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Design, Construction and Demonstration of a Robotic Platform for the Inspection of Unpiggable Pipelines under Live Conditions (#146)

Design, Construction and Testing of a Segmented MFL Sensor for Use in the Inspection of Unpiggable Pipelines (#147)

FINAL REPORT

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Executive Summary

The 2002 Office of Pipeline Safety (OPS) regulations requiring the inspection of all transmission pipelines, including those that are now deemed “unpiggable”, triggered the search for technologies that would make the inspection of unpiggable pipelines possible. With the option of modifying unpiggable pipelines, so that they are rendered piggable, being a prohibitively expensive one in most cases, Direct Assessment and Hydrotesting are at the present time the only technologies available for their assessment. These technologies, while they are playing a role in the overall effort to characterize the pipeline networks, are expensive and cannot provide industry with the comprehensive information that in-line inspection tools can. The use of In-line Inspection (ILI) technologies is the preferred tool among operators because it offers the most comprehensive and accurate means of pipeline inspection.

As a result, in 2001, NYSEARCH initiated an effort to develop ILI technologies for unpiggable pipelines. Following a feasibility study that proved the potential of robotics and sensory technologies to meet the system requirements, a development effort was undertaken in 2004 with cofunding from NYSEARCH, PHMSA/DoT, NETL/DoE and OTD to develop the necessary tools. The Explorer II and TIGRE robotics systems resulted from this effort.

The objective of this project was to develop two robotics platforms, named Explorer II and TIGRE, which equipped with Non Destructive Evaluation (NDE) sensors would be able to provide ILI of unpiggable natural gas transmission pipelines. Explorer II is a tool for the inspection of 6” – 8” pipelines with pressures up to 750 psig, using a Remote Field Eddy Current (RFEC) sensor for NDE inspection of the pipeline’s walls. TIGRE is a tool for the inspection of 20” – 26” pipelines with pressures up to 750 psig, using a Magnetic Flux Leakage (MFL) sensor for NDE inspection of the pipeline’s walls. Both the platforms and the sensors were developed as part of this effort or parallel to this one efforts. Once developed, sensors and platforms were integrated under the auspices of this program and field demonstrated successfully. The Explorer II tool was commercialized at the time that this program ended, while TIGRE required another step in its development effort in order to be completed and commercialized. This additional effort is now under way through a follow up program funded by NYSEARCH/NGA, DoT/PHMSA and OTD.

This program has successfully developed the first ever commercial system for the inspection of unpiggable pipelines able to function in pipelines with or without gas flow and in the presence of major obstacles such as short radius and mitered bends, tees, back to back bends and, in the case of TIGRE, plug valves. It is not an exaggeration to state that the technology developed through this program has created a new industry in the US, its size estimated at 75 million dollar per year.

1. INTRODUCTION

New Office of Pipeline Safety (OPS) regulations that went into effect in 2002 require the inspection of all transmission pipelines in High consequence Areas (HCAs), including those that are now deemed “unpiggable”. Given that a substantial percentage of natural gas transmission pipelines are unpiggable, the use of smart pigs is not an option in these cases. With the option of modifying unpiggable pipelines so they are rendered piggable being a prohibitively expensive one in most cases, Direct Assessment and Hydrotesting are at the present time the only technologies available for their assessment. These technologies, while they are playing and will continue to play a role in the overall effort to characterize these pipeline networks, are expensive and cannot provide utilities with the comprehensive information that in-line inspection can.

The use of In-line Inspection (ILI) technologies is the preferred tool among operators, for it offers the most comprehensive and accurate means of pipeline inspection. However, existing ILI technologies depend on “pigs” for the delivery of the sensory systems into the pipelines. These pigs depend for their propulsion on the flow itself. Therefore in the case of limited pressure/flow such pigs cannot be used. In addition, when obstacles are present in the pipeline (such as plug valves, mitered bends, and back-to-back in or out of plane 90-degree bends) these pigs cannot be used since they cannot negotiate these obstacles. Therefore the need to develop the appropriate platforms for the deployment of Non-Destructive Evaluation (NDE) sensors into such pipelines becomes obvious.

A consortium of natural gas industry and governmental organizations undertook the effort of developing ILI technologies for the inspection of unpiggable pipelines. The effort leading to this program was initiated by NYSEARCH earlier, in 2001, without funding from DoT/PHMSA. A feasibility study was carried out to determine technology gaps and develop potential solutions to the problem of in-line inspection of unpiggable pipelines. Two different teams proposed two different solutions. One of these solutions was selected to move forward. Following a technology assessment of the proposed solutions, it was establishe4d that the concept developed had merit and could form the foundation of a robotics program for inspecting unpiggable pipelines.

NYSEARCH decided to pursue the development of two robotic devices; one to cover the range of 6" – 8" pipelines and one to cover 20" – 26" pipelines. These ranges were selected for two reasons:

a. These two ranges are the most common pipe sizes encountered in the industry (in addition to the 10" – 12" range)
b. These two ranges represent two distinct scenarios that impose different limits on the robotic systems to serve them. The smaller size could allow for an easier and more efficient deployment while facing stringent space availability issues for the mechanical, electronic and sensory components of the system. The larger size could result in a more massive system imposing deployment efficiency issues while providing amble space for mechanical, electrical and sensory systems.

Initial funding for the smaller 6" – 8" robotic platform, named EXPLORER II, was provided by NYSEARCH and the US Department of Energy (USDoE) through the National Energy Technology Laboratory (NETL). The National Robotics Institute at Carnegie Mellon University was selected to develop this platform. The sensor for this system was the focus of a DoT/PHMSA program that explored four different technologies. Following a review of the relative merits of the technologies developed through that program, a Remote Field Eddy Current (RFEC) sensor was selected for integration on Explorer II, designed and built by Southwest Research Institute. Once prototypes of the robotic platform and the RFEC sensor were developed, they were integrated in the present program for integration, lab testing, and field testing.

Following the feasibility study and the technology assessment of the critical technologies involved, funding for the larger 20" – 26" robotic system, named

TIGRE, was provided by NYSEARCH and DoT/PHMSA through this program. Automatika inc., a robotics company out of Pittsburgh, PA, was selected to develop the systems robotic platform, while Invodane Engineering, of Toronto, Canada, was selected to develop the Magnetic Flux Leakage (MFL) sensor. These two parallel efforts (white papers #146 and #147) were part of this integrated program. Once sensor and platform were developed the two were integrated and then tested extensively in the laboratory and in the field.

This report provides an overall description of the Consolidated Program, followed by detailed reports on each system involved.

2. OBJECTIVES

The objectives of this program were to:

- Develop a robotic platform **(TIGRE)** that would allow the inspection of presently unpiggable transmission pipelines in the 20” – 26” range. The platform, based on a locomotor developed for another robotic application (*Explorer;* developed for visual inspection of distribution mains), will be able to propel itself independently of flow conditions, and will be able to negotiate all obstacles encountered in a pipeline, such as mitered bends and plug valves. The robot will be powered by batteries, which will have the capability of being recharged during operation by extracting energy from the gas flow. The operator will have live control of the robot using two-way through-the-pipe wireless communication, thus eliminating the need for any tether.
- Develop a Magnetic Flux Leakage (MFL) sensor, also able to negotiate all pipeline obstacles, for NDE of the pipeline and integration into the TIGRE platform. The sensor will provide performance comparable to that of state-of-the-art smart pigs used by the ILI industry at the present time.
- Integrate the platform and sensor to develop the final system and carry out an extensive laboratory program to ensure proper operation, reliability and performance.
- Carry out field deployments of the system to prove commercial feasibility
- Integrate a robotic platform and RFEC sensor into one system (Explorer II) and carry out an extensive laboratory program to ensure proper operation, reliability and performance.
- Carry out a number of field deployments of the integrated system in live pipelines to prepare the system for commercial deployment.

The deliverables of this program are:

- A fully functioning engineering prototype TIGRE robotic system equipped with an MFL sensor able to operate under live conditions and inspect 20” – 26” unpiggable natural gas transmission pipelines.
- A fully functioning pre-commercial prototype Explorer II robotic system equipped with an RFEC sensor able to operate under live conditions and inspect 6” – 8” unpiggable natural gas transmission pipelines

3. TECHNICAL APPROACH

3.1 Background to present effort

While there are no exact data regarding the number of miles of unpiggable natural gas pipelines in the US, studies indicate that there are well over 100,000 miles of such pipelines in operation at the present time. Of these unpiggable pipelines, about 40% are in High Consequence Areas (HCAs) and cannot comply with the 2002 Gas Pipeline Integrity Ruling issued by PHMSA. The most challenging market is that of pipelines owned by Local Distribution Companies (LDCs) because these pipelines look more like a distribution network rather than a transmission one, in the sense that they contain obstacles and features very common to the distribution network, such a mitered bends, back-to-back bends, and plug valves. These obstacles make the use of current state-of-the-art technology smart pigs either highly impractical or in most cases impossible. In New York State, for which very detailed data is available, there are over 1,600 miles of Local Distribution Company (LDC) owned gas transmission pipelines of which the vast majority are unpiggable. Of these, more than 810 miles are in HCAs, of which also the vast majority 95% are unpiggable. This effort is one focusing on advancing the state-of-the-art in technology to address the most challenging parts of the unpiggable pipeline market, thus **generating a solution able to inspect more than 98% of the entire market** and complying with the 2002 Gas Pipeline Integrity Ruling.

NYSEARCH, the R&D organization within the Northeast Gas Association, formed a working group in early 2001 to assess the impact on its members companies of the then anticipated PHMSA rule regarding the integrity of the country's gas transmission pipeline. The working group was to assess the impact of those upcoming regulations on the operation of the member companies and identify technology gaps that needed to be filled. The working group identified numerous technology gaps and prioritized them. Two major areas were identified in which R&D would be needed. The first was in the field of direct assessment (DA) and the second was in the field of in-line inspection (ILI).

NYSEARCH moved forward by initiating a number of efforts in the DA area, one of which was funded by PHMSA as part of this Consolidated program (a final report for that project was submitted; that project was closed). In parallel, NYSEARCH funded two Technology Assessment studies by two consortia identified through the issuance of a Request For Proposals (RFPs). The two consortia were those of Foster-Miller and PII (FM-PII), and of Automatika Inc. and Maurer Engineering (AI-ME). The scope of these two parallel technology assessments was to identify the technology challenges imposed by the Integrity Ruling, and to identify possible solutions to the problem of inspecting pipelines which are not possible to inspect with present generation "smart pigs". The presence of short radius and mitered bends, plug valves, back-to-back bends and other obstacles make the use of pigs in these pipelines either highly impractical or in many cases impossible. While there was no requirement for these pipelines to be inspected under the old rules, the new rules would necessitate the determination of their integrity. As a result, the issue of inspecting unpiggable pipelines became the focus of these two studies that were commenced in early 2002 and were completed by late 2002. Two different technology options emerged on how to conduct ILI in these unpiggable pipelines. The FM-PII option provided for a robotic platform, based on the Pipe-Mouse robot built in the early 1990s for the natural gas distribution industry that would carry a Magnetic Flux Leakage (MFL) sensor. The platform and sensor would be able to negotiate all pipeline obstacles, would be powered by on-board batteries, and would be communicating with the operator (for control and data transfer) via a fiberoptic tether that provide a link between robot and operator. The AI-ME option provided for a robotic platform, based on the Explorer robot built in the early 2000s for the natural gas distribution industry by Carnegie Mellon University that would carry a Magnetic Flux Leakage (MFL) sensor. The platform and sensor would be able to negotiate all pipeline obstacles, would be powered by on-board batteries, would allow for the in-line recharge of the batteries via an on-board turbine-generator system (if the flow conditions are adequate), and would be communicating with the operator (for control and data transfer) via a wireless link, thus not requiring any tether for operation.

Upon the conclusion of the two technology assessment studies, NYSEARCH reviewed the recommendations and technologies proposed. They found that both options merited further study and initiated the second phase of both studies. The FM-PII effort focused on the preliminary design of a robotic system based on the PipeMouse platform for pipe sizes of 18”-24” and of a sensor system able to negotiate plug valves and mitered bends for this pipe size range. The effort was initiated in February 2003 and was concluded in March 2004.

The outcome of the AI-ME study was for NYSEARCH to initiate two parallel efforts based on the Explorer design. One effort, called TIGRE, would be considered as Phase II of the AI work and would develop a robotic system based on the Explorer platform for pipe sizes 20”-26”. In this second phase, work focused on the viability of the drive system, wireless communications, and on-board turbine based battery recharge systems. This effort would not include the development of an MFL sensor, since such an effort was part of the FM-PII program. This Phase II of this work was initiated in March 2003 and was completed in September 2004.

A second effort that grew out of the AI-ME study, called Explorer II, would be to develop a robotic system based on the Explorer platform for pipe sizes 6” – 8”, the pipe sizes served by the original Explorer system. In this effort the Explorer system would be upgraded to operate at transmission pipeline pressure levels and would be modified to accept a sensor allowing the wall inspection of pipelines. This effort was initiated with NYSEARCH and NETL/DoE cofunding in October 2004 and was completed in March 2007 (at which point the effort was integrated into this consolidated program). The preferred inspection for NYSEARCH would be MFL, however, NETL/DoE preferred to have a new technology developed and integrated into Explorer II. Given that an MFL sensor would require a major redesign of the original Explorer system, adding to risk, cost, and time to market, it was decided that a sensor based on a technology other than MFL be used. Four sensors were identified as potential systems for integration into Explorer II. Two of them were under development though a NETL/DoE program while two were under development through a separate PHMSA program. The two DoE funded sensor development efforts were: (a) a Remote Field Eddy Current (RFEC) sensor by the Gas Technology Institute (GTI); (b) a Guided Waved acoustic sensor by Los Alamos National Laboratory. The two PHMSA-funded sensor development efforts were: (a) a RFEC sensor under development at Southwest Research Institute (SwRI);

(b) a rotating magnet magnetic leakage sensor by Battelle. All these sensors promised to have power requirements substantially lower than MFL sensors, thus simplifying the design as well as operation of the robotic system. During the kickoff meeting of the Explorer II effort at CMU, all four sensor developers were present. It was agreed that all sensors would compete for selection and subsequent integration into the Explorer II platform, following a one year development effort that would be concluded in late 2005 with a detailed design of a sensor system able to get integrated into the Explorer II platform.

The second phases of the Automatika and FM-PII projects concentrated on the preliminary design of these systems and evaluation of the critical technologies involved. These studies were initiated in early 2003. The Automatika effort was funded by NYSEARCH, Southern California Gas Company (then not yet a NYSEARCH member), and OTD. The FM-PII study was cofunded by NYSEARCH and NETL/DoE. The FM-PII study was completed in early 2004, while the Automatika study was concluded in the fall of 2004. The FM-PII study concluded that a PipeMouse based robotic platform, now called RoboScan, is a viable option for carrying out MFL inspections in unpiggable pipelines. The platform would be powered via on-board batteries and would communicate with the operator via a fiberoptic tether. Extensive analysis was carried out to study the reliability and integrity of a tether in a transmission pipeline, in order to address the concerns of the funders on the issue. The study also concluded that while an MFL sensor is a viable option, the burden on the particular platform, in terms of loads and power requirements, would be excessive. In addition, in order for the sensor to negotiate a plug valve, a segmented sensor would have to be built (providing partial coverage of the pipe’s circumference), thus necessitating multiple passes to inspect a certain segment of a pipeline. As a result, FM-PII presented a proposal to NYSEARCH for the adaptation and integration into RoboScan of a Pulsating Eddy Current sensor, under development at GE Laboratories. The sensor was still in the development phase and GE was proposing an aggressive funding and testing program to complete sensor development in two years. The Automatika study concluded that the driver system was adequate for the high loads and power requirements of the system and that the wireless communication offered enough range, particularly at high pipe diameter sizes, not to be the range limiting factor. Adequate battery storage could be provided on the platform; however, given the weight of the batteries, it would become the range-limiting factor. This problem could be solved either by introducing a tethered system (in violation of the specifications developed) or including a turbine-based battery-charging system, a necessity in high flow, i.e. high power consumption, environments. The turbine recharge system was shown to be a viable solution to the power management challenges, potentially providing under high flow conditions enough power to run the robot without depleting the batteries. In a review meeting for both projects, held in September 2004, NYSEARCH analyzed the results of the two studies. It was decided to further fund the development of the TIGRE and Explorer II systems and to discontinue its support for the FM-PII program. The primary reasons for the decision were the untethered operation of the TIGRE system and the desire to field a system based on an MFL sensor, the industry standard, rather than on a new and not yet demonstrated inspection technology (pulsating eddy current). Since the discontinuation of the FM-PII project deprived the overall program of an MFL sensor development effort, NYSEARCH contracted Invodane Engineering to develop a (segmented) MFL sensor module for the TIGRE platform, a sensor that would be able to negotiate mitered bends and plug valves in transmission pipelines. Invodane Engineering is a world leader in developing MFL systems for inspection platforms.

3.2 Initiation of present effort

In late 2004 proposals that had been submitted to PHMSA for funding the development of the TIGRE platform (Automatika; PHMSA WP#146) and sensor (Invodane; PHMSA WP#147) efforts were approved for funding. A Consolidated Program that included these two efforts was created (that also included a DA technology development effort involving guided wave technology). These two projects were initiated in December 2004, with cofunding by PHMSA, NYSEARCH, OTD and PRCI (platform effort only). The sensor effort developed a series of concepts for an MFL sensor module able to negotiate mitered bends and plug valves, while the platform effort was evaluating these designs for their effect on the platform design. A design based on a segmented sensor, that would require multiple passes to inspect a certain pipeline segment emerged as the simplest mechanical option. However, upon review of the sensor's operations and data analysis characteristics, it was clear that the sensor would not be easily accepted by service providers and would thus render commercialization difficult. It was then decided to accept more complex mechanical designs that would result in one-pass inspections, and data sets that could be analyzed using existing state-of-the-art MFL data analysis software. This required the commitment of very significant additional resources by the funders, who, supported the anticipated benefits and decided to provide the necessary additional cofunding (Mod #1 & #2). A new sensor design was then developed and approved by the funders, together with a new platform design that was significantly longer and heavier in order to support a heavier and more power demanding sensor. The sensor was successfully demonstrated in the laboratory in June 2006, thus meeting a major project milestone. At the same time the TIGRE platform design had been completed and its assembly had been initiated. With these successes achieved, in the summer of 2006, the cofunders decided to commit additional funds towards the development of a sensor Graphic User Interface (GUI) and control system for efficient sensor operation and communication with the platform (Mod #3), as well as additional funds towards the development of a launcher for the live insertion of the integrated system in a transmission pipeline (mod #4). The commitment of the launcher funds was necessitated by the long lead time of this tool, which would have to be available by the summer of 2007, if the deployment of the technology was to stay on course.

In the meantime, with the Explorer II platform effort progressing without any major issues, in January 2006, representatives of NETL/DoE, DoT/PHMSA and NYSEARCH met to review the final designs of the four sensor systems that had been developed by the respective four organizations. Following a systematic and comprehensive review, the SwRI RFEC sensor was unanimously selected as the best one for integration into the Explorer II platform. Following the selection, DoT/PHMSA provided additional funding to SwRI (still outside this program) to complete the design and construction of a prototype system, and its integration into the Explorer II platform. That effort was initiated in early summer 2006 and was completed in February 2007.

Thus, in the summer of 2006 the overall robotics effort for the inspection of unpiggable pipelines was meeting its objectives and was on a very good track. Under this program, the MFL sensor for TIGRE had been successfully demonstrated and the TIGRE platform was under assembly. Under the parallel effort (not funded through this program) the Explorer II platform was under assembly also, and the design and construction of the RFEC sensor was being initiated. It was at that same time that a persistent multi-year NYSEARCH effort to identify a commercialization partner for the technology seemed to bear fruit. In 2003, NYSEARCH started efforts to identify a company that would provide input in the design of the platforms and sensors, thus making the end product more likely to succeed. Following this long process, NYSEARCH reached a preliminary agreement for transferring the technology to a new company to be formed by the principals of CPIG. CPIG was a very successful startup in 2000, which was sold three years later to Baker Hughes having succeeded in the very competitive pipeline inspection market through its advanced technology solutions and high performance operations. The new company, named Trinity Pipeline Inspection (TPA), was planning to commercialize the robotics technology and invest significant resources into providing comprehensive inspection services in the unpiggable pipelines market. A Memorandum of Understanding (MOU) between NYSEARCH and TPA was signed. The MOU called for funding of the sensor-platform integration efforts, extensive laboratory testing and finally the field demonstration of the two robotic systems under development in live gas transmission pipelines. Specifically, the TIGRE platform and the MFL sensor were to be integrated into one system and tested in the lab and in the field. In addition, a second generation MFL sensor in the 24” – 26” pipe size range able to negotiate plug valves and with an eddy current sensor integrated into it to provide internal/external defect discrimination was to be built to complement the original 20” – 22” sensor already built. It was decided that this sensor would be waterproofed thus, (a) allowing its use in the presence of liquids in pipelines , and (b) allowing it to be power washed at the end of each run. Thus, the range of pipelines that the sensor can be used in would be expanded substantially, while the operational efficiency of using the sensor would increase dramatically, reducing the associated costs. This was the first in the world sensor with such capabilities, clearly moving forward the state-of-the-art.

The Explorer II system would be integrated with the RFEC sensor and also tested extensively in the lab and in the field. Funding for these efforts were provided via contract Mod#5 and Mod#6 in mid 2007.

Two laboratory acceptance demonstrations were held on June 6, 2007; one for the TIGRE platform (with the MFL sensor integrated into it) and one for the Explorer-II platform (with the RFEC sensor integrated into it). The TIGRE platform demonstration was held at Automatika Inc. in Pittsburgh, PA. The sponsors were able to witness the integrated TIGRE platform and sensor systems perform a number of operations (Fig. 3.2.1), including the inspection of a short length if pipe, the negotiation of an 18” plug valve and the negotiation of a short radius elbow. The turbine recharge system had not been integrated at that point in time in the robot, but was operating on a separate test stand. The pictures below are from this demonstration.

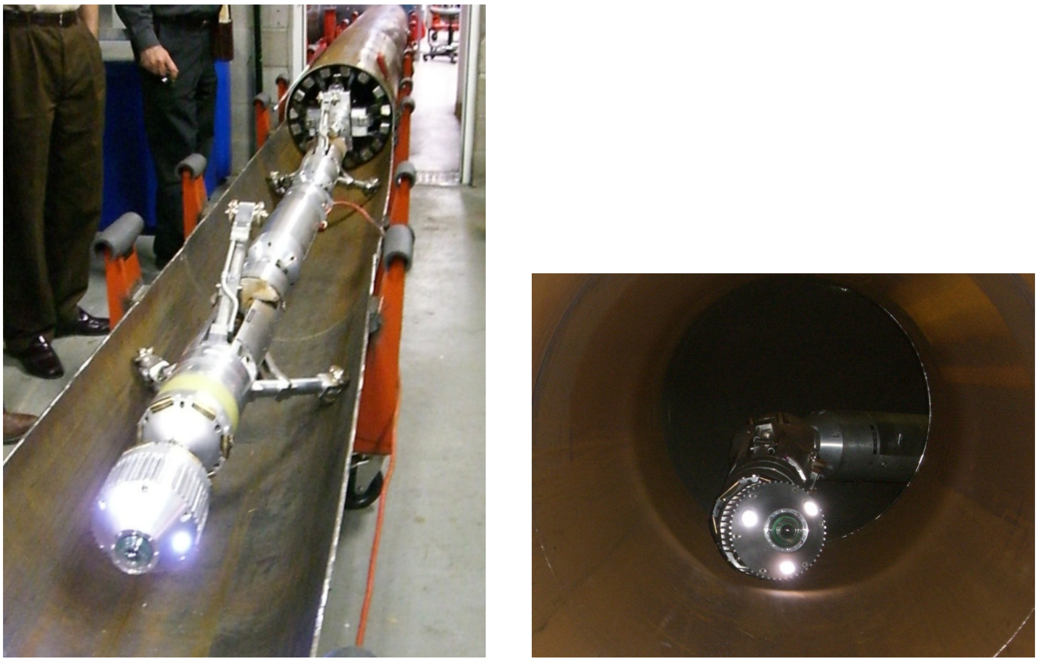


Fig. 3.2.1: *TIGRE Demonstration on June 6, 2007*

The Explorer II platform with the RFEC sensor integrated into it was demonstrated at the Robotics Institute of Carnegie Mellon University in Pittsburgh, PA. The sponsors were able to witness the integrated Explorer II platform and sensor systems perform a number operations (Fig. 3.2.2), including the launching and retrieving of the robot through the launching system developed as part of the program, the inspection of a short length of 8” pipe, and the negotiation of a short radius elbow. The pictures below are from this demonstration.

Fig. 3.2.2: *Explorer II Demonstration on June 6, 2007*

Unfortunately, at about the same time TPA, decided (in the final analysis) not to sign the final contract with NYSEARCH. The program was then slightly modified to allow completion of the remaining tasks by the existing contractors (resulting in Mod #7 and Mod#8). During the summer of 2007, extensive testing was carried out of the two integrated systems in the laboratories of Automatika Inc. and Carnegie Mellon

University focusing on eliminating any problems with the interface between platforms and sensors. At the same time many additional hours of endurance testing were carried out that identified various issues that, when corrected, proved to improve significantly the reliability of these systems.

In September 2007, a one week long demonstration of the Explorer II system was carried out in a live 8” pipeline owned by the National Fuel Gas Company (a member of NYSEARCH) in Brookville, PA. The platform and sensor were deployed via a 45-degree off-the-shelf fitting. A number of issues were identified as requiring design modifications in order to improve reliability and deployment efficiency. The robot travelled more than 3,000 ft of pipeline and was launched and un-launched successfully more than eight times.

In October 2007, a one week demonstration of the TIGRE system was carried out in a 20” pipe test loop at the NYSEARCH Test Bed facility in Binghamton, NY. This loop operates at ambient pressure and consists of a 1,000 ft segment that includes two back to back in-plane 45-degree bends, two 90-degree bends (one mitered and short radius, and a 20” plug valve. In addition, a significant number of defects have been machined on the pipe to allow the testing of inspection technologies. As with Explorer II, a number of issues were identified necessitating design modifications.

Following the fall 2007 demonstrations, NYSEARCH and PHMSA reviewed the status of the program and concluded that the time was ideal to transition the technology from the prototype builders to a commercial partner. Invodane Engineering Ltd., the developer of the MFL sensor for TIGRE, was selected as our commercialization partner. The Principal of the company, Poul Laursen, has had a long and successful career in developing and deploying new state-of-the-art technologies for the inspection of pipelines. Following the signing of a commercialization agreement between NYSEARCH and Invodane, technology transfer agreements were reached with Carnegie Mellon University, Automatika Inc. and Southwest Research Institute. The technology transfer process was completed in early 2009 for Explorer II and in mid 2009 for TIGRE. Invodane proceeded with a complete technology review for each system, training of its personnel in operating and maintaining these systems and initiating a program of laboratory testing to identify and implement design modification needs that were needed in order for the tools to become field ready. Additional funding was provided to complete this task through Mod # 9.

With the identified needed design changes implemented, a program was developed to prepare the tools for field deployments, subject of Mod #10. A series of three additional field deployments were carried out for Explorer II in late 2009 and in 2010. The first one was a repeat inspection in Brookville, PA, at the previously used 8” NFG pipeline. About 2,000 of pipeline were inspected over a period of two days, a small number of features identified and subsequently excavated for verification. The robot was launched and retrieved via a 45-degree off-the-shelf fitting. The second one was successfully carried out in Phoenix, AZ, in an 8” pipeline owned and operated by Southwest Gas Company (a member of NYSEARCH). Over a three day period, more than 3,500 ft of pipeline were inspected, the robot launched and retrieved via a 90-degree off-the-shelf fitting. Some of the data quality was not at the level anticipated/needed, so a redesign effort was undertaken to improve the data generated by the RFEC sensor. With the redesign complete, a final field deployment was carried out over a period of six days in Oneida, NY, in a 6” pipeline owned and operated by National Grid (a member of NYSEARCH). For the first time in the history of the program, the robot was deployed and retrieved in two different launchers, both installed with 45-deg fittings. The two launchers were about 3,000 ft apart. A total of about 5,000 ft of pipeline was inspected during this deployment, with verification digs planned for the summer of 2011. This demonstration was atthe end of the Explorer II effort under this program.

In parallel to the Explorer II effort, the TIGRE system was tested in detail in the lab to determine its level of readiness for field testing. It was determined that major redesign was needed in the drive system, electronics, and overall system architecture. A redesign effort was thus undertaken, resulting in a new sensor system and a modified drive system. A prototype system based on this new architecture (called “intermediate TIGRE”), was assembled and prepared for testing in an abandoned pipeline owned by the Southern California Gas Company, north of Los Angeles, thus completing this program. The testing effort itself, which was successful, was undertaken under a different, follow up to program that is being reported on..

4. STATE OF READINESS OF THE TECHNOLOGY

At the conclusion of this project, the development of the Explorer II system was nearly complete while the TIGRE system was undergoing the validation of the final design. In a follow up program, initiated in October 2010, the Explorer II modifications initiated during the last six months of this program are to be completed and fully implemented and validated. These modifications /additions are the installation of new connectors between neighboring modules, the installation of new technology batteries, the development of the launch Assist and Tether system, and the development of commercial grade sizing algorithms for the RFEC sensor. Similarly, in a follow up program, the Final TIGRE is to be designed, constructed, tested in the laboratory, tested in the field and finally, commercialized in 2012. This TIGRE program was initiated in October 2010 and is currently underway.

Most importantly, in December 2010, the last month of this project, Invodane Engineering announced that through its sister company Pipetel Technologies Inc. that Explorer II is commercially available to the market. An industry-wide press release was issued to announce the launching of this enterprise.

It is expected that a 10” – 14” system will be commercially available in 2011, while TIGRE (20” – 26”) will be commercially available in 2012.

5. WORK PERFORMED

The work performed under this program is presented in six separate sections, each summarizing the technology developed and tested as well as the technology transfer process, i.e. the TIGRE platform, the Explorer II platform, the MFL sensor for TIGRE, the RFEC sensor for Explorer II, the technology transfer of the NYSEARCH robotics technology to Invodane and the technology development effort undertaken by Invodane. Detailed reports, including proprietary information for each one of these subjects is included in six different Appendices, each dedicated to each of these subjects.

5.1 TIGRE Platform (Detailed Report in Appendix A)

As part of earlier system design efforts funded by NYSEARCH (prior to the initiation of this PHMSA/DoT cofounded effort) a robotic train design concept was developed. Following a proof-of-technology stage, during which the critical technologies incorporated in this system were analyzed, tested in the laboratory and validated, the first systematic design of TIGRE was undertaken by Automatika Inc. The initial design was of a modular nature, but of a simpler and shorter configuration than the system design that was actually built and demonstrated. This was due to the fact that the original MFL sensor design was a segmented one, which would be required to be dragged while also being rotated in order to cover the entire inside pipe-wall surface through a spiraling scan-pattern.

Upon review by the Project's Advisory Board of this design, it was deemed that a segmented sensor, even though lighter and smaller than a full-circle sensor presented serious challenges to the actual operation and data-reconstruction of a commercial system for the following two main reasons:

1. rotational forces (and torques) and speeds required for complete circumferential coverage at acceptable/required traverse speeds were excessive and would cause potential mechanism damage and uncontrollable corkscrewing.

2. data-reconstruction in terms of progress and angle for a spiraling scan-pattern was deemed too inaccurate and piecing simple linear scans together was also deemed to be too inaccurate for registration and accurate (to within a few feet over multiple miles) position determination for follow-on activities.

It was mainly due to these two reasons that it was decided to abandon the segmented sensor concept and explore instead a full-encirclement design concept. It was clear at the time that this meant a longer and heavier platform that would need to be designed to withstand significantly higher forces and that would require significantly higher levels of power to operate. However, the benefits from a commercial operation point of view made the adoption of the dull sensor option a necessity, so a new design effort was undertaken to develop a platform suitable to such a sensor. The remaining description in this section details the effort to develop this system.

TIGRE was designed on the concept of an un-tethered, self-propelled, in-pipe, real-time, visual and NDE assessment tool for long-range inspection of 20” – 26” unpiggable natural gas pipelines. It consists of a set of functional modules arranged in a train, with each module having a specific function, such as power-storage, computing, sensing, locomotion, etc. The system is capable of handling a large range of pipe-diameters in a single unit (20- to 26-inch I.D.), and capable of handling sharp turns, bends, Tees and plug valves, while operating safely within a pure natural gas environment. The module-train consists of (i) a fish-eye visual inspection module, (ii) a non-contact corrosion-assessment and third-party damage sensor-module, (iii) several push-and-pull expandable bracing wheeled locomotion modules, (iv) a dual-ended wireless high-frequency communication system, (v) a high-power computing module, with power to the system being provided through (vi) several battery-modules, which are in-line rechargeable via (vii) a trailing gas-flow powered turbine-generator. The system is designed to be launched using off-the-shelf commercial fittings through a launcher attached to such fittings. Real-time data, including snapshot video-imagery, sensory- and system-status data are relayed through the pipe via RF wireless telemetry to an antenna deployed into the line through the launcher, and displayed on a local control console and/or relayed back to a remote location for monitoring. The system is capable of traversing large distances, without requiring either power recharging or downstream antenna taps into the transmission line. Traversing at a rate of 4 inches per second, it is envisioned that the system will perform a one mile inspection in an 8-hour shift.

The basic configuration of TIGRE is given in Figures 5.1.1 and 5.1.2. The system is symmetric about the sensor, which is located in the middle of the platform. A camera module that includes a fisheye camera and wireless transceivers can be found at either end of the robot. Next a drive module provides the necessary driving force using a three arm/wheel configuration. This drive module is also home to a specially designed sonde. The sonde consists of the driver-electronics (custom PCB) and a custom hollow doughnut coil used for generating the magnetic EM pulse-wave that the detector is capable of picking up aboveground. Furthermore, a battery backup was included to guard against complete power-failure on the robot. The sonde gets automatically activated in case of full power failure in the robot.

The arms can be deployed to the necessary extent depending on the diameter of the pipe the system is operating in, while they can be retracted as necessary when the robot is negotiating various obstacles. Next a battery module is found, where Lithium Polymer batteries are stored. These high power density batteries require their own safety circuits, which are also built in the same module. Following are another drive module, another battery module and another drive module. Between the last drive module and the sensor there is a “mini” module, designed to support the sensor during obstacle negotiation. This mini module is also equipped with two mini-cameras that allow the operator to view the sensor to ensure its proper status.

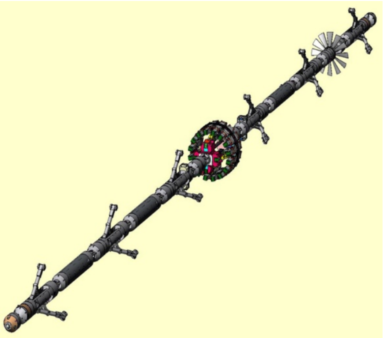


Figure 5.1.1: *Basic configuration of TIGRE Global View*

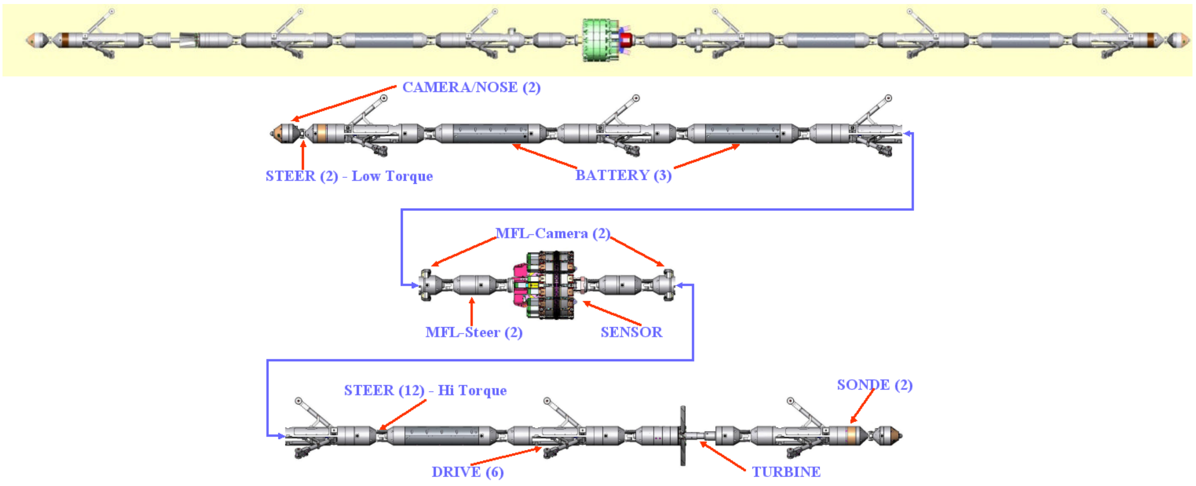


Figure 5.1.2: *Basic configuration of TIGRE – Module Layout*

It is envisioned that depending on the requirements of each particular inspection, the robot can be configured in different ways to optimize its performance for the particular job. Following is a list of possible configurations:


Scout A


Scout B


Scout C


Scout D


TIGRE

Scout A	Straight Line Visual Inspection with Limited Range
Scout B	Smallest configuration that can negotiate obstacles. Used for intermediate-range visual inspection.
Scout C	Long-range visual inspection configuration – Can negotiate obstacles.
Scout D	Long-range visual inspection.
Full TIGRE	Long-range visual and MFL inspection

The system offers a power-generating option via a turbine module that can be used in place of a battery module. The turbine could be deployed inside the pipe in case of sufficiently high flow/pressure and generate electricity so trickle-charge the batteries. The overall turbine design is based on an in-pipe module capable of deploying-cllapsible a set of articulated turbine-blades, capable of extracting electrical power from the kinetic flow-energy of the gas diverted around the outside of the turbine-module and through the turbine-blades or vanes/airfoils. The airfoil design was bid out to a turbo machinery design subcontractor (PASDT, Inc.) and was rapid-prototyped prior to system assembly at Automatika. The generator was specified in conjunction with the turbine design-house and procure as a custom-would brushless AC-generator with power-rectification to generate DC-current(s) that would be fed to the power-bus(es) through a set of DC/DC converters.

For the prototype, it was decided that a 20in OD (18.812in ID) pipe would be used for the initial design. It is understood that this approach, once verified by field testing, could be used to quickly design corresponding turbine blades for alternative pipe diameters (and alternate flow-conditions). Further, it was decided that a 0.5in radial gap between the blade tip and inner pipe wall would be used. The design conditions for the blade design were set as follows:

Table 5.1.1: *Design Conditions for Turbine Airfoil*

Description	**Value**
Fluid Temperature (□C)	14.0
Fluid pressure (psig)	250.0
Fluid pipe velocity (ft/s)	25.0
Operational density (kg/m^3)	11.591

The final blade geometry, including the platform, is shown below in Fig. 5.1.3.

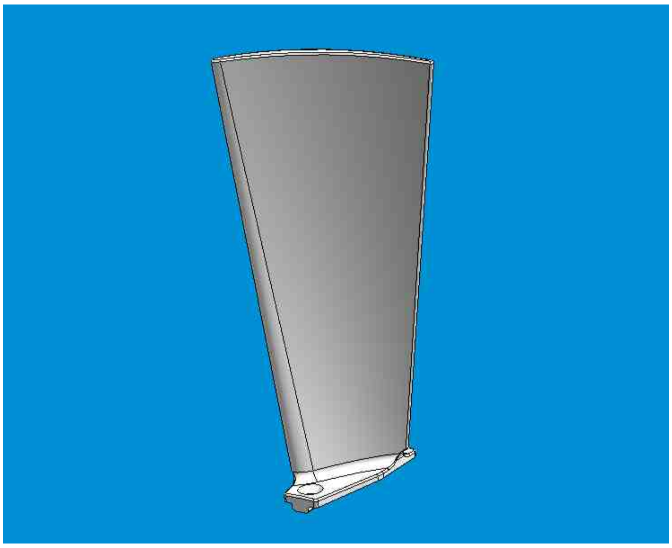


Figure 5.1.3: *Final turbine blade geometry*

All components of the robot were tested individually, in their subassemblies and as an integral part of the entire robot. Some critical components were tested upfront to determine their proper sizing. This included:

LED Lighting system

LED lighting imaging tests were carried out with a new ceramic-based LED lighting technology system using clustered white LEDs. Experiments involved evaluation of efficiency, lighting range, spread and blooming, hot-spots, etc. After multiple test scenarios, it was determined that this new LED technology was viable and could be used in clusters. A range of three to four clusters was deemed sufficient to light all the walls and the pipe up to 6 feet (18 second look-ahead based on 4 inches per second travel speed) in front of the robot.

Component pressure testing

Component pressure testing was carried out on some of the more critical main components. All tested components including CPUs and entire development boards passed simple functional tests up to 750 psig. The batteries were also tested (under load) and survived. The imaging system (CCD-array and lens) had to be modified to allow for operation in ventilated compartments – both units survived such testing, allowing for a future unventilated camera-nose design. Imagery of the pressure-chamber test setup is depicted below in Fig. 5.1.4.

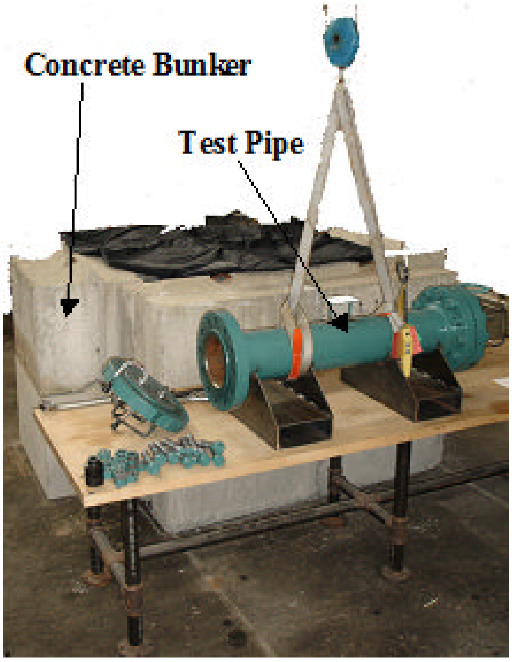


Figure 5.1.4: *Pressure test setup*

Traction testing

A set of traction testing experiments were carried out for different wheels under different surface treatments and preload conditions in order to select the most appropriate configuration. A specially designed set up was used as seen in Fig. 5.1.5 below.

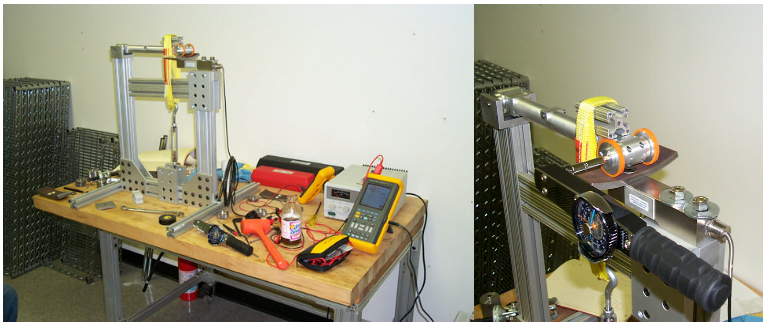


Figure 5.1.5: *Wheel Traction Test Setup*

The result of these tests was that the cross-knurled wheel was the best design for running on bare steel.

Arm deploy force testing

Testing of the arm deploy motors was carried out to determine their ability to provide the necessary traction force. The drive module arms were deployed against a load cell and forces recorded.

Battery testing

The life of Li-Po batteries can be maximized by maintaining a nominal state of charge, assuring that neither over-charging nor under-discharging occurred subjecting the battery to temperature extremes. The battery packs were tested to verify operation at 50 Amps (as required by TIGRE), noting in particular the temperature rise. The temperature rise was recorded to be 12.5 deg-C during the 11 minutes that it took to discharge this battery. This results in an ambient operating temperature of 24.1C + 12.5C = 36.6 deg-C (98 deg-F), well within the recommended operating range of 60 deg-C and the absolute maximum temperature of 70 deg-C (160 deg-F).

The completed battery blocks were tested next and verified to abort discharge at 50 amps and/or at temperatures of 60C or above. Please note that discharge abort was controlled by hardware and was not under control of the local microprocessor.

Following these tests, the platform was assembled in stages. A Scout A configuration was assembled and tested first followed by the Scout B configuration. Finally, a Scout C configuration was assembled and successfully tested, followed by the integration of the MFL sensor on this platform which was initiated in April 2007. Initial effort concentrated on establishing proper communication between platform and sensor followed by successful execution of sensor mode changes: scanning mode to plug-valve mode, scanning mode to miter-bend mode and vice-versa. A variety of minor and major obstacles surfaced and were dealt with during this process. This effort was followed by testing the ability of the system to negotiate the three main obstacle types defined for the program: 1.5D elbow, miter-bend and an undersized plug-valve (PV). All three of these capabilities were successfully demonstrated.

5.2 Explorer II Platform (Detailed Report in Appendix B)

Explorer II shown in Fig.5.2.1, consists of eleven modules organized on a symmetric design. At its two ends reside the modules carrying the fisheye cameras and lighting system. The fisheye cameras, with a 190-degree field of view, allow for the visual inspection of the pipeline and the driving of the robot. The lighting system used high-efficiency, low power LCDs, the intensity of which is controllable so that power consumption can be minimized when lighting is not needed. Residing in these two modules are also sondes, which allow for the location of the robot from above ground, as well as the wireless receivers and transceivers that allow for the robot to communicate with and stream video images and data from its sensors to the operator. An antenna placed in the pipeline at the launcher provides the necessary link between robot and operator. The next two modules are the drive modules, each equipped with three powered arms that are deployed and retracted by the operator. High friction wheels allow for enough traction so that the robot can travel up and down vertical segments of pipelines. The next two modules carry the high density polymer ion batteries that provide all power needed by the system, thus eliminating the need for tether, that would limit its range to about 300 ft from the launching point. The next two

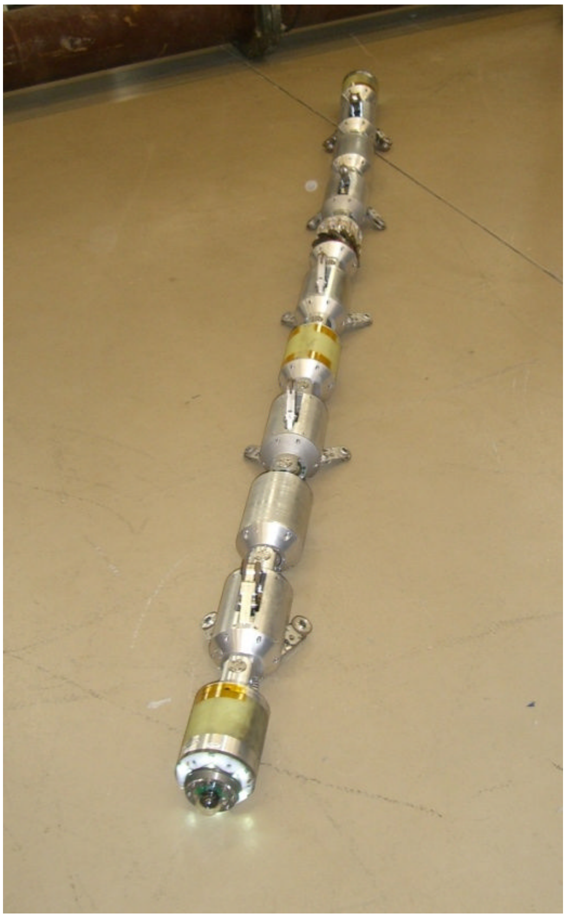


Figure 5.2.1: *Explorer II; modular, non-tethered, remotely controlled system for the live inspection of unpiggable transmission pipelines*

Figure 5.2.2: *Excitation coil module and sensor module negotiation a 90-deg bend.*

modules in are support modules that are designed to provide support for the next two modules that make up the sensor of the system. The support modules are similar to the drive modules, with the exception of the lack of drive power to their wheels. The RFEC sensor, shown in Fig. 5.2.2, consists of two modules, the excitation coil module and the sensor module. The excitation coil generates the electric field that induces the electric currents that are detected by the sensors on the sensor module in the coil's remote field. In the sensor module, 48 Hall effect sensors detect the electric currents and variations in the distribution are translated to wall thickness measurements and thus detections of anomalies in wall thickness due to corrosion and mechanical damage. Finally, an eleventh module between the excitation coil module and the sensor module provides additional support for these two modules that need to remain centered in the pipeline to warranty high accuracy of measurement. Advanced state-of-the-art electronics reside in each module providing for the control of the system.

The modular design allows for the negotiation of bends and tees in the pipe (including that of mitered 90-deg bends). It also allows for the future addition of more modules that will enhance the capabilities of this tool, which is launched a retrieved under live conditions using a specially designed launcher. The launcher consists of a 10 foot long pipe with a flange at its end that houses a wireless antenna as well as a mechanism that allows holding the robot in place. The robot and launching systems are rated at 750 psig. The launcher is attached to the pipeline using a TD Williamson off- the- shelf 45-degree fitting. A sandwich valve between launcher and fitting provides the needed isolation of the launcher from the rest of the pipeline network.

In order to warranty the safe operation of the system, a deployment and operational procedure is followed that is based on the absence of any contact between natural gas and air. After the launcher is installed on the TDW fitting and valve, it is purged of air through the use of a vacuum pump. The Launcher is then filled with nitrogen, followed by the opening of the sandwich valve and a small valve at the top of the launcher. The high pressure natural gas displaces the nitrogen in the launcher. Once the launcher is filled with natural gas, the robot is ready to be launched. A similar procedure is followed during robot retrieval.

Assembly of the Explorer II prototype platform system (funded by NYSEARCH and NETL/USDoE) as well as that of the RFEC sensor modules (funded by PHMSA/DoT) was completed in early 2007. The present program was modified in mid-2007 in order to provide funding for the integration of the Explorer II platform with the RFEC sensor, testing of the integrated system, and carrying out field demonstrations of the integrated system. During the summer of 2007, CMU and SwRI engineers worked together to carry out this integration. SwRI personnel repeatedly travelled to CMU in order to integrate the two systems and solve any problems identified. Simulated corrosion defects were manufactured in pipe samples that could be used to validate the RFEC system response to defects. NGA provided a schedule of defect sizes and configurations that included 16 defects to be manufactured in the outside surface of schedule 40 pipe. Most of the defects were circular in shape, but some were elongated in the axial direction and some in the circumferential direction. One consisted of two separate defects in close proximity. Mechanical measurements of the final defect sizes were made to confirm dimensions.

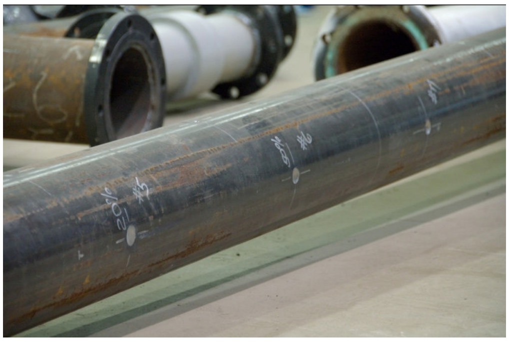


Figure 5.2.3*: Sample of defects manufactured on pipes*

Endurance testing of the integrated system was carried out in the July – August 2007 period at the outdoor loop at CMU (constructed earlier and consisting of about 800 ft of 6” and 8” pipe with short and long radius turns, tees, vertical segments and other features). Thousands of feet of pipe were traveled and dozens of sensor deployments/retrievals were carried out together with dozens of negotiations of bends and tees by the entire system. Some of the problems encountered included intermittent action of the detector deployment/retraction motor and detector signal data that was not meaningful; failure of a capacitor on the printed circuit board that drives the exciter coil; and a problem with the CAN communications. All these problems were troubleshooted and solved. Finally, the sensor was tested for ability to operate at high pressures in natural gas. The entire system was inserted in a natural gas filled pipe at a pressure of 540 psig. Both platform and sensor operated properly without any issues emerging.

The CMU/SwRI Explorer II/RFEC integration effort was completed with the first ever deployment of a robotics device designed to inspect unpiggable pipelines into a live transmission pipeline (Fig. 5.2.4).

***Figure 5.2.4**: Launcher attached to pipeline in Brookville, PA*

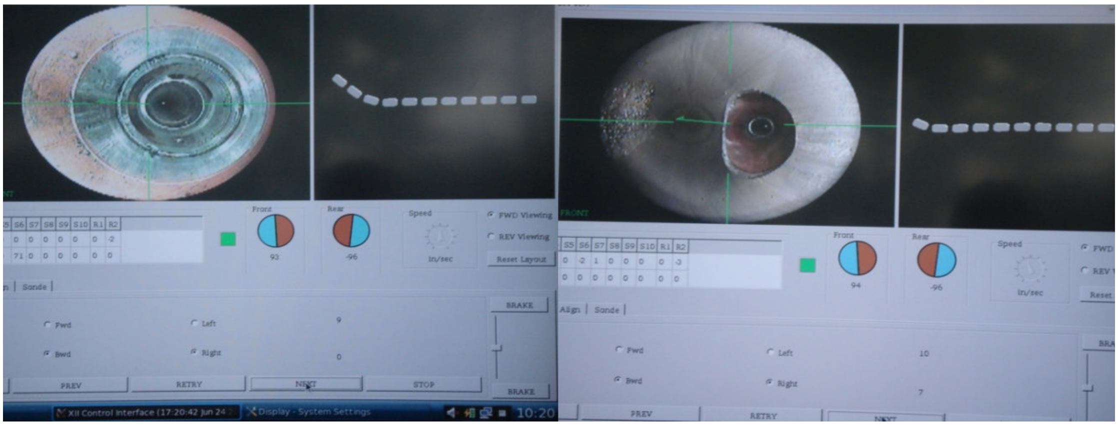


Figure 5.2.5: *GUI images showing the view from Explorer II's camera: (left) looking into the valve in the launcher, (right) looking from the pipe into the launcher and the pipe in front of it.*

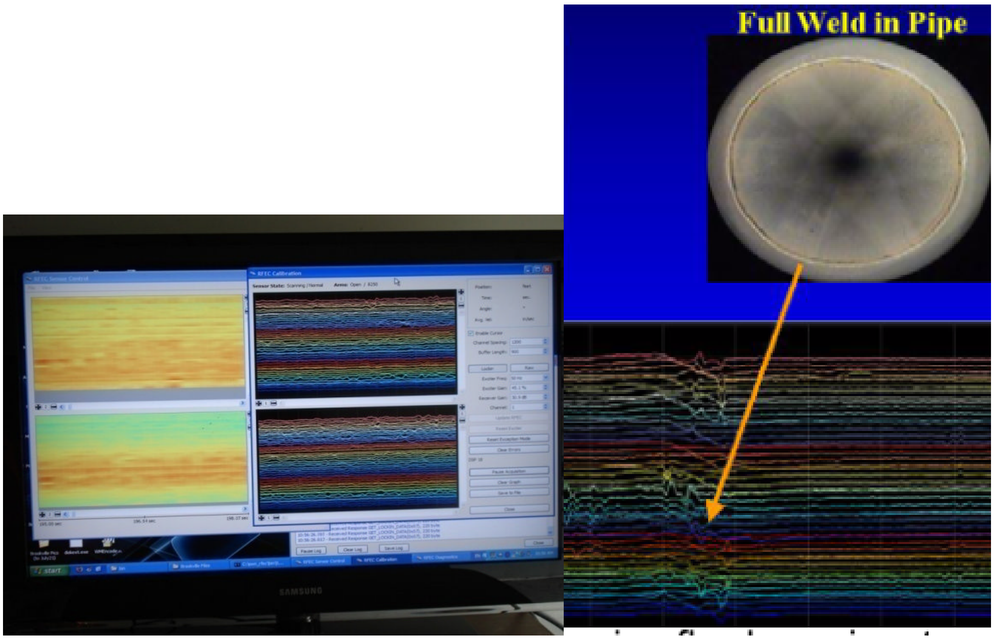


Figure 5.2.6: On the left, *GUI showing signals from each of the RFEC 48 sensors, fed live to the operator; on the right, image of a weld via the camera and corresponding signal modifications due to its presence*

During this deployment the robot traveled a distance of more than one-half of a mile in multiple runs over a period of three days, the largest distance travelled from the launching point being 1,100 ft. with significant levels of wireless range and battery energy still being available at that distance. A total of six launchings and retrievals were carried out successfully accompanied by six successful antenna installations and removals. Images from the cameras were transmitted live to the operator (Fig. 5.2.5), while the sensor transmitted collected data live to the operators also (Fig. 5.2.6). However, during one of the robot deployments, one of the gears in the "front" drive modules broke necessitating a successful emergency retrieval. In addition, during, one of the antenna installation procedures, the antenna fitting broke due to excessive torque applied to it. A successful retrieval of the compromised antenna fitting was carried out followed by the installation of a spare one. Also, due to issues encountered with the interaction of the platform with the sensor, only 400 ft of data was collected by the RFEC sensor.

The issues encountered at the Brockport, PA, deployment triggered a review by CMU of the design of the platform components that exhibited problematic operation. It was decided that:

(a) the drive mechanism of the platform had to be redesigned to afford it larger load and torque levels,
(b) the antenna fitting had to be redesigned to eliminate the possibility of it braking during installation/retrieval,
(c) the wheel mechanisms had to be redesigned since in a couple of occasions the wheels had difficulty going over certain welds,
(d) certain "bugs" in the software controlling the communication of the platform with the sensor needed to be corrected.

These corrective measures were ultimately not carried out by CMU. As mentioned above due to the transfer of the technology in the aftermath of this demonstration to Invodane Engineering, these issues were addressed by Invodane.

5.3 Remote Field Eddy Current (RFEC) Sensor(Detailed Report in Appendix C)

The RFEC sensor, as mentioned earlier, was designed and built under a separate PHMSA/DoT funded effort. In order to have a complete picture of this project a brief description of the sensor is presented here.

The RFEC sensor consists of two modules; (a) an “exciter” module and (b) a “sensing” module (detector). The exciter module contains a 4” excitation coil with its axis coinciding with that of the pipe. The coil is driven with alternating currents which induce an alternating magnetic field. In turn, this magnetic field induces eddy currents in the pipe. A series of sensors are placed along the circumference at a distance of about (3) pipe diameters away from the exciter, where the magnetic field is very small so it does not affect the sensors. These sensors measure the magnetic field after is has penetrated back to the pipe through the wall. Thus, these signals are sensitive to any changes in wall thickness, which allows us to measure any wall loss present. Figure 5.3.1 below shows the configuration of the RFEC sensor on the Explorer II platform. The exciter module contains the 4” excitation coil and the electronics driving the sensor. The sensing module (detector) consists of 48 sensors located on twelve arms (each arm carrying 4 sensors) that are able to be deployed to diameters between 4.5” and 8” and collapsed down to 4” thus allowing the sensor module to negotiate bends and tees in the pipeline. The two sensor modules are separated by a “support” module which allows for the centering of the exciter and detector modules in the pipe (which is essential for high quality data).

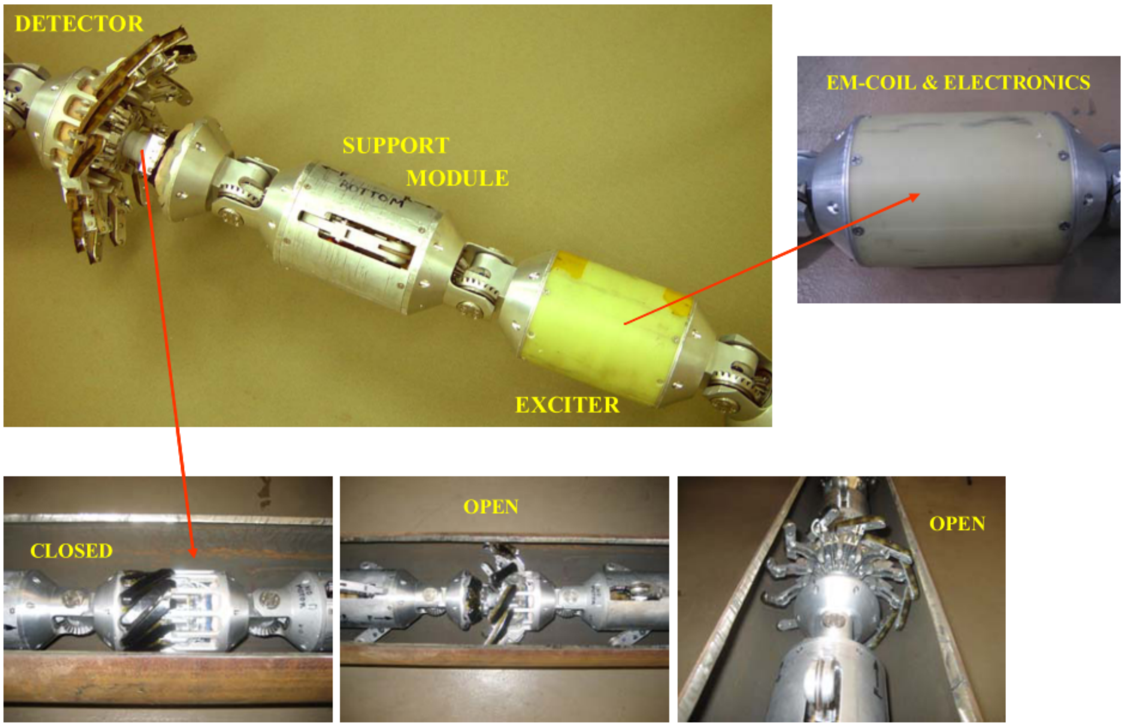


Fig. 5.3.1: *RFEC sensor integrated into Explorer II platform*

Endurance testing of the integrated system was carried out in the July – August 2007 period at the outdoor loop at CMU (constructed earlier and consisting of about 800 ft of 6” and 8” pipe with short and long radius turns, tees, vertical segments and other features). Thousands of feet of pipe were traveled and dozens of sensor deployments/retrievals were carried out together with dozens of negotiations of bends and tees by the entire system. Some of the problems encountered included intermittent action of the detector deployment/retraction motor and detector signal data that was not meaningful; failure of a capacitor on the printed circuit board that drives the exciter coil; and a problem with the CAN communications. All these problems were troubleshooted and solved. Finally, the sensor was tested for ability to operate at high pressures in natural gas. The entire system was inserted in a natural gas filled pipe at a pressure of 540 psig. Both platform and sensor operated properly without any issues emerging.

At the same time, data collected by the sensor as it traversed the pipes with the manufactured defects (0.322 and 0.250-inch wall) was analyzed. This purpose of this analysis was to verify operation of the RFEC system, determine the capability to detect the defects as well as to determine their size (depth, length, and circumferential width), and form the basis for calibration of the system on a wide range of defect configurations and pipe wall thicknesses. Validation data included approximately 50 data sets (different excitation frequencies, repeat runs, different clock positions, etc.) with 16 flaw signals in each set for the thick pipe and 10 for the thin pipe. All of the data were plotted and examined visually, and representative sets were selected for further analysis. Analysis was performed using a process and software developed under the SwRI DOT/PHMSA project to determine defect size parameters.

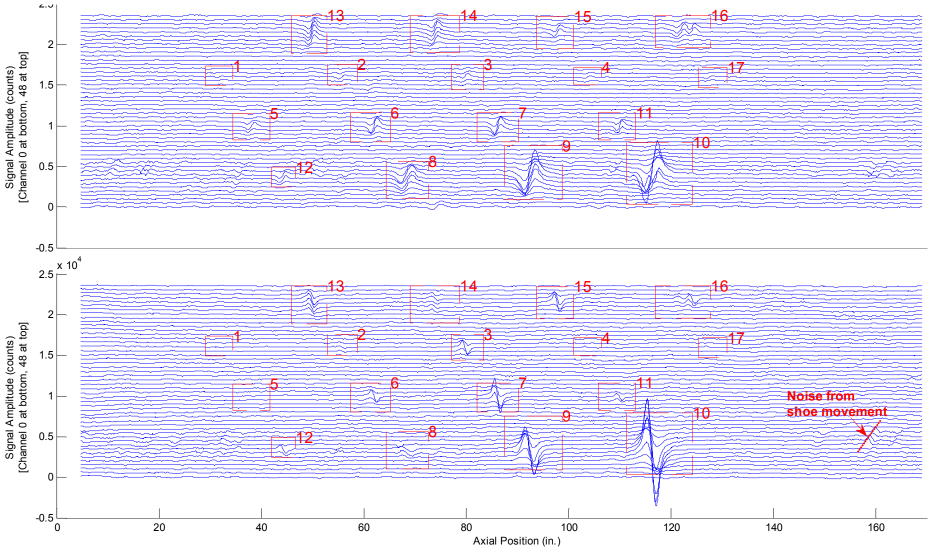


Fig. 5.3.2: *RFEC signals from 0.322 in. wall schedule 40 validation pipe sample taken with the robot traveling at 50% full speed. In-phase signal at top and quadrature at bottom.*

Figure 5.3.2 shows a data stream for each of the 48 detectors with each displaced slightly to form a “waterfall” plot. The detectors are equally spaced around the circumference and therefore the data represent an inspection of the entire circumference of the pipe. Figure 5.3.3 shows the processed signal for one of the defects identified. Signal processing was carried out with a software package developed by SwRI.

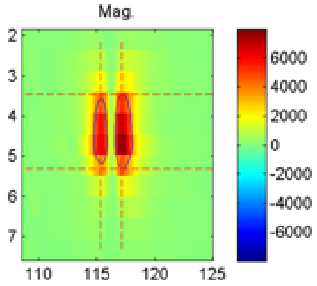


Fig. 5.3.3: *RFEC signals from 0.322 in. wall schedule 40 validation pipe sample taken with the robot traveling at 50% full speed.*

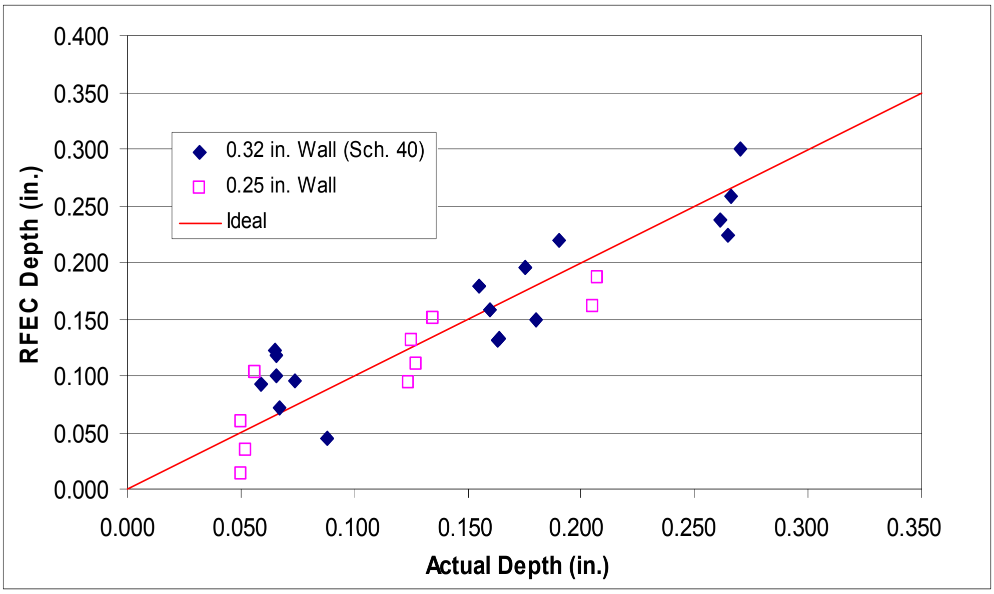


Figure 5.3.4: *Calculated maximum flaw depth determined from RFEC signals plotted vs. actual maximum flaw depth*

Following the analysis of the data collected from all defects on the pipes regarding defect depth, axial length and circumferential length, the results were compared with the actual sizes of these defects. Figure 5.3.4 shows the comparison between sensor determined depth of defect and actual (measured depth). The comparison is rather favorable, but it also indicates that additional work needed to be carried out in order to improve the accuracy of the system.

The sensor was tested as part of the Explorer II Brockport, PA, field deployment in a live 8” pipeline operating at 140 psig in September 2007. The sensor was successfully launched and retrieved with the platform six times over a period of three days. While in the pipeline, the sensor legs were deployed and retrieved numerous times. The sensor data collection system was activated numerous times and data streams flowed into the operator under live conditions. However, some problems were identified in the communication between the platform and the sensor that prevented us for collecting large sets of data. At the end only 400 ft of good quality data was collected. As in the case of the platform, all corrective measures were ultimately not carried out by SwRI, but by Invodane engineering to which the technology was transferred in the aftermath of this demonstration.

5.4 Magnetic Flux Leakage (MFL) Sensors (Detailed Report in Appendix D)

Two MFL sensor modules were developed, built, tested, and integrated into TIGRE, a robotic platform developed through a parallel effort, for inspection of 20” – 26” unpiggable pipelines. Two different sensor modules were developed; one for inspecting 20” – 22” pipelines and one for inspecting 24” – 26” pipelines. These sensor modules magnetize a circumferential section of a pipeline globally and hence are capable of inspecting pipeline in a single pass identical to traditional pipeline inspection pigs. These sensor modules differ from traditional MFL pipeline inspection pigs in that they can be configured or manipulated into three different modes for negotiation of different pipeline obstacles. First, in its inspection mode, the sensors inspect 20 to 22 inch and 24 to 26 inch diameter pipes. Secondly, they negotiate plug valves of 18 inch to 22 inch and 22 inch to 26 inch respectively. Thirdly, for launching, retrieving, and negotiation of a miter bend, the MFL sensor modules are configured into their miter bend mode. Various mechanisms on the sensors work in conjunction to facilitate the mode changing. A master controller on the MFL sensor modules executes all modes changing. Commands sent by the operator from an MFL GUI are streamed to the MFL master controller via the TIGRE GUI.

The master controller and 8 sensor controllers synchronize the MFL data collection from the 256 Hall sensors on the MFL sensors. The MFL data is saved onboard the MFL sensors in addition to being displayed on the MFL GUI. The data displayed is unprocessed raw data directly sent from the MFL sensors via TIGRE and its wireless connection. At the end of an inspection, all MFL data is downloaded via the master controller for post-processing. Post-processing and data analysis software is not part of the current program.

The Project Advisory Board developed and agreed upon the following specification for the sensors (Table 5.4.1):

Table 5.4.1: *Specifications for MFL Sensor*

Issue	**Prototype System**
Type of sensor	MFL
Inspection accuracy/ Wall thickness	Maximize At least 40/20 @ 0.5" wt (final attained is **20/10 @ 0.5"wt**)
Sensor portability	Maximum 24" – 26" (22" PV) and 20" – 22" (18" PV)
Magnet shunting	Yes
Internal/external detection	24"-26" sensor only
Pipe cleanliness	Not to be considered now
Operational mode – number of passes	Single
Operational mode – leave in pipe overnight?	Yes
Inspection speed	4 in/sec (0.1 m/s)
Obstacles	PV (see above) Miter bend Back to back 90 deg out of plane miter bends
Launch hot tap size	Minimize

Ultimately, the MFL sensor modules developed are capable of detecting defects of 20/10 (instead of original spec of 40/20). Twenty refers to the depth of the defect as a percentage of pipeline wall thickness for defects with a diameter twice the wall thickness. Similarly, these sensor modules can detect defects with a depth of 10% of wall thickness with a diameter three times that of the wall thickness. This inspection specification is comparable to high resolution traditional pigs and exceeded the initial target specification. The magnetic energy on these tools, that generates the magnetic circuit in pipelines that they inspect, can be shunted. During inspection, the magnetic energy is channeled into the pipe for maximum inspection performance. During negotiation of pipeline obstacles, mechanisms and control electronics work to shunt the magnetic energy to prevent the magnets from coupling to these pipeline obstacles. If coupled, TIGRE may not be able to generate the tow force required to decouple the magnets from the obstacles.

Figure 5.4.1 shows the CAD model of the final 20” to 22” MFL sensor design in its inspection and plug valve mode. The 24” to 26” design is practically identical; the only real difference being that this larger sensor module has the capacity to discriminate between internal and external defects via an eddy current sensor and is also waterproof. The MFL sensor consists of 16 magnets arranged in a circular fashion. Each magnet bar generates sufficient magnetic flux, as seen in Fig. 5.4.2, to saturate the pipe wall, a requirement for detecting defects to the level set by the specifications adopted. A total of 256 Hall sensors which detect the change in magnetic field caused by the presence of anomalies in the pipe wall are mounted on these magnets. The Hall sensors are aligned at the same position axially but distributed equally in the circular direction. This arrangement permits the MFL sensor to inspect pipes in a single pass globally in the same fashion as traditional inline inspection systems. Four magnets are mounted to a lifting mechanism which raises or lowers the magnets towards or away from the pipe wall. This allows the MFL sensor to inspect 20 or 22 inch pipe of different wall thicknesses. Each magnet is equipped with a motor which actuates the shunting mechanism. The shunting mechanism permits or prohibits the magnetic energy from being channeled into the pipe wall. A telescoping structure allows reconfiguration of the MFL sensor from a single circular section to one allowing the module to go through a plug valve. All electronics are housed in various vessels to prevent damage.

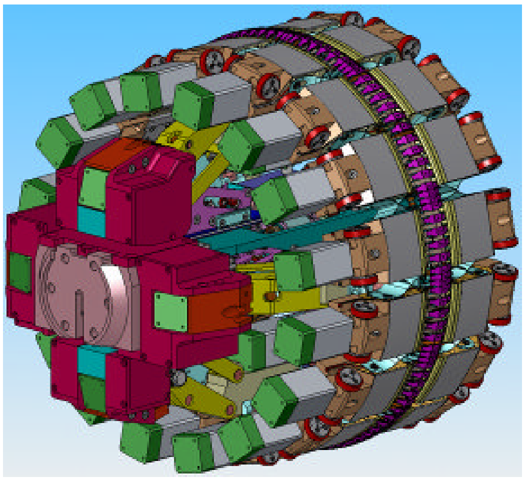


Figure 5.4.1: *CAD model of final MFL sensor design*

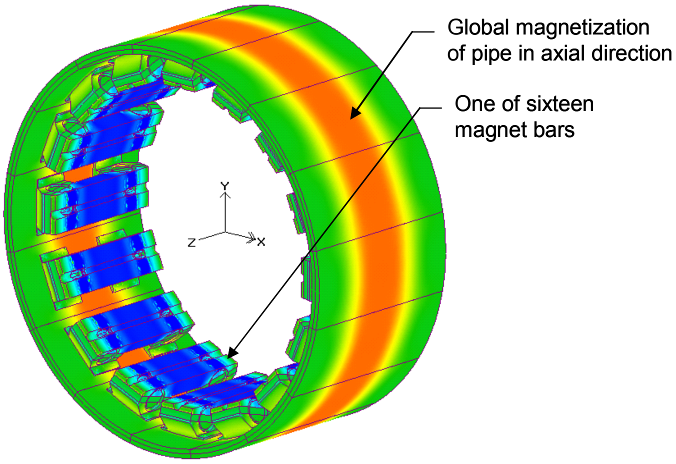
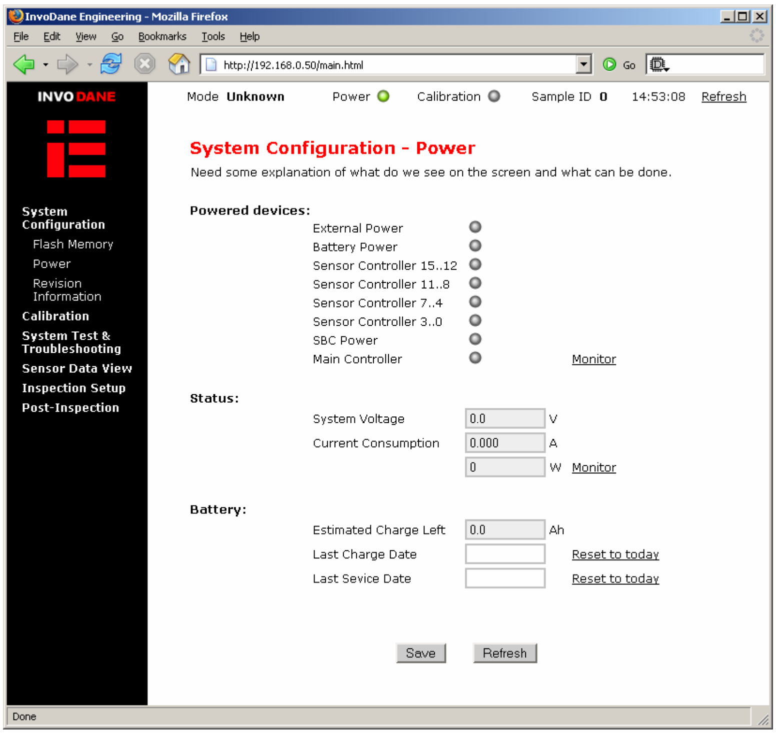


Figure 5.7.4.2: Plot of magnetic flux density induced by magnet bars into pipe

The magnetic circuit design focused on the system being able to meet inspection specification, to shunt the magnetic circuit, and to stay within the mechanical envelope imposed on the MFL sensor by the robot design and the operational demands. Each magnet bar has four wheels that prevent the poles from contacting the pipe during inspection.

A data acquisition system, developed by Invodane, has been modified and adapted for the specific requirements of the MFL sensor module developed. This system consists of a Master Controller and 8 Sensor Controllers, each of which is connected to 4 Sensor Elements. Each Sensor Element reads the magnetic field strength from 8 Hall Effect sensors. This gives a total of 256 Hall Effect sensors on the entire tool. The Sensor Elements and Sensor Controllers are mechanically protected in a non-pressurized housing such that the electronics operate at ambient pressure. This can be done with confidence based on the results of the pressure tests performed on the electronics (as described later). The Master Controller is located in a central, pressure-sealed enclosure at the front or leading side of the MFL.

One of the main functions of the Master Controller is the coordination of the data acquisition activities for the MFL. It is also connected to a number of additional sensors, referred to as auxiliary sensors, which provide information regarding the environmental and physical conditions surrounding the MFL. Specifically, the system is equipped with pressure, temperature, and acceleration sensors as well as two odometers. All of the data from these auxiliary sensors is stored on a Compact Flash storage device located on the Master Controller. The odometers are used continually during an inspection as they indicate the distance traveled and current speed of the tool. The Master Controller uses the distance and/or speed information to determine when to collect data from the Hall Effect sensors. The Master Controller also provides an interface through which the operator can enter certain inspection parameters, including: auxiliary sensor calibration constants, sampling rates and sampling methods. This user interface, hosted on the Master Controller, is accessed via a website (as seen in Fig. 5.4.3) and accessible through an Ethernet connection directly to the Master Controller. Since the Ethernet connection to the Master Controller is inaccessible during an inspection, the website can only be accessed when the MFL is outside the pipeline before and after the inspection. The inspection and calibration data is also downloaded using the Ethernet port once the inspection is complete.



Mode **Unknown** Power ● Calibration ● Sample ID **0** 14:53:08

System Configuration - Power

Need some explanation of what do we see on the screen and what can be done.

Powered devices:

External Power ●
Battery Power ●
Sensor Controller 15..12 ●
Sensor Controller 11..8 ●
Sensor Controller 7..4 ●
Sensor Controller 3..0 ●
SBC Power ●
Main Controller ●

Status:

System Voltage 0.0 V
Current Consumption 0.000 A
0 W

Battery:

Estimated Charge Left 0.0 Ah
Last Charge Date
Last Sevice Date

Figure 5.4.3: *MFL Master Controller user interface website*

Experiments were performed to determine the effect of pressure on the operation of the electronic component on the MFL sensor module. For these tests, a pressure vessel was designed and constructed to allow for a test pressure of 750 psig. To allow controlling and monitoring of the electronics inside the vessel, a number of access ports with pressurized electrical connectors were included in the design. Nitrogen gas was selected because it is inert, non-flammable & non-explosive as well as its comparable molecular size to methane, the primary component of natural gas.

Integration of the MFL sensor module to TIGRE began in April, 2007. The sensor was integrated into the version of TIGRE called Scout C (see above) consisting of four drive modules, and two battery modules filled with Nickel Metal Hydride batteries. The first step in the integration process was to mechanically integrate the MFL sensor module to the mini-steering module of TIGRE, which also involved electrically connecting the numerous cables that go from one half of TIGRE to the other half through the MFL sensor module. After the MFL sensor module was physically integrated to TIGRE Scout C, various checks were performed to ensure the mechanical and electrical integration was successful. The integrated system was powered to ensure electrical connectivity both in the MFL and both halves of TIGRE. The second stage to the integration process was to integrate the TIGRE and MFL operator GUIs. All messages destined for the MFL module are generated by the MFL operator through the MFL GUI. These messages are then sent to the TIGRE GUI via an Ethernet connection. Recognizing that messages are intended for the MFL sensor module, the TIGRE GUI simply passes these messages onto TIGRE via the wireless connection. Once it reaches TIGRE, it passes these MFL messages to the MFL sensor module. When the MFL sensor

Figure 5.4.4: *TIGRE and MFL operators controlling the system via their respective GUI*

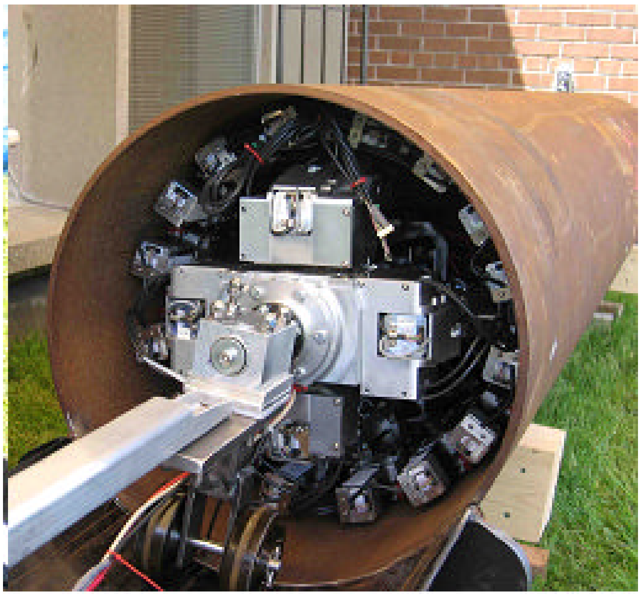


Figure 5.4.5: *Test setup consisting of a pipe and plug valve; sensor configured in insertion mode is shown inside a pipe*

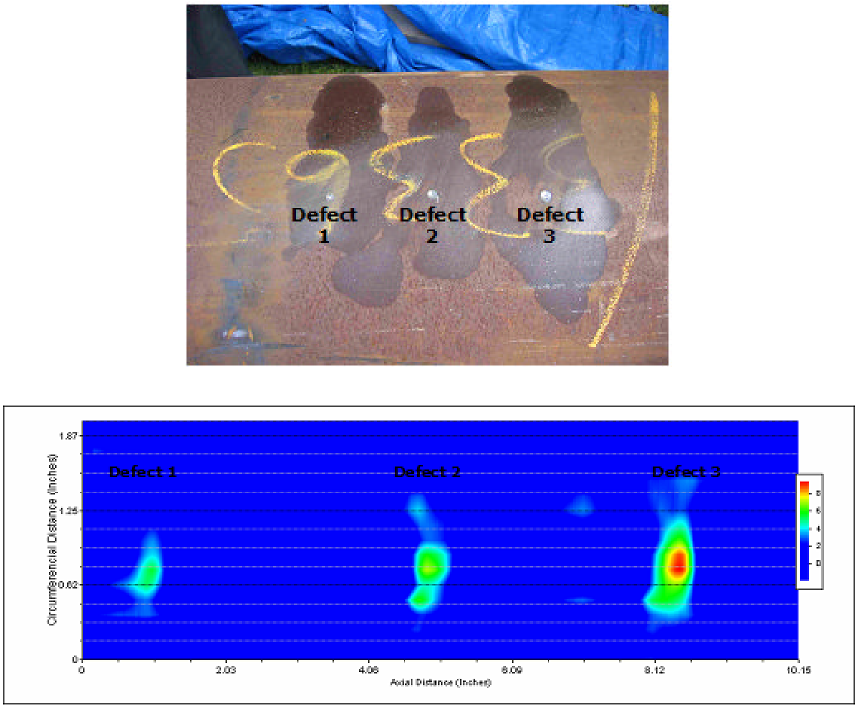


Figure 5.4.6: *Man-made defects on pipe and corresponding MFL signals obtained by sensor module*

module successfully receives these messages, it sends a reply message back to confirm recipient of messages. When TIGRE receives such message intended for the MFL GUI, it passes the messages to the TIGRE GUI which then relays them to the MFL GUI. This process was tested and successfully integrated during the integration effort.

This effort was followed by testing the ability of the system to negotiate the three main obstacle types defined for the program: 1.5D elbow, miter-bend and an undersized plug-valve (PV). All three of these capabilities were successfully demonstrated.

The Automatika/Invodane TIGRE/MFL integration effort was completed with the first deployment of the robot at the NYSEARCH Test Bed in Binghamton, NY, in October 2007.

Figure 5.4.7: *Setup to deploy TIGRE system at NYSEARCH Test Bed*

The NYSEARCH Test Bed is a piping system built to test pipeline integrity technologies, including ECDA and in-line inspection tools. It consists of over 1,000 ft of underground and above ground, 20” and 12” pipeline, with machined defects on parts of it. It contains bends, tees, and a 20” plug valve. The system has two entry points, both above ground.

The TIGRE robot was inserted in the 20” segment of the pipeline, as shown in Fig. 5.4.7. As mentioned earlier, numerous problems were encountered with the platform itself and as a result we were not able to test the system’s ability to negotiate bends and the plug valve. The sensor (Fig. 5.4.8), however, performed as expected in the limited run that it was involved in. The communication between platform and sensor did not exhibit any problems, while we were able to deploy and retract the sensor numerous times. A limited set of data was collected that were of good to excellent quality.

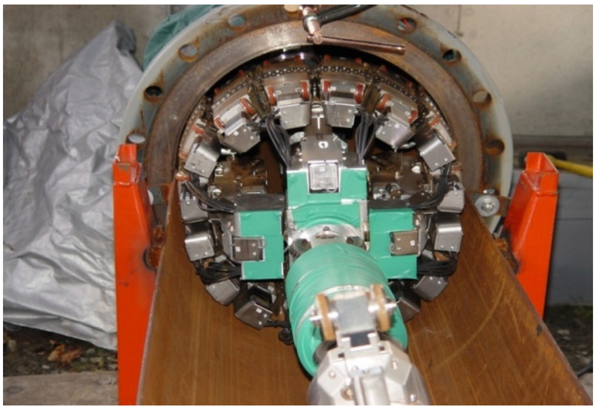


Figure 5.4.8: *MFL sensor deployment at NYSEARCH Test Bed*

As mentioned earlier, after this deployment the funders decided to transfer the entire robotics technology to Invodane (the commercializer of the technology). All further developments related to the sensor were undertaken under that program, which is described next.

5.5 Transfer of Technology to Invodane Engineering (Detailed Report in Appendix E)

NYSEARCH/Northeast Gas Association (NGA) and Invodane Engineering Ltd. (IE) completed a technology license agreement in 2008 that had the entire NYSEARCH robotics technology (Explorer II and TIGRE) transferred from NYSEARCH to IE. The overall objective of the technology transfer was to prepare the Explorer II and TIGRE technologies for operational deployment, demonstrations, and subsequently commercialization in the North America market.

The technology transfer process was initiated in January 2009 with all available equipment, software and mechanical and electronics drawings transferred from the technology developers (CMU, Automatika and SwRI) to IE. Consultants were hired to help with this technology transfer effort, in order to expedite the process. Overall, the process proved to be efficient and effective despite some issues with missing information, data and hardware. Two different teams were formed within Invodane, one dedicated to the Explorer II system and one to the TIGRE system.

5.5.1. TIGRE Technology Transfer and Further Development

The technology transfer process began in February 2009 with the transfer of hardware, software, and documentation related to the TIGRE robot from AI to IE. The MFL sensors, originally developed by IE, were already in the possession of IE. This transfer process took place in several phases. The first phase saw the transportation of TIGRE modules and the experimental pipe network for testing and simulation (see Fig. 5.5.1.1). Follow-on phases of the process saw software and documentation transferred to IE. Initial evaluation of the hardware, software, and documentation revealed some of the software and documentation were omitted from the transfer process. The software omitted was necessary for any modification of the software. However, all modules were already programmed with software allowing IE engineers to assemble and perform basic function testing of each module over the next several months.

Each TIGRE module that was transferred to IE during the technology transfer process was evaluated. Basic function testing was first performed on each module. IE engineers also estimated the amount of electrical and mechanical repairs necessary on each module and the amount of work to revitalize each module. The goal was to assemble all modules to reconstruct TIGRE. IE engineers identified a number of critical issues during the evaluation process. The lack of original software was one of the most critical issues as substantial effort would be required to reconstruct the software. While there were some mechanical and electrical damages to various modules, they could be replaced, repaired and overcome. Other critical issues identified included the complexity of the power bus design, complexity of control, lack of reliability, tight tolerance, and limited inspection range.

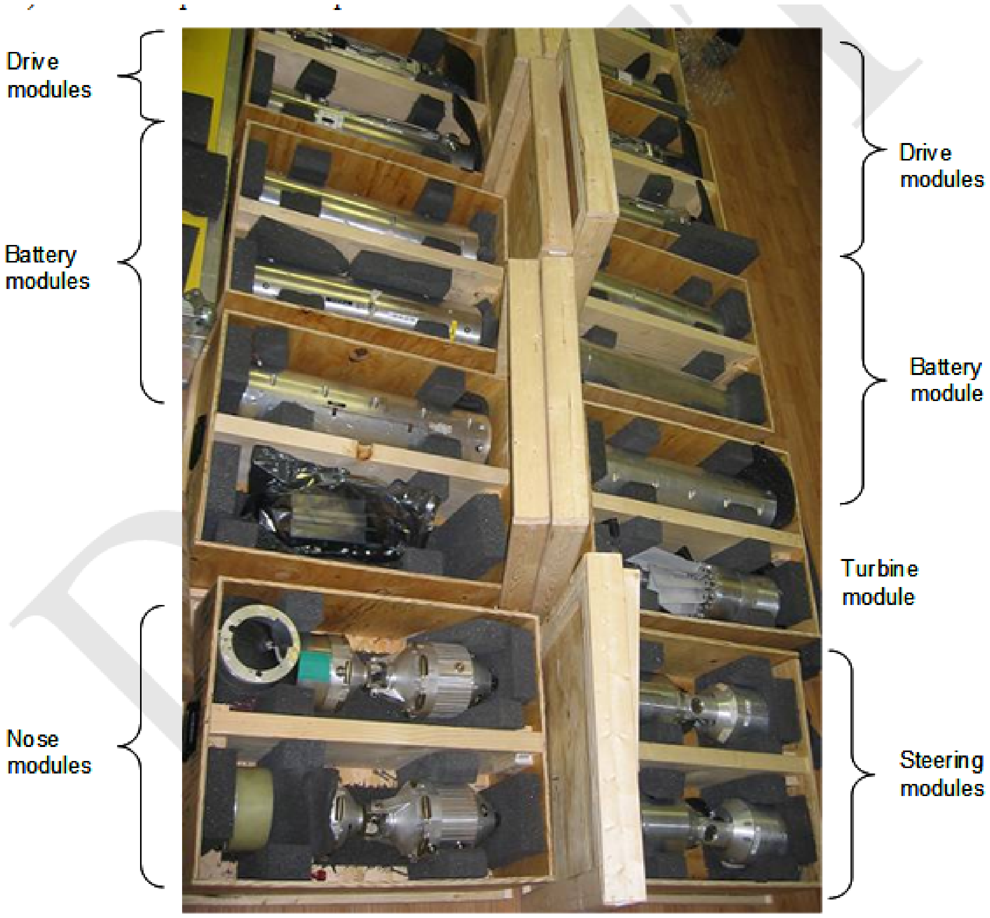


Figure 5.5.1.1: *TIGRE hardware as shipped to Invodane*

During the TIGRE test at the NYSEARCH Test Bed in 2007, before the technology transfer process, it was suspected that the wireless communication system was misbehaving, potentially due to the specific configuration of the test loop, resulting in a series of control issues during the test. Consequently, IE engineers decided to configure the nose modules of TIGRE where the wireless communication system resides and revisit the test loop to verify the behavior of the system see Fig. 5.5.1.2).

The original TIGRE wireless system performed reliably during this test eliminating doubts of any fundamental issues with the wireless system.

Figure 5.5.1.2: *Vehicle built for wireless test at NYSEARCH Test Bed*

Upon completion of the evaluation of the original TIGRE, the following implementation plan was developed. The original TIGRE system would be simplified to a final TIGRE that is operationally more efficient and friendly without any sacrifice in performance and compromise to the target specification (see Table 5.5.1.1). However, an “Intermediate TIGRE” version would be constructed, prior to the final TIGRE, from as much of the original TIGRE hardware as possible. The intermediate TIGRE would serve as a building block and a test platform for the final TIGRE. Any software that requires reconstruction or further development would be first tested on the intermediate TIGRE before further refined and developed on the final TIGRE. Referring to Fig. 5.5.1.3, the final TIGRE would be substantially reduced in length and weight by eliminating some modules thereby simplifying the original TIGRE and enhancing operational efficiency. Operational equipment such as launcher will be designed and developed. Data analysis software for sizing and processing data also needs to be developed.

***Table 5.5.1.1:** Target specification of final TIGRE*

Parameter	**Target**
Pipeline product	Natural gas
Pipeline diameter	20 to 26 inch
Maximum pressure	750 psi
Inspection range	1 to 2 miles
Weight	600 to 700 lb
Length	10 to 15 ft
Inspection speed	4 inch/s
Inspectable wall thickness	.5 in
Launch and retrieve	Hot tap fitting
Time required to negotiate mitered bends and plug valves	15 to 20 minutes
Battery consumption during launch or retrieve	3 to 5%
Minimum diameter	75% of OD
Smallest bend radius	Mitered bend
Valve negotiation	18 inch plug valve

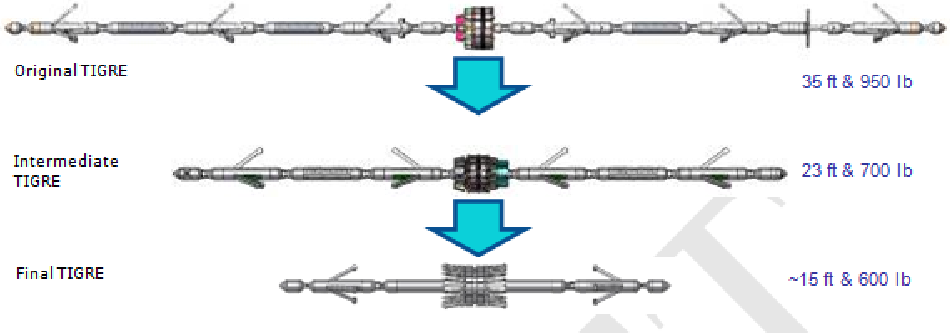


***Figure 5.5.1.3:** Schematic illustrating simplification of original TIGRE to final TIGRE and building of the Intermediate TIGRE during this process*

Figure 5.5.1.4 shows a schematic of the Intermediate TIGRE while its specifications are given in Table 5.5.1.2. It is approximately 23 ft in length and 700 lb. It consists of 2 nose modules, 2 drive modules, 2 battery modules, and a new, modified MFL sensor.

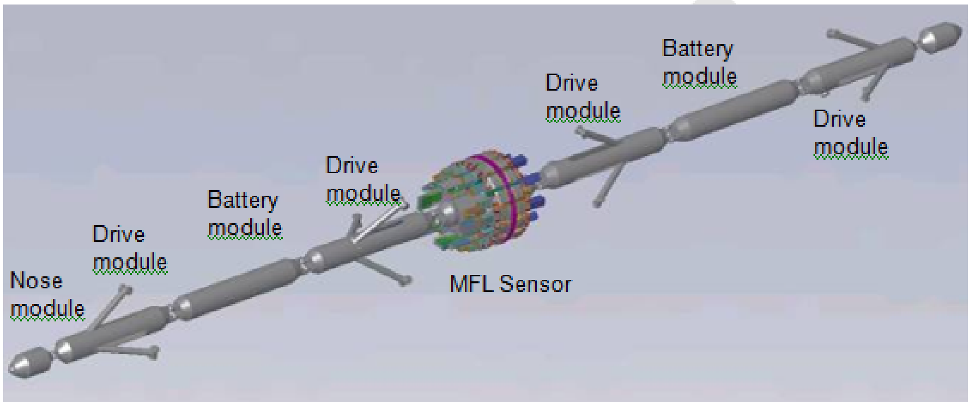


Figure 5.5.1.4: *Schematic of Intermediate TIGRE*

Table 5.5.1.2: Specification of Intermediate TIGRE

Parameter	**Target**
Pipeline product	Natural gas
Pipeline diameter	20 to 22 inch
Maximum pressure	Atmospheric pressure
Inspection range	2,000 ft
Weight	600 to 700 lb
Length	23 ft
Inspection speed	4 inch/s
Inspectable wall thickness	.5 in
Launch and retrieve	Open ended straight pipe
Minimum diameter	17 inches
Smallest bend radius	1.5D
Valve negotiation	No

The intermediate TIGRE design included redesign and modification of the nose modules, drive modules, battery modules, steering modules and graphical user interface, as well as a major redesign of the MFL sensor module. The magnetic circuits on the original 20 to 22 inch MFL sensor were retained and modified for use on the Intermediate TIGRE. The most substantial changes on the MFL sensor were the addition of battery units that are dedicated for powering the MFL sensor and the addition of drive capability on the MFL sensor. These additions eliminated the need of two battery modules and two drive modules on TIGRE. While this MFL sensor on the Intermediate TIGRE is capable of varying diameter from a maximum of 22 inches to a minimum of 17 inches, the ability to go through plug valves was sacrificed for simplicity. The Final TIGRE, however, would retain the ability to negotiate plug valve.

At the end of this phase of the project, the Intermediate TIGRE was constructed and prepared for testing in an abandoned pipeline in Van Nuys, CA owned and operated by the Southern California Gas Company. This testing will take place under a different program, which includes the development and commercialization of the final TIGRE by 2012. Remaining efforts in this follow up program includes completion of the Final TIGRE by adopting many of the design improvements, software and hardware components that were successfully developed and tested on the Intermediate TIGRE. Other remaining efforts include development of operational equipment such launching and retrieving equipment, and data analysis software for sizing and processing data. The TIGRE technology will be thoroughly validated through a series of tests and demonstrations in the underground pipeline network in Binghamton and several live pipeline locations.

5.5.2. Explorer II Technology Transfer

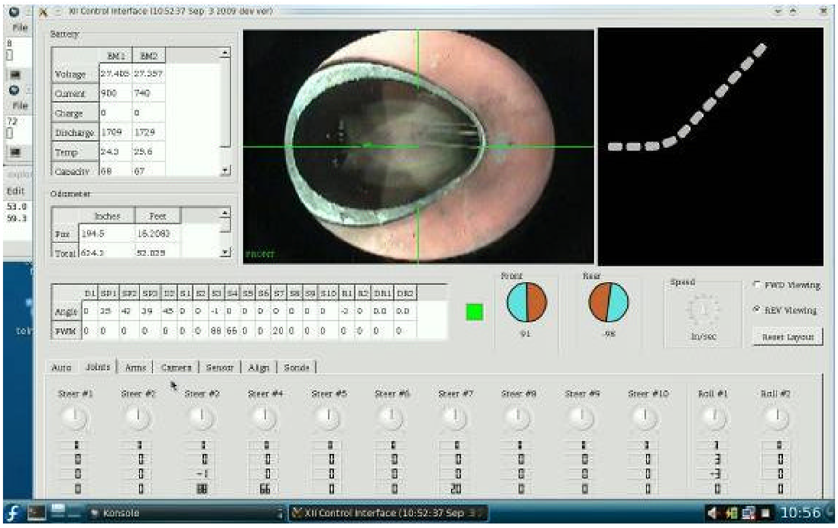
In early 2009, the Explorer II robot was delivered to IE along with all associated spares and development equipment. Shortly thereafter a consultant, familiar with the Explorer II platform, was hired to train IE personnel on the design of the system and to provide instruction on how to operate the robot. To facilitate the instruction, a short pipe loop was built in the IE warehouse, seen in Fig. 5.5.2.1, consisting of a number of 8” pipe segments, a 90 degree elbow bend and a 45 degree hot-tap connected to a gate valve and launch tube.

Following the training on the Explorer II platform, a number of IE personnel began a training program with the designers of the RFEC-based sensor module at SwRI. The training on the RFEC sensor began with a series of web meetings and conference calls over the course of two days to review the microprocessor firmware and user interface software as well as a step-by-step instruction on the method for analysis of pipeline defect data. This online training was followed by person to person training by two IE engineers at SwRI in Texas. This stage of the training was focused on the design and construction of the mechanical and electrical systems on the sensor. Included during this three-day training course was a review of all mechanical and electrical drawings, a partial disassembly and assembly of the module, setup of the system, scans of pipes with machined defects and the analysis of the resulting data. Following the training, the sensor module and all associated spare parts were sent to IE for integration with the Explorer II robot.

Figure 5.5.2.1: *Invodane in-house pipe loop for Explorer II with typical pipeline features*

Once the operators and engineers had run Explorer II for long enough to understand the workings and limitations of the system, the team performed a failure mode analysis on the entire robot. Each part of the system was looked at in isolation to create a list of ways that part could fail. From there, the operational impacts of each method of failure were listed. Each method of failure was analyzed by the group to determine the probability of failure and the severity of each corresponding impact of the failure was determined. Finally, each failure was analyzed to determine the ease of detection and repair. The results of these analyses were used to rank the failures – with the highest being the most critical and the lowest being the least critical. This list was then used to determine where improvements should be made to Explorer II which would have the greatest positive impact on the operation and reliability of the system. This failure mode analysis was performed again a number of times throughout this program to continually re-focus attention to the next most important piece of the system for improvement.

During in-house testing, it became clear that, while functional, the operator interface was not intuitive to use and the layout was confusing and occasionally caused the operator to make errors in the manipulation of the robot. As a result, during testing and practicing prior to the first field demonstration and, to a lesser extent, throughout the entire commercialization effort of the robot, the operator interface was gradually improved to make operation of the robot more intuitive and to eliminate functional problems.



	BM1	BM2
Voltage	27.405	27.357
Current	900	740
Charge	0	0
Discharge	1709	1729
Temp	24.3	25.6
Capacity	68	67

	Inches	Feet
Pos	194.5	16.2083
Total	624.3	52.025

	D1	SP1	SP2	SP3	D2	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	R1	R2	DR1	DR2
Angle	0	25	42	39	45	0	0	-1	0	0	0	0	0	0	0	-2	0	0.0	0.0
PWM	0	0	0	0	0	0	0	88	66	0	0	20	0	0	0	0	0	0	0

Figure 5.5.2.2: *New Explorer II operator interface*

During training at SwRI, the original designers expressed concern about the specific connector used in various locations on the RFEC sensor. During mating of the RFEC sensor module with the Explorer II robot, it was clear that the connector used to electrically connect the RFEC sensor with the robot was not robust and was prone to failure. Soon after the initial function testing of the RFEC sensor mated to the robot a smaller, yet more robust connector was found and used to replace those used on the RFEC sensor.

Also during the training at SwRI, the original electrical designer suggested that the circuit boards installed on the sensor should be redesigned and replaced before extensive field use due to the patches and modifications made to the boards to fix layout errors or modify functionality. As a result, all five circuit boards on the RFEC sensor were redesigned and replaced thus, increasing the overall reliability of the operation of the RFEC sensor. Other issues were also identified and corrected such as repeated crashing of the RFEC sensor user interface and the microprocessor on the sensor module that would not always boot up properly after being powered on.

After running Explorer II for half a year (including hundreds of simulated pipeline launches and un-launches and negotiation of bends) a mechanical overhaul was performed to evaluate the wear on the robot’s mechanical systems. This was also crucial in generating a service/maintenance schedule for the robot, detailing when certain parts should be inspected and replaced.

In addition to the above described changes in the system, a number of major redesign efforts and new hardware additions were undertaken to improve the operational reliability, performance and operational efficiency of Explorer II. These efforts were initiated under this program, but were completed in a follow up program. They are as follows:

Electrical connectors between modules

A significant improvement made to Explorer II was the re-designing and replacing of the electrical connection between each module. As originally designed, power and communication was carried from one module to its mated module through a series of spring-loaded contacts. This design resulted in a simple assembly process, but also proved quite unreliable over time. As a result, a new interconnect design that features a solid connection between pins and mating sockets was adopted and implemented. This design was to be later verified and finalized in a follow up program to this one.

New higher capacity batteries

As seen during the field demonstration in Brookville, the primary limitation to inspection range was the capacity of the on-board batteries. Because of this, there has been a continual effort to increase the inspection range. After gaining experience into the behavior of the system and after some mechanical modeling, it was determined that the size of the modules on the robot could be increased with little impact on the operation (such as fitting through a hot tap opening for launch and unlaunch). The additional volume inside this increased module size would be best used in the two battery modules, where larger batteries, with increased capacity, would increase the distance the robot could travel before needing to be recharged.

Higher capacity batteries were selected that fit inside the larger module, with an effective capacity increase of near 60% (see Fig. 5.5.2.3). The assembled modules were extensively tested, charged and discharged prior to field use. All indications were that the new modules functioned as designed while allowing for the increased inspection distance.

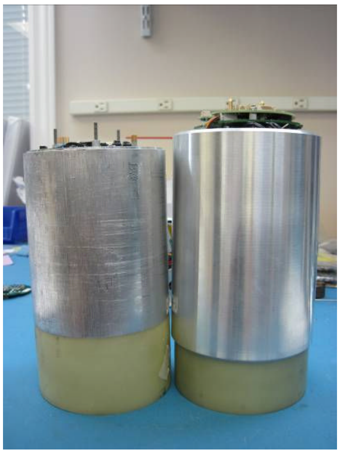


Figure 5.5.2.3: *An original Explorer II battery module (left) and a new, higher capacity battery module (right). (Yellow ring on bottom of both modules is for support and is not part of the module.)*

Launch Assist and Tether Module (LAT)

Another effort to increase the inspection distance per deployment was the development of the Launch Assist and Tether (or LAT) module. A substantial amount of power during Explorer II's deployment was consumed during the site preparation (i.e.: loading

Explorer II into the launch tube, hoisting the launcher into place and bolting to the pipeline, pressure equalization of the launcher, etc), launching Explorer II into the pipeline, unlaunching Explorer II and removing the launcher from the pipeline. Added together, roughly 15% of the available on-board battery capacity was being consumed during these stages in an inspection. Further, one factor in the deployment cost for an inspection is the requirement for the pipeline operator to install a 2 inch hot tap to allow installation of the in-pipe antenna for wireless communication with Explorer II. If the need for this tap could be eliminated, this would decrease the cost of the inspection for the operator.

A separate device was envisioned that could achieve both improvements while providing a platform for future development and addition of capabilities to the platform such as: rescue vehicles, coupon retrieval and providing power to Explorer II for hundreds of feet down the pipe via a tether mechanism. Following a concept development phase, a final design was chosen based on a modular mechanical construction, similar to Explorer II, with self-contained drive, battery, tether spool and tether payout modules. A lockable socket would be connected to the end of a short tether that would provide power to Explorer II until the robot was launched into the pipe, when the socket would be detached from Explorer II's nose module and the robot would return to operation using its internal batteries for the remainder of the inspection. The in-pipe antenna is attached to the end of the LAT sticking into the pipeline. Wireless

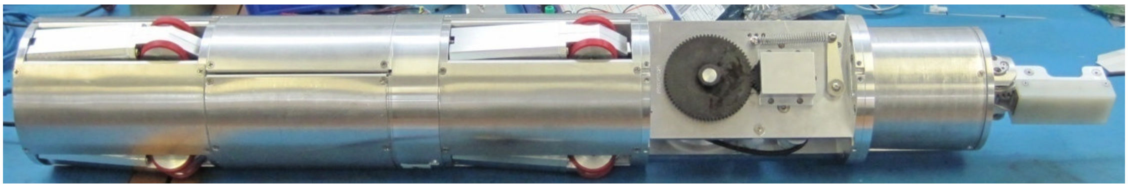


Figure 5.2.2.4: *Picture of the final Launch Assist and Tether vehicle, as shown with only 1 battery module.*

communication with the robot will take place via this antenna, negating the need for the additional in-pipe antenna. When Explorer II returns to the launch site, it would re-attach to the socket and draw power from the LAT's internal batteries during the unlaunching and retrieval process. In the first deployment of the system, the range of the wireless signal coming from the modified antenna on the LAT was less than that seen with the normal in-pipe antenna; the cause of this difference has yet to be determined but will be addressed in the follow up phase of this work.

Pipeline Feature Scripting

Explorer II, as developed by CMU, was capable of negotiating pipeline features (hot taps, bends) by using an approximated mathematical model of the feature. Over time it was observed that this model did not take into account the variances found between two features of similar types nor did it properly account for the real-life operation of the Explorer II system, with its associated mechanical tolerances and while moving with or against gravity. This behavior of the model exhibited itself during tests in-house, negotiating simulated launches and bends, where the robot frequently became jammed in the pipe as the actual behavior of the robot progressively diverged from the ideal model.

A new feature scripting approach was developed that models the movement of Explorer II through the pipeline feature to be negotiated with a Computer Aided Design software package. A script is created with this model which describes the required movement of each module to negotiate each pipeline feature. This method yields much more consistent behavior of the robot during feature negotiation and substantially improved negotiation of actual features in pipelines. This improved response, during launching and un-launching, for instance, yields quicker negotiation of features and, hence improved power consumption figures and greater inspection distances.

Finally, following the first deployment of Explorer II under this phase of the program, it was determined that the "shoes" of the RFEC sensor, each carrying four sensors against the pipeline wall, were not reliable enough and were not always able to provide high quality data. In addition, occasionally the arms carrying the sensors had problems negotiating the welds encountered in pipelines. Consequently an effort was undertaken to improve this component of the sensor module. The twelve arms, each carrying 4 sensors, were replaced with 48 arms, each carrying one sensor. This configuration ensures that each sensing element is capable of independent movement during operation and is capable of compression down to the hard diameter of the sensor module body in order to comply with even the most aggressive welds or other pipeline features with no impact on operation. This design modification was proven to resolve the issues of data quality and weld negotiation that the previous encountered. All of the existing electronics were unmodified.

5.6 Field Testing of Explorer II (Detailed Report in Appendix E)

5.6.1 Brookville, PA – First Deployment

Explorer II was deployed in an 8 inch diameter live pipeline owned and operated by National Fuel Gas Distribution Corporation (NFG) in Brookville, Pennsylvania during the week of July 20, 2009. This was the first field deployment since the technology transfer from NGA to Invodane. The location of the demonstration was set to be the same location as a previous, CMU-led, demonstration of the robot in September 2007. The launch site had a 6 inch, 45 degree hot tap for launching the robot as well as a 2 inch hot tap for the wireless antenna installed prior to this previous demonstration.

Figure 5.6.1.1: *Picture of Explorer II launch site in Brookville, PA*

Explorer II was deployed into and out of the pipeline twice, traveling as far as 600 ft from the launch point. About 100 ft of integrity data was collected and valuable operational experience was gained. A communication issue prevented a third deployment as a safety measure. Initial diagnosis of the root cause to this issue suggests that an intermittent electrical connection overloaded the communication bus leading to the communication and control issues experienced.

5.6.2 Brookville – Second Deployment

Explorer II was re-deployed into the same National Fuel Gas' pipeline during a field demonstration in September 2009. Over 2,000 feet of this pipeline was successfully inspected. Good correlation between the length of each pipe predicted by the RFEC sensor (by analyzing the odometer signal between weld signatures) and the indicated as-built lengths provided by NFG (in the weld location report) was obtained.

5.6.3 Phoenix – Third Deployment

As part of a technology demonstration program led by the Northeast Gas Association (NGA), two Explorer II surveys were performed by the Invodane Engineering team over a period of two days on an 8 inch natural gas pipeline in Phoenix, Arizona, in June 2010. Figure 5.6.3.1 shows the excavation site and launcher installed on the pipeline.

Figure 5.6.3.1: *Launching apparatus for Explorer II in Phoenix demonstration; (a) fitting and valve, (b) launcher (yellow pipe) attached to valve.*

Survey 1 covered a line length of about 2,000 ft north of the launch site. The full line length of video data was accepted for analysis, but only about 900 ft of sensor data of the survey were accepted for analysis. The rest was rejected because the signals from this length of pipeline were of insufficient quality for data analysis. Survey 2 covered a line length of about 1,500 ft south of the launcher, both the sensor and video data of this survey being of good enough quality to be accepted. The issue faced with data quality triggered the redesign of the sensor, as described earlier, which resolved these issues.

5.6.4 Oneida – Fourth Deployment

The surveyed pipeline, owned and operated by National Grid, is a 6” pipeline operated at pressures above 400 psig. This deployment took place under harsh weather conditions, with constant rain for the first three days that soaked the ground and flooded the excavation sites. Two launch/un-launch sites, Site A and Site B, were used for the three surveys performed during the demonstration. The first two and a half days of the demonstration, which took place in October, 2010, were used by National Grid and T.D. Williamson to complete the hot tap and mount a valve at Site B. During the launch process, a feedback sensor in one of the support modules ceased to communicate with the control system. The launch operation was aborted and the sensor was replaced. Once the robot was launched the next day, a large helical metal ribbon - residue from the hot tap - obstructed the pipeline at the hot tap. The launch was aborted until the ribbon could be removed from the pipeline. Once this issue was resolved, Survey 1 was initiated that covered a line length of about 250 ft, covering the pipeline segment south of Site B (Fig. 5.6.4.1). However, two 90º bends spaced approximately 5 ft apart were discovered in the pipeline - a bend configuration that was not expected by Invodane or National Gird. While Explorer II is capable of crossing this bend configuration, Invodane decided against navigating the two bends during the demonstration without prior simulation. Explorer II was stopped at the entrance of the first 90º bend and scanned the pipeline while returning to Site B.

Survey 2 covered a line length of about 1600 ft north of Site A (Fig. 5.6.4.2) that was used to launch and retrieve the robot. After scanning the pipeline, the SONDE transmitter onboard Explorer II was used to successfully locate the tool within the pipeline at the end of the scan location thus validating the functionality of the SONDE. Finally, Survey 3 covered a line length of about 3,000 ft, beginning at Site B and scanning north toward Site A. Site B was used as the launch site and Site A was used as the un-launch site. In all these surveys the robot successfully scanned the pipeline collecting good quality data thus validating all hardware and software changes implemented after the Phoenix demonstration. This completed the final field demonstration of Explorer II prior to commercialization.

Figure 5.6.4.1: *Launching Site B in Oneida, NY; (a) fitting and valve, (b) launcher (yellow pipe) attached to valve.*

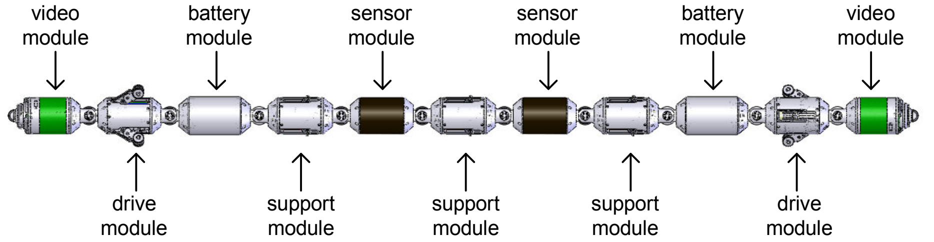
Figure 5.6.4.2: *Launching Site A in Oneida, NY.*

This demonstration was the end of the Explorer II effort under this program. As mentioned earlier, Pipetel Technologies, a sister company to Invodane Engineering formed to commercialize the robotics technologies and provide inspection services to the industry, announced the commercial launching of this technology just prior to the completion of this program in December 2010.

5.7 Explorer II Final Specification

In December 2010, at the conclusion of this project, the final specifications of the Explorer II system are summarized in table 5.7.1.

Table 5.7.1: *Explorer II inspection robot technical data.*

Explorer II		
General Information	tool applications	pipe mapping and feature detection, identification, and sizing
	detection technologies	RFEC and video capture
Mechanical Specifications	tool length	9 ft
	operational tool weight	65 lbs
Pipeline Requirements	surveyable pipe diameters	6 or 8 NPS
	minimum clearance diameter	4.5 in
Technical Specifications	maximum inspection range	0.6 mi per launch/un-launch site
	speed range	0 - 4 in/s
	maximum operating pressure	750 psig
	launch method	hot tap
	un-launch method	hot tap
Detection Technology Details	RFEC sensor count	32 (6 NPS) or 42 (8 NPS)
	RFEC axial resolution	0.05 in
	RFEC circumferential resolution	11.2° (6 NPS) or 8.5° (8 NPS)
	video module count	2
	video module locations	front and rear
General Metal Loss Reporting Specifications	minimum anomaly size	20% wall loss with a diameter of 3x pipe wall thickness
	anomaly length (axial) sizing accuracy	TBD
	anomaly depth (radial) sizing accuracy	TBD

6. RESEARCH FINDINGS AND DISCOVERIES

This research and development program, initiated in 2003, has proven that:

1. The inspection of unpiggable natural gas transmission pipelines is viable, no matter what the reason for the pipeline being unpiggable is.
2. Robotics technology is mature enough to offer solutions to the problem of inspecting unpiggable pipelines.
3. Sensor technology options exist to accommodate the special restraints imposed on NDE inspection systems by the extreme limitations of the robotics platforms that carry them in unpiggable pipelines.
4. Wireless technologies provide an excellent solution to communication needs of robotic systems for the inspection of unpiggable pipelines, thus eliminating the need for range-limiting tethers.
5. Negotiation of the most challenging obstacles is possible by these robotics devices, including back-to-back bends and plug valves.
6. The deployments of these robotic systems do not require special launch and receive facilities, as is the case with smart pigs. They can be launched and retrieved using off-the-shelf fittings.
7. The Explorer II platform can successfully, reliably, and efficiently inspect 6” – 8” unpiggable pipelines. It can accomplish that in the absence of any flow in the pipeline and in the presence of practically any obstacle (excluding a plug valve).
8. The RFEC sensor integrated in the Explorer II platform can provide accurate and reliable data regarding the presence of defects in unpiggable pipelines, and size those defects to an acceptable level.
9. The TIGRE platform can successfully, reliably, and efficiently inspect 20” – 26” unpiggable pipelines. It can accomplish that in the absence of any flow in the pipeline and in the presence of practically any obstacle (including a plug valve).
10. The MFL sensor integrated in the TIGRE platform can provide accurate and reliable data regarding the presence of defects in unpiggable pipelines, and size those defects to a level comparable of present day state-of-the-art smart pigs.

The discoveries made in the course of this project are protected as know-how by the interested parties. Background intellectual property includes two patents. No patent applications have been filed under this program.

7. CONCLUDING REMARKS

This program, which is focused on developing technologies to inspect unpiggable natural gas transmission pipelines, has been a major strategic investment by government and industry and there is every indication that it will become a major success in the market. Through this collaborative effort NYSEARCH and PHMSA (with additional support by the USDoE and OTD) have addressed a technology gap associated with the most challenging segments of the natural gas unpiggable pipelines market. While pigging companies have slowly started addressing various aspects of the unpiggable pipelines market, no company has attacked the cases of pipelines with no flow; pipelines with mitered bands; or pipelines with plug valves.

The technology developed through this program is based on robotic platforms using state of the art electronics, software, communication and sensing technologies. The integration of such technologies in a complete engineering system is extremely challenging, as indicated by the time needed to complete the development of the Explorer II and TIGRE prototypes. Equally challenging is the requirement for reliability, operational efficiency and robustness needed by any commercial grade tool. The extensive field demonstrations carried out as part of this program allowed us to make necessary design modifications and improvements to make sure that the final tools are indeed of commercial grade.

Explorer II has already entered the market and is carrying out inspections on a commercial basis. TIGRE is now in the final stage of its development, which is expected to result in a commercial grade prototype in early 2012 and commercialization later that year. In addition, Pipetel Technologies with funding outside this program is going to introduce in the market a 10” to 14” tool later in 2011. It is anticipated that by 2014, Pipetel Technologies will be able to service the entire 6” – 36” pipeline sizes range thus concluding a development and commercialization effort started in 2001 that will transform the in-line inspection industry.

8. ADDITIONAL WORK

As mentioned above, additional work is needed to complete the development of the Explorer II and TIGRE systems. As a result, a program was proposed to DoT/PHMSA in order to accomplish that. The program has been approved for funding and was initiated in October 2010 with cofunding from NYSEARCH/NGA, DoT/PHMSA, OTD, Invodane Engineering and SD7C (an organization funded by the Canadian Government). The objective of this project is to complete the development of the Explorer II and TIGRE robotic systems for the inspection of natural gas unpiggable pipelines. Design modifications, aimed at increasing the reliability of the system and its operational range, will be implemented on the Explorer II platform in order to minimize deployment and operational costs. In addition, commercial grade sizing algorithms will be developed for the RFEC sensor, which are essential to the quality of the data generated and will ultimately determine the success of this product in the market. Regarding the TIGRE system, and based on experience gained through the first deployment of the system in a dead pipeline network, design modifications will be implemented to make the system lighter and smaller, thus conserving power and improving operational deployment characteristics. These system enhancements will be followed by a number of field deployments which will be carried out to prepare it for commercial deployment. The Explorer II effort will be completed in early 2011, while the TIGRE effort will be completed in 2012.

9. DISSEMINATION OF RESULTS - PUBLICATIONS

A number of conference/workshop presentations, conference papers, and gas industry publications were prepared to disseminate the results of this program as given in the following list.

1. *R. Lee, P. Laursen, D. D'Zurko and J. Vitelli,* Robotic Inline Inspection of a 6 inch Unpiggable Natural Gas Pipeline with Explorer II, Unpiggable Pipeline Solutions Forum Houston, TX, March 30-31, 2011.
2. *P. Laursen and D. D'Zurko,* Development of a Robotic System for the Inspection of Large Diameter Unpiggable Natural Gas Pipelines Using an MFL Sensor, Unpiggable Pipeline Solutions Forum, Houston, TX, March 30-31, 2011.
3. P. Laursen, D. D'Zurko, G. Vradis, and C. Swiech, Robotic inspection of unpiggable natural gas transmission and distribution pipeline, Proceedings of the 8th International Pipeline Conference , IPC2010-31270, September 27-October 1, 2010, Calgary, Alberta, Canada.
4. P. Laursen, G. Vradis, and C. Swiech, First robotics device to inspect unpiggable gas transmission pipeline, Pipeline & Gas Journal, November 2009, Vol. 236, No. 11.
5. G. Vradis, Robotics program for the inspection of unpiggable natural gas transmission pipelines, US Department of Transportation Workshop, Arlington, VA, June 2009.
6. *G. Vradis* , New Robotics-Based Technologies for the Inspection of Natural Gas Unpiggable Pipelines, International Gas Research Conference, Paris, France, October 2008