUS (PIPE DIA)	MAX W.T. (INCH)	MINI-BORE CONT. (INCH)	MINI-BORE DELTA (INCH)	PIG LENGTH (INCH)	UNBART (MAX INCH)
MFL	24	2		1500	3D	0.500	22.55		94.4	
MFL	24	1		1300	1.5D	1.000	22.09		49.2	
GPS	24	2		2200	1.5D				62.4	
MFL	24	2	400	2200	3D	0.660	22.63		153.6	
MFL	24	3		2176	3D		22.34	14.40	211.9	
UT	24	4		1740	1.5D	0.870	20.47		225.0	
UT	24	4		1450	3D		22.05		217.0	
MFL	24	3		3191	1.5D	1.220	22.34		172.2	14.40
UT	24	3		1740	3D	0.787			169.3	
UT	24	3		1740	3D	1.970			153.5	
UT	24	3		1233	1.5D	0.925			204.0	
MFL	24	4		1740	1.5D	0.750	18.00		68.0	
MFL	24	3			3D	1.000	20.50		47.0	
MFL	24	3		1232	3D	0.551	20.40		101.6	
MFL	24	1		2000	1.5D	1.000	21.60		60.0	
MFL	26	2		1500	3D	0.500	23.40		97.0	
MFL	26	2		1500	1.5D	0.500	23.40		92.3	
GPS	26	2		2200	1.5D				62.4	
MFL	26	2	400	2200	3D	0.660	24.20		153.6	
MFL	26	3		2176	3D		23.97	15.60	211.9	
UT	26	4		1740	1.5D	0.870	22.05		225.0	
UT	26	4		1450	3D		23.62		217.0	
MFL	26	3		3191	1.5D	1.060	23.97		173.2	15.60
UT	26	3		1233	1.5D	0.925			204.0	
MFL	26	4		1740	1.5D	0.750	19.50		68.0	
MFL	26	3			3D	1.000	22.50		47.0	
MFL	28	2		1500	1.5D	0.500	26.28		110.3	
GPS	28	2		2200	1.5D				82.8	
MFL	28	2	400	2200	3D	0.660	26.63		153.6	
MFL	28	3		2176	3D		26.03	16.80	222.8	
UT	28	4		1450	1.5D	0.870	23.82		252.0	
UT	28	4		1450	3D		25.98		248.0	
MFL	28	3		3191	1.5D	0.830	25.86		180.7	16.80
UT	28	3		1740	1.5D	1.970			173.2	
UT	28	3		1233	1.5D	0.925			204.0	
MFL	28	4		1740	1.5D	1.000	21.00		110.0	
MFL	28	3			3D	1.000	24.50		47.0	
MFL	30	3	400		1.5D	0.625	28.50		138.0	
MFL	30	3	400		1.5D	0.625	28.50		153.0	
MFL	30	4	400		1.5D	0.625	28.50		171.0	
MFL	30	4	400		1.5D	0.625	28.50		195.0	
MFL	30	2		2000	1.5D	0.500	27.50		121.0	
MFL	30	2		1500	1.5D	0.500	27.00		110.3	
GPS	30	2		2200	1.5D				82.8	
MFL	30	2	400	2200	3D	0.660	28.74		162.0	
MFL	30	3		2176	3D		28.03	18.00	222.8	
UT	30	3		1450	1.5D	0.870	25.59		217.0	
UT	30	4		1450	5D		26.77		248.0	
MFL	30	3		3191	1.5D	0.710	27.67		180.7	18.00

INSPEC-TION METHOD	PIPE SIZE (INCH)	NO. OF MOD-ULES	MIN P (PSI)	MAX P (PSI)	BEND RADIUS (PIPE DIA)	MAX W.T. (INCH)	MINI-BORE CONT. (INCH)	MINI-BORE DELTA (INCH)	PIG LENGTH (INCH)	UNBART (MAX INCH)
UT	30	3		1740	3D	0.787			216.5	
UT	30	3		1233	1.5D	0.925			204.0	
MFL	30	4		1740	1.5D	1.000	22.50		110.0	
MFL	30	3			3D	1.000	26.50		47.0	
MFL	32	3	400		3D	0.750	29.00		133.0	
MFL	32	3	400		3D	0.750	29.00		148.0	
MFL	32	2		1500	1.5D	0.500	28.80		114.9	
GPS	32	2		2200	1.5D				90.0	
UT	32	3		1450	1.5D	0.870	21.17		217.0	
MFL	32	2		3191	3D	1.180	29.58		160.4	19.20
UT	32	3		1233	1.5D	0.925			204.0	
MFL	32	3			3D	1.000	28.50		47.0	
MFL	34	2		1500	1.5D	0.500	30.60		114.9	
GPS	34	2		2200	1.5D				90.0	
MFL	34	2	400	2200	3D	0.660	32.50		165.6	
UT	34	3		1450	1.5D	0.870	29.14		213.0	
UT	34	4		1450	5D		31.10		248.0	
MFL	34	2		3191	3D	1.060	31.39		160.4	20.40
UT	34	3		1233	1.5D	0.925			204.0	
MFL	36	3	400		3D	0.625	34.50		139.0	
MFL	36	3	400		3D	0.625	34.50		154.0	
MFL	36	4	400		3D	0.625	34.50		172.0	
MFL	36	4	400		3D	0.625	34.50		196.0	
MFL	36	2		1500	1.5D	0.500	33.50		122.0	
MFL	36	2		1500	1.5D	0.500	32.40		124.0	
MFL	36	1		1300	1.5D	1.000	33.11		66.9	
GPS	36	2		2200	1.5D				90.0	
MFL	36	2	400	2200	3D	0.660	34.57		169.2	
MFL	36	2	400	2200	3D	1.000	34.57		169.2	
UT	36	3		1450	1.5D	0.870	30.71		213.0	
MFL	36	2		3191	1.5D	1.180	33.20		161.8	21.60
UT	36	3		1233	1.5D	0.925			204.0	
GPS	38	2		2200	1.5D				94.8	
UT	38	3		1305	3D	0.870	32.29		217.0	
MFL	38	2		3191	3D	1.180	35.02		168.6	22.80
UT	38	2		1233	2D	0.925			171.6	
MFL	40	2		3250	1.5D	0.750	37.00		122.0	
UT	40	2		1450	1.5D	0.870	34.06		165.0	
MFL	40	2		3191	3D	1.110	36.80		176.3	24.00
UT	40	2		1233	1.5D	0.925			171.6	
MFL	40	2		1232	3D	0.709	34.60		153.5	
UT	40	2		1232	1.5D	1.180	34.00		170.5	
MFL	42	2		3250	1.5D	1.250	38.65		122.0	
GPS	42	2		2200	1.5D				106.8	
MFL	42	2	400	2200	3D	0.660	40.50		184.8	
UT	42	2		1450	1.5D	0.870	35.83		165.0	
MFL	42	2		3191	3D	1.250	38.85		175.4	25.20
UT	42	2		1233	1.5D	0.925			171.6	
UT	44	2		1450	1.5D	0.870	37.40		165.0	

INSPEC-TION METHOD	PIPE SIZE (INCH)	NO. OF MOD-ULES	MIN P (PSI)	MAX P (PSI)	BEND RADIUS (PIPE DIA)	MAX W.T. (INCH)	MINI - BORE CONT. (INCH)	MINI - BORE DELTA (INCH)	PIG LENGTH (INCH)	UNBAR T (MAX INCH)
UT	44	2		1233	1.5D	0.925			171.6	
UT	46	2		1450	1.5D	0.870	39.18		165.0	
UT	46	2		1233	1.5D	0.925			186.0	
MFL	48	2		2000	3D	0.660	44.65		113.0	
GPS	48	2		2200	1.5D				134.4	
UT	48	2		1450	1.5D	0.870	40.95		165.0	
MFL	48	2		3191	3D	1.830	44.35		179.5	28.80
UT	48	2		1233	1.5D	0.925			186.0	
UT	52	2		1450	1.5D	0.870	44.29		165.0	
MFL	56	2		3191	3D	0.890	52.81		218.4	33.60

4.2 List of Companies Surveyed

BJ Process and Pipeline Services

Baker Petrolite Corporation

A. Hak Industrial Services bv

NDT Systems & Services AG

NGKS Pipeline International Corp

3P Services GmbH & Co., KG

PII Pipeline Solutions (GE Power Systems)

Positive Projects (USA) Inc. (GE Power Systems)

Tuboscope Pipeline Services (Varco International)

Diascan Technical Diagnostics Center

5. ROBOTIC CONCEPTS

A robot, for the purposes of this report, is defined as a machine that is capable of performing useful functions inside a pipeline, either connected to the outside by a tether or free-swimming, carrying all necessary power and "intelligence" onboard. Robots that will be presented here would move through the pipeline supported by wheels, tracks, or both. Their position in the pipeline is independent of the flow of the transported medium in the pipeline. To that extent, smart pigs that have fluid bypass to allow them to move slower than the gas flow meet our definition for a robot.

Most of the descriptive data for the following robotic devices has come from the web sites of the developers or providers of the devices. Requests have been made for permission to use the descriptive data (including photographs) from those web sites.

5.1 Internal Pipeline Vehicles

This section of the report will discuss different robotic concepts that are under development for use in pipelines.

5.1.1 Sandia National Laboratories

Personal contact was made with an investigator in the robotics group at Sandia. This group has developed a concept that is a group of connected modules that can be configured like a spring and can conform to differing pipe diameters. The prototype, now in the third generation, has powered wheels on the modules to move the device in the pipe. The modules can contain inspection devices. An artist's rendition of the prototype may be found in a DOE report entitled "Sensor Developed for IPP Robotic Vehicle" (Mark Garrett/Michael Hassard). The report can be found at http://www.netl.doe.gov/publications/proceedings/02/naturalgas/5-1.pdf. Other Sandia robotics work can be seen at http://www.sandia.gov/isrc/Roboticvehicles.html. An article that describes the impetus behind Sandia's interest in pipeline robotics can be found at http://www.sandia.gov/LabNews/LN10-06-00/gas_story.html.

5.1.2 Polytechnic University

Dr. George Vradis of Polytechnic University was also contacted. He is a technical consultant involved in two projects, each entailing a robotic approach for internal inspection. The first is the Tigre project, which is similar to the Explorer device, an untethered, articulated. in-bore device that is self-propelled and carries a video module to monitor pipe condition. The Explorer was designed to work in 6- and 8-inch-diameter pipe, negotiate 90-degree turns and elevations, and includes a wireless communication capability. The Tigre is a larger scale device designed to work in 18-inch-diameter pipe. It is battery-powered. The goal is to have a 5-mile range. Sensor development is being done by PII Pipeline Solutions (GE Power Systems). The Explorer is described in a presentation by Dr. Vradis at NETL's Gas Infrastructure forum. See http://www.netl.doe.gov/publications/proceedings/02/naturalgas/5-2.pdf. This Explorer should not be confused with the PipeExplorer™, developed by Science & Engineering Associates, Inc. and described in a technical paper by staff members of SEA and found at http://216.239.57.100/

search?q=cache:_4iT7f2MYpgC:www.cemp.doe.gov/tech/pipe.pdf+piping+crawlers&hl=en&ie=UTF-8.

5.1.3 Foster-Miller, Inc., Pipe Mouse

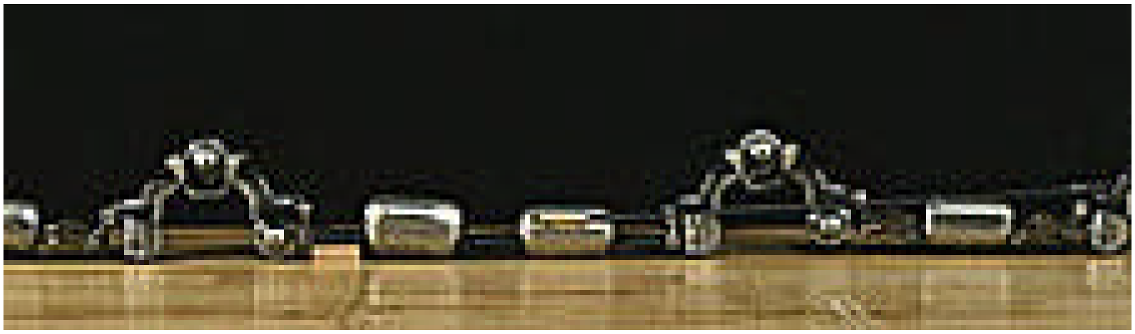


Figure 7. Foster-Miller, Inc., Pipe Mouse

Dr. Vradis is also involved with a second-generation Pipe Mouse, as shown in Figure 7. Foster-Miller, Inc., developed the first Pipe Mouse with funding from the Gas Research Institute. Foster-Miller describes the device as "the innovative marriage of a highly adaptable/ flexible robotic platform with advanced sensor technologies operating as an autonomous inspection system in a live natural gas environment." The Pipe Mouse is a robotic platform with front and rear drive cars to move the device in the forward and reverse directions inside the pipeline. The Pipe Mouse is a train-like robotic platform. The platform includes additional cars for various purposes including sensor modules, power supplies, data components, and onboard electronics. The system includes launching and retrieval stations similar to those used for conventional pipe inspection cameras. It has the ability to travel up to 2000 feet from the entry point; steer down a branch line of pipe tees and crosses; negotiate 90-degree 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. The first Pipe Mouse was designed for small-diameter distribution pipe, whereas the next generation Pipe Mouse will be designed to work in larger (18- to 24-inch) pipeline.

The following description is adapted from the Foster Miller web site at http://www.foster-miller.com/ees_pipmse.htm.

The inspection of gas transmission mains requires the innovative marriage of a highly adaptable/flexible robotic platform with advanced sensor technologies operating as an autonomous inspection system in a live natural gas environment. Working with New York Gas and the Department of Energy, Foster-Miller has developed and is using a unique robotic system called Pipe Mouse to meet the demanding requirements of gas pipe inspection. Their approach involves the integration of advanced modular technologies to construct a robotic system that has the flexibility to adapt to changes in gas piping.

The Pipe Mouse is a robotic platform that is train-like in nature and travels through pipes 3.5 to 6.5 inches in diameter. Both front and rear drive cars propel the train forwards and backwards 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, system power supply, data acquisition/storage components, location/position devices, and onboard microprocessors/electronics.

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 those used for conventional pipe inspection cameras, while the Pipe Mouse enables inspection through multiple turns and long distances (up to 2,000 feet) that cannot be achieved with conventional pipe snake-mounted cameras.

The Pipe Mouse was built to a strict set of performance criteria appropriate for low-pressure gas distribution networks. It was designed to be highly mobile and agile. Consequently, it has the ability to travel long distances from the entry point; steer down branch lines of pipe tees and crosses; negotiate mitered (90-degree) elbows; navigate in both the horizontal and vertical planes; pass through partial section valves, and adapt, by a factor of two, to change in pipe diameter.

5.1.4 SRI International's MAGPIE

Figure 8. SRI "MAGPIE" pipeline inspection vehicle

SRI International has developed the "Magnetically Attached General Purpose Inspection Engine (MAGPIE), shown in Figure 8, to inspect natural-gas pipelines for corrosion and leakage. Magnetic wheels enable the robot to travel on the top and sides of pipes and to navigate obstacles such as T-joints, vertical climbs, and sleeve joints. With self-contained battery power, the vehicle sends control signals and pipeline images to the outside of the pipeline through a fiber-optic cable.

A patent has been issued for the robot's wheels, and other patents are pending.

Other details can be found at http://www.erg.sri.com/automation/robots.html, from which this description was derived.

5.1.5 RTD Pipeline Inspection Tool (PIT)

Figure 9. RTD Pipeline Inspection Tool (PIT) lowered into offshore riser pipe

Roentgen Technische Dienst bv has offered tethered tools, such as that shown in Figure 9, for internal pipeline inspection for many years. The tools, described at http://www.-rtd.nl/en/diensten/10303.html, are self-propelled devices offered primarily for inspection of pipelines that connect offshore production facilities with onshore installations. Significant inspection distances can be accommodated (up to 17,000 m) in pipe sizes from 6 to 56 inches. The primary inspection method is ultrasonics.

5.1.6 ROVVER Crawlers from Envirosight, Inc.

Figure 10. ROVVER tethered crawler adapted for horizontal pipelines

Information gathered from http://www.envirosight.com/products/crawlers.html.

ROVVER crawlers use a modular design in which the camera, control unit, cable reel, and lighting interchange on three models, allowing an operator to adapt to lines 4 to 60 inches in diameter. ROVVERs provide viewing in a horizontal pipeline using a pan-and-tilt or forward-viewing color video camera. These cameras have remotely adjustable focus, ensuring a clear view at all times.

5.1.7 Fraunhofer Institute for Autonomous Intelligent Systems (AIS)

Information gathered from http://ais.gmd.de/index.en.html

Fraunhofer AIS is a leading center of development of knowledge computing and autonomous robots. They have created several robots, like that shown in Figure 11, that could have direct application to inspection inside pipelines.

Figure 11. MAKRO internal device for sewer pipe inspection

MAKRO is a joint project funded by the German Ministry of Education, Research, and Technology. Partners in this effort are Rhenag Rheinische Energie Aktiengesellschaft, Köln (coordinator), FZI, Karlsruhe, GMD–National Research Center for Information Technology, Sankt Augustin, and Inspector Systems Rainer Hitzel GmbH, Rödermark.

The system developers point out that the current state of the art in sewer inspection is to:

- Run tele-operated video platforms through the pipes
- Store the video-data
- Evaluate it off-line or during the tele-operation.

They explain that the area of the sewer system to be inspected has to be bypassed or shut off and cleaned. The inspection itself must be done in relatively small stages of up to about 200 m, as the video platforms are unable to follow all but the mildest bends, and the operator must be concerned with the friction between the cable and the inside surface of the pipe. In summary, it is noted that the whole inspection procedure is suboptimal, lengthy, and hence costly.

In this joint BMBF-funded project, AIS was developing a prototype untethered multisegment robot platform, as shown in Figure 12. Its purpose was to operate autonomously in sewer pipes that are inaccessible for humans. The planned prototype was for pipes 300 to 600 mm in diameter.

Figure 12. AIS multisection snake robot

Additionally, the AIS Biomimetic Autonomous Robots team describes two snake robots, Snake 1 and Snake 2. Information can be obtained from the AIS website: http://www.ais.-fhg.de/BAR/snake2.htm. The following description is from that site.

The goal of this effort was to imitate the movement of a living snake as closely as possible. The movement of a real snake is very flexible as it can be adapted to various environments. The developers point out that snakes are able to move on rough surfaces, they cross obstacles, and they can creep into areas that are very difficult to reach with any other kind of movement. This means a snake-like robot with such properties would be an ideal inspection system (e.g., for tight tubes).

In 1996, AIS built their first snake-like robot, Snake 1. Based on the experiences gained from Snake 1, they began to build the first prototype of a new robot, Snake 2, in 1998. The new robot was more than 10 times faster than the original. The following detailed description is taken from the AIS web site.

The newly developed Snake 2 includes the following capabilities

- Up to 15 sections can be mounted together to form the snake robot.
- Three motors within each section adjust the universal joint, which connects two adjacent sections.
- Each section has six infrared distance sensors, three torque sensors, one tilt sensor, and two angle sensors to measure the joint's position.
- A video camera in the head of the snake sends pictures to a remote monitor.
- Ultrasonic sensors at the head of the snake are used to detect obstacles
- A special tail element with batteries can also be attached to the snake.
- The snake will be able to work in a fully autonomous mode for up to 30 minutes.

In future applications, it is anticipated that the video camera link will be extended to serve as a means for supervised autonomous operation modes. This operational scenario will require an operator monitoring the pictures on a screen and directing the robot to zoom in on interesting objects.

The first Snake 2 system consisted of a head, five sections, and a tail element. The complete control of the complex kinematics is distributed in the snake robot in the same way as in biological systems. In each section, a 16-bit microcontroller controls the motors and reads and processes sensor data. The microcontroller in the head element plans and supervises all actions of the robot. The controllers communicate via a serial bus. The execution of a complex task results from coordinated activities of many different snake components that are working asynchronously.

To teach the snake robot planar motion, AIS also developed a modeling and simulation tool, MOSES. The technical specification for the five-section snake includes the following:

1. Weight: head 0.8 kg, tail 1.75 kg, body section 1.5 kg, total 10 kg
2. Size: length 0.9 m, diameter 0.18 m
3. Power consumption: electronics 20W, motion 25W, lift of head plus two sections 40W

5.1.8 NDT International Magnetic Crawlers

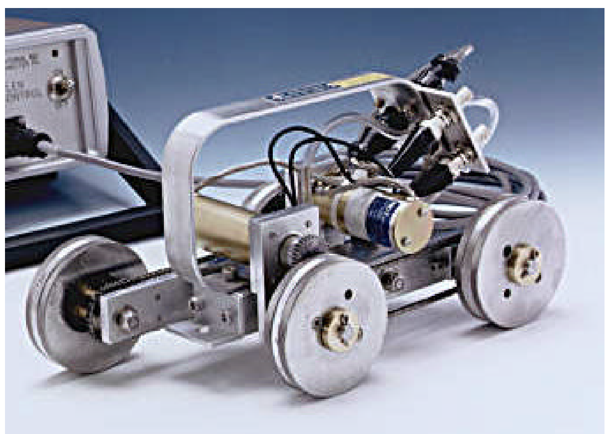


Figure 13. Magnetic-wheeled steerable crawler for piping and tanks

Description taken from http://www.ndtint.com/crawl.htm.

NDT International, Inc. has developed an inspection system that offers:

- A magnetic-wheeled crawler
- A complete, portable, AC-powered inspection and data-recording system
- Ultrasonic thickness measurement of steel storage tanks, piping, and other steel structures not easily accessible by normal methods
- Two 12-VDC gear motors
- A spring-loaded ultrasonic transducer and water line.

5.1.9 De Montfort University (UK) and MSTU-STANKIN (Russia)

Description from http://ttc.stankin.ru/repair.html.

The inspection and maintenance of underground pipelines in urban environments is a major issue for developed countries where refurbishing water and sewage networks alone runs into millions of dollars. Noninvasive and environmentally friendly techniques are in urgent demand. This multinational group is investigating the use of mobile robots in underground pipelines (e.g., water supply pipes, sewerage, etc.) to carry out essential inspection, repairs, and maintenance work. Current generation robots used for this work are remotely controlled systems where a human operator sends commands through long umbilical cables linked to the robot. Feedback is provided from an onboard camera and displayed on a TV monitor.

The ongoing project's aims are to develop new techniques, systems, and application trials for highly intelligent sensor-oriented robotic inspection and repair of pipelines in severe environmental conditions. The main objectives are as follows:

1. To develop specific sensor-based control systems in mobile robotics for pipeline inspection and repair.
2. To develop sensory systems for mobile robots operating in underground pipelines with sensor-based autonomous and remote control regimes.
3. To build a demonstrator of a mobile robotic system, integrating the new noninvasive sensory techniques, the reactive control system, and responsive operator interfaces developed.
4. To conduct application trials based on pipeline inspection and repair scenarios in extreme environmental conditions.

The deliverables for this effort include:

1. A new generation of advanced mobile robotic system for inspection, repair, and testing of pipeline environments.
2. Prototypes and technology demonstrators of mobile robotic systems.
3. Documented application trials and case study examples for the techniques and systems developed in pipeline inspection, testing, and repair.

5.1.10 Inuktun Services, Ltd,. MiniTrac and MicroTrac

Figure 14. MicroTrac and MiniTrac from Inuktun Services Ltd.

See http://www.inuktun.com/products/parts/parts.asp?categoryid=17

Inuktun Services Ltd. is a designer and manufacturer of modular, remotely operated systems and components, like those shown in Figure 14, for use in confined spaces, underwater, and hazardous environments. The characteristics of MiniTrac Transporter Modules are:

- Self-contained, powerful crawler units.
- Depth rated to 30 m/100 ft.
- Pair of MiniTracs can easily carry in excess of 90 kg/200 lbs.
- Can pull up to 450 m/1500 ft of tether cable.
- Can operate at speeds of 9 m/30 ft per minute.

The MicroTrac Transporter Modules are smaller versions of the MiniTracs. These MicroTrac crawlers:

- Are suited for operation in confined spaces and hazardous environments.
- Can carry in excess of 8 kg/20 lbs.
- Can pull up to 90 m/300 ft of tether.
- Can operate at speeds of up to 9 m/30 ft per minute.

5.1.11 ASI Group Tethered Tunnel Inspections

From http://www.asi-group.com/tunnelinspections.html.

Tunnel and Pipeline Inspections

The Canada-based ASI Group pioneered the use of specialized remotely operated vehicles (ROV) for inspection of long water conveyance tunnels. The ASI Mantaro, a long tunnel inspection ROV, is tethered by a 33,000-foot umbilical cable that transmits sonar and video data realtime to the surface via fiber optic telemetry. ASI Group has completed continuous surveys of 6.2 miles from a single access point using this extreme length robotic system. Recent inspections include a 72-mile water supply tunnel in Finland and a 5.8-mile tailrace tunnel in New Zealand.

Dewatering poses identifiable risks in water conveyance tunnels that are affected by the reversal of significant hydrostatic pressure that can lead to structural instability. Remote inspection technology eliminates structural and human risk, while reducing the cost of spillage and lost revenue incurred during lengthy shutdowns.

ROV data collection technology provides the capability of accurate dimensioning of voids or debris fields in these confined spaces. Clients have also applied this remote technology prior to dewatering to make informed decisions regarding outage scheduling and remediation strategies that minimize downtime. ASI Group's fleet also includes ROVs for small pipeline and open water survey inspections:

- Civil Engineering inspections using various unmanned robotic vehicles for tunnels, pipelines, and open water.
- ROV Fleet includes vehicles for tracked inspection systems up to 2,220 ft./ 700 m, medium-sized conduits up to 5,000 ft./1,500 m, and long tunnels up to 33,000 ft./10 km.

5.1.12 Visual Robotic Welding

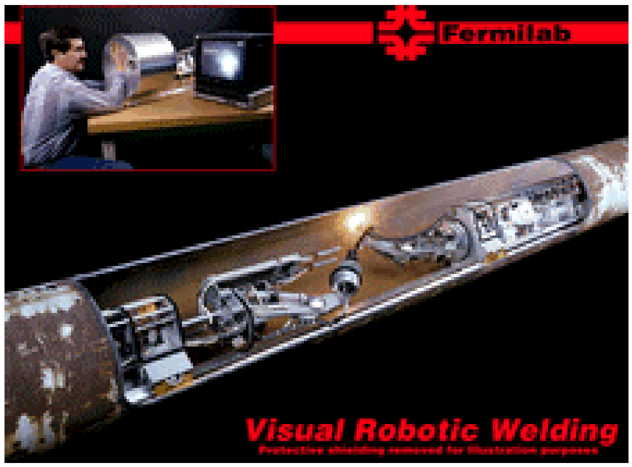


Figure 15. Remote welding system for internal pipeline repair

See http://viworld.com/kendziora/vrw.htm.

The Visual Robotic Welding (VRW) process, shown in Figure 15, was developed to allow welding to be done in areas inaccessible to a human and where automated welding is not possible because of unknown or changing weld conditions. Although VRW was designed for remote internal pipe repair, the technique could be adapted to other situations. One example would be inspection of unpiggable portions of a pipeline. VRW presently travels through a pipe by means of motorized winches located at each end of the pipe under repair. The current prototype is sized to repair pipes from 12 to 24 inches in diameter, but the basic design can be adapted to larger or smaller sizes.

5.1.13 Hirose & Yoneda Robotics Laboratory Snake Robots

See http://mozu.mes.titech.ac.jp/.

Often during natural disasters such as earthquakes, people are trapped in broken buildings and must be rescued immediately. It is very difficult and dangerous to creep into the debris to find victims. So it is desirable to develop a machine that can maneuver in this environment in order to find these victims by TV camera and microphone.

Souryu Tracked Snake

Figure 16. Robotic snake with tapered tracks for use inside pipes

Hirose & Yoneda Robotics (H&YR) developed the Souryu I Tracked Snake, shown in Figure 16, for this purpose. The Souryu:

- Consists of three segments—front body, center body, and rear body.
- Has each body equipped with a crawler on each side.
- Has a front body that includes a CCD camera and a microphone to find victims.
- Has a center body that includes the driving actuators and batteries.
- Has a rear body that includes the radio receiver.
- Is a self-contained system and tele-operated by a remote operator.
- Is driven all at once by the motor of the center body via torque tubes connected by a universal joint that makes motion to move forward and back.
- Has front and rear bodies connected to the center body by special two-dimensional joint mechanisms.
- Has posture changed symmetrically around the yaw and the pitch axis by two motors of the center body.
- Has only 3 degrees of freedom but can change posture to fit the terrain, and can execute roll-over motion.

The Souryu II is a practical model. It is designed so that the three segments could be separated easily to make it portable and to make it possible to add segments with special functions. Souryu II is exhibited at the “National Museum of Emerging Science and Innovation” in Japan.

Slim Slime Robot

Figure 17. Tethered snake from H&YR Laboratory

The Slim Slime Robot, shown in Figure 17, is an Active Cord Mechanism (ACM) with three-dimensional workspace composed of serially connected modules driven by pneumatic actuators. The Slim Slime Robot:

- Was developed for application to operations dangerous to man—specifically, in-pipe inspection at chemical or nuclear energy plants and rescue of victims under collapsed houses by making use of its shape, and mine detection by distributing its own weight, and so on.
- Has a main tube and three flexible pneumatic actuators, bellows, and compressed air is introduced into each bellows from the main tube through an inlet valve built in the bellows.
- Has inlet and outlet valves built in each bellows to make the bellows stretch, shrink, and lock its length; therefore, the module can stretch and bend in any direction actively.
- Can exhibit the locomotion modalities of: creep motion of snake, pedal waves of snail and limpet, lateral rolling, and pivot turn.
- Has six modules with a total length from 1120 to 730 mm, a total mass of 12 kg, and a maximum speed of about 60mm/sec.

H&YR Snake Robot Design Considerations

H&YR had two motives for beginning biomechanical research on the movement of snakes. The first motive was that, up until that time, the fundamental problem of "How is it that a snake can go forward without legs?" largely remained unanswered, and this required an engineering analysis. The second motive grew from the expectation that a "snake-like robot," which would be modeled on a snake, would have a particularly broad functionality while maintaining a simple shape. The future possibilities of serpent robots can be anticipated from the fact http://www-robot.mes.titech.ac.jp/research/snake/bio/bio_page.html that the body of a snake, which has the simple form of a rope, functions as "legs" when moving, as "arms" when traversing branches, and as "fingers" when grasping something.

When beginning this research, in order to explain the dynamics of the creeping propulsion movement of snakes on level ground, a basic motion equation for this was derived, and numerous running experiments were conducted using striped snakes. The conditions for moving on level ground were investigated by rigging an electro-muscular meter and a normal force meter on the torso of the snake. From these experiments, it was found that:

1. The waveform that the snake assumes during creeping movement is a curve which changes sinusoidally along the curvature of the body, and we made a formula for this, calling it a serpenoid curve.
2. The action by which one part of the body floats up during advancement, called sinus-lifting, can be interpreted as an action which concentrates the body weight on the part that can most easily slip, and this functions to prevent slippage.
3. A variety of positions can be considered for the propulsion motion, and this was also experimentally verified.

5.1.14 Carnegie Mellon University Robots

Figure 18. Various forms of snake robots from Carnegie Mellon University

From http://voronoi.sbp.ri.cmu.edu/projects/modsnake/modsnake.html.

The following is copied verbatim from the Carnegie Mellon University (CMU) web site, with permission. Examples of their robots are shown in Figure 18.

The work at CMU considers two issues: serpentine robot locomotion and modularity. Biological snakes move by different cyclic forms of locomotion, termed gaits. Adapting these gaits for mechanical snakes, the goal is to enable serpentine robots to maneuver through three-dimensional terrains. Since the specific snake robot we are studying is modular, there is an opportunity to examine the benefits and drawbacks of such a design. One goal is to establish a conversation that measures the tradeoffs between modular and nonmodular designs, citing examples and situations to weigh the options.

Gaits

Biological snakes have the widest variety of gaits in the animal kingdom. To provide locomotion for robotic snakes, CMU modeled gaits found in nature, designed easy-to-control gaits, and adapted them both to our mechanisms. Below are descriptions of various gaits CMU has developed and are working on.

Sinusoidal Motion. In sinusoidal motion, the basic waveform that causes motion by propagating down the length of the snake is a sine wave. In order for the snake to be stable, at least two periods must be present in the snake at all times to establish at least two contact points. The amplitude governs how high an obstacle the snake can move over; however, this motion was not designed to take on obstacles, only flat terrain.

Sinusoidal motion works by using the links touching the ground as a base to move the other links up and forward. The speed of the robot's forward motion is dictated by the speed of the servos, the speed at which the wave propagates, and to a certain extent the amplitude of the wave. Higher amplitudes are the equivalent of larger steps; smaller amplitudes are smaller steps. The speed at which the wave propagates through the robot also controls the speed the robot moves forward. All this has an upper bound dictated by how fast the slowest servo can achieve its angles.

Rolling. A gait definitely not found in biological snakes, rolling can best be described as turning the snake into a loop by connecting the front and back portions and allowing the loop to roll across the floor like a wheel.

To implement rolling, CMU arranged to give the servos the angles that will create a loop shape. These joint angles are actually describing exactly one period of a wave that, when propagated down the robot in time, produces motion. Propagating the wave backwards will, of course, produce motion in the opposite direction.

The loop is not perfectly round so that it can provide a stable base for the robot. This flattened loop also makes the wave easier to program, since the servos not in the forward and rear "bent" parts are simply programmed to the middle of their motion, making a straight line.

The speed of the motion is somewhat dictated by the speed of the servos. Because they are designed to respond to joint angles only, servo speeds cannot be controlled. However, CMU has control over the speed of propagation of the joint angles through the robot. This means that there is an upper limit to the speed (dictated by the speed of the servos), and all speeds slower become increasingly step-like. When moving very slowly, the robot can demonstrate how the individual servos' movements come into play, and how each servo takes on its new signal can be observed.

Concertina Motion. Concertina motion is achieved by alternately coiling up, elongating in front of the coil, then bringing the rear of the snake forward into a coil again. An actual snake using concertina motion can make use of the ground, vertical walls, or even a tunnel ceiling to move forward; CMU's robotic snake will use vertical walls or the ceiling and floor of a tunnel.

CMU initially attempted to achieve concertina locomotion experimentally in three phases. Phase 1 established the initial wedge of the rear of the robot. Phase 2 established a wedge of the front of the robot. Phase 3 was the elongation and coiling up of the robot when part of it is wedged. Putting the three phases together and working out the timing issues would have completed the project. The surface used currently is plywood, and wedging happens between two vertical boards held in place over the plywood. The course is adjustable.

However, problems arose in Phase 2. It is basically a problem of flexibility. The motors being used, servos, always try to reach and remain at some angle—they cannot be told to "relax." As a result, they will always attempt to reach some angle, the default being the middle of their motion, which in our case straightens out the joint. With concertina motion, the basic difficulty is a conflict of interests between the wedging and nonwedging servos. Using the stability of the wedged rear part of the snake, in Phase 2, the front half stretches out and wedges itself—making both the front and rear of the snake wedged for a brief time while the middle is stretched between them. That is when the problem occurs.

When the front stretches out to wedge itself, irregularities and surface variation cause the stretched out part to end up in a slightly different position each time; the surface the snake is traveling across is not perfect. In addition, variations in the surfaces the snake is wedging against, both the rear and the front, cause the resulting position to be different each time the snake wedges, elongates, and wedges again. There is no way, right now, to recalibrate the robot's position between the vertical walls, due to the servos' inability to turn off and the fact that there is no feedback. So if the robot does not manage to find itself in the exact position the programmed angles predict, either due to nonuniform friction or irregularities in the surfaces of the course, the servos in the middle get overloaded with the torque from the two wedged parts. When this happens, plastic gears get stripped, output arms break, and general mechanical failure ensues.

During the Spring semester 2002, CMU tabled further development of concertina motion until Summer 2002 when the semester is over. Potential fixes include things as minor as inserting a flexible passive joint with resistance lower than the servos but not enough freedom to inhibit motion, or slightly more invasive procedures such as adding a switch to each servo so we can turn them off at will (causing them to act like the passive joint described above), or a major overhaul like replacing the motors with motors that have behavior more like what is wanted. This is, of course, without adding feedback. Feedback would change the problem from a mechanical/electrical issue to a controls issue.

Stairs

The initial attempt at moving up stairs was a simple "end over end" gait, best described as a modified slinky gait—with just eight modules, using the first four as a stable base, lifting up the remaining four over and onto the stair above, then coordinating the movements of the snake on the bottom stair and the snake on the top stair to push the rest onto the top stair, then starting over.

The problem with that method of climbing stairs is that with just eight modules, it was not long enough to provide a stable enough base to support the rest of the snake as it looped over itself. So CMU attempted the same type of movement with 12 modules and found that the snake did not have the necessary torque to support this type of movement.

The next attempt was a modified sinusoidal gait up the stairs. CMU took our standard sinusoidal pattern and added a slope dependent on the height and depth of the stairs. In order to facilitate programming and also be able to adapt it to any staircase, CMU wrote a program that, for a given height and depth of stairs, would find the joint angles needed by the snake to make that curve.

5.1.15 Dr. Gavin Miller's Snake Robots

From http://www.snakerobots.com/main.htm.

Dr. Gavin Miller has done development work with snake robots for several years.

This site describes his own snake robots as well as giving links to important lists of other snake robot research projects. The robots shown below in Figures 18 through 21 were created as part of his private research project into snake locomotion started in 1987. Go to the web site to see more information about each of the prototypes, including video clips in MPEG format.

Requirements for the designs included that they were to be untethered, which meant they had to carry their own computers and batteries. They were to be radio-controlled to avoid the problem of artificial intelligence and sensing. They needed to be simple to drive. The large number of segments had to be controlled using one or two joysticks. The snakes were given the designation S1©,[1] S2©, and so on, in homage to John Harrison's clocks H1, H2, etc.

The snake robots were inspired by his work on physically based computer animation at Alias Research, Inc., and Apple Computer, Inc.

S1© (1992-93)

Figure 19. First version of Gavin Miller's snake

[1] S1, S2, S3, and S5 are all ©1999, Gavin Miller.

Material Basswood

Components: Discrete TTL Control Unit, 14 servos, 16 batteries, 2-channel radio control

S1© was a recreation of earlier work by Shigeo Hirose of H&YR in Japan, in which a single train of deflection travels down the length of the snake. Oscillatory deflections cause the snake to move forward. An offset to the oscillations causes the snake to steer. The wheels on each segment allow the snake to slide along its length while gripping laterally. Novel features include the use of servos of different sizes along the length of the snake to give a more tapered appearance. This feature increases the realism and efficiency of the snake but means that each segment has to be custom designed. Remote control is achieved using a vertical joystick for speed and a horizontal one for steering.

S2© (1994-95)

Figure 20. Second iteration of Gavin Miller's snake

Materials: Plywood and PVC Pipe

This variant on the S1© design reduced the visibility of the wheels and wiring.

S3© (1996-97)

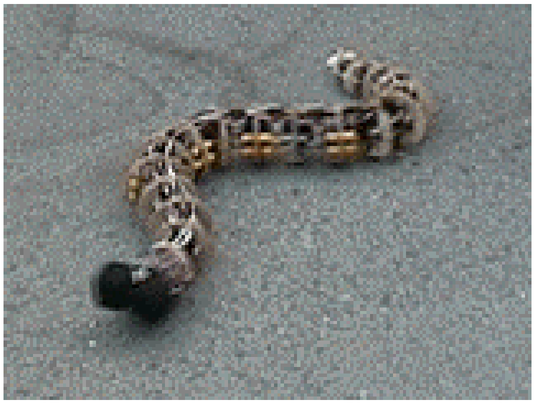


Figure 21. Third iteration of Miller's snake adds more degrees of freedom

Materials: Plywood, brass rod, and plastic

Components: Two Basic Stamp II microprocessors (20 MHz), 35 servos, 5 servo control units, 24 batteries, 4-channel radio control

S3© represented a new design based on the cross section of a real snake. The spinal column along the top is created using a train of universal joints that gives 2 degrees of freedom to each segment. Pairs of servos are used in opposition in a novel arrangement. This enables the snake to undulate vertically as well as horizontally. The goal of this snake was to demonstrate side-winding motion as well as conventional horizontal undulatory progression. A second feature is the use of a single wheel under the middle of each segment, allowing the snake to move along like a train of rollerblades. Steering and speed are controlled using one joystick while a second joystick controls lift and the amount of side-winding. S3© was first shown publicly when it served as the ring-bearer at his wedding on June 19, 1999.

S5© (1998-99)

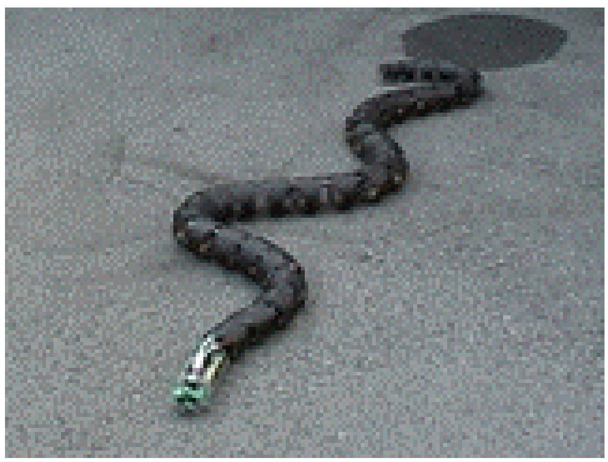


Figure 22. Latest completed version of Miller's snake has more realistic aspect ratio

Materials: Polycarbonate plastic, brass rod, and vinyl cladding

Components: One Basic Stamp II microprocessor (20 MHz), One Scenix Microprocessor (50 MHz), 64 servos, 8 servo control units, 42 batteries, 4-channel radio control

S5© represents a refinement of the S3© design. Parts were created using a numerically controlled milling machine. This allowed for much more accuracy and a smaller cross section. Almost doubling the number of segments allowed a robot that begins to resemble the length-to-width ratio of chubby real snakes. As the snake grows in size, the design starts to place heavier requirements on the wiring and control capability. The Basic Stamp controller drives a second, faster processor that supports four simultaneous serial buses along the length of the snake. Segmented cladding was used to give a more continuous feel to the overall shape.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions and Broad-based Recommendations

Today's smart pigs are meeting the needs for inspection of piggable transmission pipelines. Sensing technologies are available for detection and characterization of metal loss, cracking, dents, and stress anomalies. While the pipeline operators would welcome improvements in the measuring capabilities of those methods, those improvements would not result in a greater number of pipelines seeing ILI use. Expansion of in-line inspection requires changes to the smart-pig vehicle to make it possible to inspect unpiggable transmission pipelines and distribution pipelines.

This study has documented the vehicle characteristics of currently available ILI systems and identified other vehicle types that may have application to pipeline inspection. Our conclusion is that the next generation of ILI systems will be based on current work in robotics. Of particular interest are the biomimetic systems mimicking natural movements, particularly robotic snakes. A snake-like vehicle would have the option of several gaits of movement, including sinusoidal or slithering motion, and also a helical coil configuration to move along the inside pipe surface like an expanded spring. In either case, such a vehicle could negotiate tee connections or pass through plug valves, motion alternatives forever denied to piston-type pigs.

Pipeline inspection with autonomous or semi-autonomous robots would require technology advances in several areas:

(1) The basic vehicle transport system with associated control software.

(2) Power generation in-line to supplant battery power and permit extended run times.

(3) Communication improvements to permit two-way contact with the vehicle while in the line, either continuous or periodic.

(3) Adaptation of successful defect sensing technologies to the robotic platform.

Some work is already under way in each of these areas. There is no coordinated effort (none discovered during this project) to meet all these needs, however. We suggest that the DOT consider funding a coordinated program to address these separate needs in parallel, leading to a new generation of pipeline inspection systems: one that would have utility for both liquid and gas transmission pipelines as well as gas distribution networks. Short of that comprehensive program, the DOT may consider the current program's logical extension, outlined in the following paragraphs.

6.2 Proposed Follow-On Research

The findings of the current project suggest that the most productive autonomous vehicle design to confront the myriad challenges of unpiggable pipelines while offering enhanced capabilities to piggable lines will be a robotic snake. As pointed out in some detail in this report, there are several active programs under way in the USA and elsewhere developing snake-like vehicles. What is missing is the focus on adapting these designs to the task of inspection and monitoring of pipelines. As mentioned above, the needed elements are a power source, a communication system, and sensors.

We recommend and request that the DOT extend and focus the investigation started in this report. We propose a project in which the principals of this project team with a leading robotic design group to address the issues relevant to pipeline inspection with a snake-like robot. As a cursory list of tasks, we offer the following:

1. Document prior attempts to use snake-like robots inside pipes and pipelines. In particular, locate records of such work in which the goal was inspection and monitoring.

2. Working with the robotic design group team member, configure an existing (or new) snake design to deploy NDE sensors inside a simulated transmission/distribution pipeline. This vehicle will be designed as a *tethered* device, acknowledging the fact that autonomous operation is a significant challenge, best handled after the problems of mobility and defect detection have been solved in the tethered case.

3. Develop sensing technology(s) that can be deployed by the robot to provide inspection coverage for the full pipe wall. Consider the findings of the companion SwRI projects involving remote-field eddy currents (RFEC) and magnetostrictive sensing (MsS) to determine if they are candidates for robotic deployment. Demonstrate the validity of the chosen sensor method in laboratory experiments.

4. Demonstrate the use of the tethered snake in the inspection of a piping mockup, which includes, as a minimum, a tee connection, an unbarred branch connection, and a plug valve. Write a comprehensive report of findings and recommendations.

5. Given success in the first three tasks, propose follow-on work to move toward the autonomous vehicle, including development or selection of technologies for power generation and communication. As part of this proposal, identify a pathway to commercialization and a commercializing partner.

The rough budgetary estimate of the cost of these tasks is $500,000 over a project term of 24 to 30 months. If budgetary constraints require a reduced effort, a staged program could be configured for 9- to 12-month phases costing on the order of $200,000 each.

7. FINANCIAL STATUS REPORT

Total project funding of $80,000.00 was provided equally by the Department of Transportation and our cofunding partner, Pipeline Research Council International (PRCI).

DOT funds have been received. Part of the PRCI funding has been received. The balance will be paid by PRCI upon receipt of this final report.

8. BIBLIOGRAPHY

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