Design, Construction and Field Demonstration of
EXPLORER:
A Long-range Untethered Live Gasline Inspection Robot
System

Semi – Annual Report

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Dr. George C. Vradis
Consultant to the RD&D Director
Northeast Gas Association

Dr. Hagen Schempf
Principal Systems Scientist
Robotics Institute, Carnegie Mellon University

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Northeast Gas Association
1515 Broadway, 43rd Floor
New York, NY 10036

Robotics Institute, Carnegie Mellon University
500 Forbes Avenue
Pittsburgh, PA 15213

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ABSTRACT

This program is undertaken in order to construct and field-demonstrate *EXPLORER*, a modular, remotely controllable, self-powered, untethered robot system for the inspection of live gas distribution 150 mm (6-inch) to 200 mm (8-inch) diameter mains. The modular design of the system allows it to accommodate various components intended to accomplish different inspection, repair, sample retrieval, and other in-pipe tasks. The prototype system being built under this project will include all the basic modules needed, i.e. the locomotor, power storage, wireless communication, and camera. The camera, a solid-state fisheye-type, is used to transmit real-time video to the operator that allows for the live inspection of gas distribution pipes.

The system under development significantly advances the state of the art in inspection systems for gas distribution mains, which presently consist of tethered systems of limited range (about 500 ft from the point of launch) and limited inspection views. Also current inspection systems have no ability to incorporate additional modules to expand their functionality.

This development program is a joint effort among the Northeast Gas Association (formerly New York Gas Group), the Jet Propulsion Laboratory (JPL), the Johnson Space Center (JSC), Carnegie Mellon University's (CMU) National Robotics Engineering Consortium (NREC), and the US Department of Energy (DOE) through the National Energy Technology Laboratory (NETL)

The present report summarizes the accomplishments of the project during its fifth six-month period. The project has in general achieved its goals for this period as outlined in the report. The prototype robot is undergoing extensive endurance testing in order to prepare for the field demonstrations planned for June 2004.

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EXECUTIVE SUMMARY

During this reporting period the project has concentrated in extensive endurance testing in preparation of the two field demonstrations planned for June 2004. In the process the robot has received upgrades in some of its electronics in order to increase system performance. A successful demonstration of the robot was given to prospective commercialization partners in November 2003. A successful acceptance demonstration was given to NETL/DoE personnel and managers on December 17, 2003, at CMU. The robot performed flawlessly demonstrating that it has achieved its goals. Subsequent to that demonstration, the electronics of the camera system were upgraded in order to increase the frame rate of the camera from two frames per second to ten frames per second. All turning routines have been developed and tested. The routines for the low pressure launching system have been completed. The routines for the high pressure vertical launcher will be developed in the next reporting period. At the end of this reporting period the robot has been accumulating operating hours without any operational problems. Additional endurance testing is however required prior to releasing the system for field demonstrations, scheduled for June 2004.

INTRODUCTION

(not updated since last report)

This project concentrates on finalizing the design, constructing a prototype and conducting laboratory and field demonstrations of an autonomous inspection camera system. This system will be used for repair/rehabilitation planning and overall maintenance purposes of the natural gas distribution infrastructure. Robotic systems that provide inspection and repair have found substantial application in the gas industry in the last decade or so. Existing systems are tethered, thus limiting the range of these tools to approximately 200 m (500 feet) of straight pipe from the launching point. As a result, in the case of inspection/repair work in long or less than straight pipes, excavations and subsequent pavement restorations are needed every 200 meters, making the deployment of these systems very expensive. In addition, the existing robotic systems do not offer any flexibility in operation. It is impractical to add to the features of these systems because a major redevelopment effort would be required.

The proposed program concentrates on the development of an advanced robotic system, called ***EXPLORER***, for use in the maintenance of gas distribution systems. ***EXPLORER*** has the following characteristics:

1. Modular design. The system is built as a series of inter-connectable modules, that can be assembled in a desired fashion to achieve specific goals. The basic system, being developed as part of this effort, includes the core modules which are: locomotion, energy storage, and camera. Additional modules will be developed in the future to provide for more functionality. Such modules could include repair tools (for conducting repair work inside a pipe), sample retrieval tools (for retrieving liquids from inside the pipeline for

chemical analysis), and sensors (for the measurement of a variety of properties of interest, such as metal loss, flow rates, pressure, stresses on pipe elements, etc.).

2. Deployment under live conditions. The robotic system is designed so that it can be inserted into the pipe in a way that minimizes deployment expenses. Operation under live conditions allows the customer to continue to have gas service at all times, but imposes strict safety design criteria.
3. Tether-free operation. The robotic system does not use a tether to provide power and two-way communication for the system. Power is provided by a stack of high-performance batteries stored on-board in one of the modules. Two-way communication is provided via a wireless system based on commercially available technology with a transmitter/receiver module being part of the basic robot.
4. Versatile locomotion system. The locomotion system has low power requirements and is able to negotiate 90 deg bends/tees in the piping system. It is also able to ascend and descend through inclined and/or vertical components of the piping network. The locomotion system is able to negotiate changes in the diameter of the pipe in the range of 150 to 200 mm (6" to 8"). Cruising speeds are about 6 m/min (20 ft/min).
5. Fish-eye camera system. **EXPLORER** features a fish-eye camera with a field of view of 190-degrees (compared to 90-degrees for existing inspection systems) in conjunction with a picture dewarping feature that allows detailed, high resolution view of the entire forward and lateral fields. The result is an increased ability of the operator to determine and identify any features in the field-of-view (FOV) without the need for any panning/tilting camera mechanism which would slow down inspections.

The work conducted in this project is the continuation of work in progress, initiated in January 2000. This earlier work concentrated in the preliminary design of the **EXPLORER** robotic system, the complete design (on paper) of the resulting concept, and the construction and testing of the camera system to be integrated in the **EXPLORER** in the proposed effort. During the earlier phase a GO decision was made by NGA (former NYGAS), based on the outcome of that effort. Following the successful completion of this on-going effort, another final program will be needed in order to develop the commercial unit as well as the auxiliary equipment that supports field deployment. These include the launching mechanism as well as keyhole access tools for the in-pipe recharging of **EXPLORER** and other keyhole tools for the insertion of wireless communication antennas into the piping network. Additional funding will be required for this effort, however, it is anticipated that it will be substantially less expensive than the present one.

The main challenges of this project lie in the areas of (i) power-autonomy, (ii) wireless bi-directional communications inside a pipe, *i.e.* cylindrical environment, (iii) adaptable locomotion inside such environments and (iv) operational issues related to reliability, safety and failure-recovery.

Power-Autonomy

During the earlier effort JPL addressed the theoretical issues related to the possibility of utilizing turbines to harness the energy available in the flowing gas to produce electricity to propel the **EXPLORER**. In that case, the system would utilize a combination of stored energy (batteries) and batteries under re-charge via the turbines in order to provide a completely autonomous power system. JPL conducted an analysis (based on flow data

provided by Keyspan for its pipe network in Brooklyn and Staten Island, and the state-of-the-art in turbine and battery technologies) in order to determine the proper turbine design and the expected power-flow from such a re-charge system. It was determined that for most of the time during the year, the vast majority of pipes do not have the necessary minimum flow rates to provide sufficient recharging power. As a result this option was eliminated in a meeting of the Project Advisory Group at CMU in May 2000. It was decided that **EXPLORER** would feature an expanded battery module able to provide more than one mile of range within the pipe prior to requiring recharging.

Wireless Communication

The technology itself is already commercially available. However, antennas must be adapted for pipe environments. The critical element is what the range of the wireless communication system is going to be within the pipes. In addition, the effects of pipe material (cast iron, steel, and plastic) as well as pipe condition (in the case of cast iron and steel) and pipe-internal features (bends, elbows, Ts, etc.) on the range of the communications system is not well understood. JPL, using material provided by NGA (former NYGAS) member companies, conducted preliminary studies with cast iron pipes (expected to offer the worst case scenario) during the earlier effort. It was determined by CMU in additional experimentation that existing technologies offer long enough ranges for the technology to be viable today. It was also determined that upcoming technologies, expected to be commercially available in the next three years, will provide dramatic improvements in this area thus greatly expanding the already acceptable ranges. The Project Advisory Group during the milestone meeting of May 2000 gave the green light to CMU to integrate this system in the **EXPLORER**.

Adaptable Locomotion

The NREC team, drawing upon a description of internal pipelines from utilities and other current/previous project knowledge, coupled with power and efficiency constraints, developed several locomotor concepts (legged, wheeled, tracked, hydro/pneumo inchworms, hybrids, etc.), which were analyzed, compared and rated. In order to reduce power consumption, the Project Advisory Group approved the implementation of a rolling-locomotion system, which offered the best combination of speed as well as minimum power requirements for the particular pipe environment. NREC proceeded with finalizing the design of the **EXPLORER** based on this locomotor concept. This complete design was reviewed by the the Project Advisory Group in late January 2001 and accepted with some minor modifications.

Camera Imaging

The use of a miniaturized color-camera with embedded fisheye lens and lighting, coupled with real-time dewarping and image mosaiquing has been demonstrated by NASA's Johnson Space Center (JSC) in Houston. The same system will be ported to the miniaturized camera system of the **EXPLORER** and the software ruggedized and outfitted with a user interface. The hardware platform was built by NREC as part of the earlier effort, and a copy shipped to JSC for software calibration and porting. The finished software system was shipped to NREC for integration and testing at the conclusion of the earlier effort. Given the present limitations of the system, it will not be integrated into the control console of Explorer, but it will be available through a separate PC with dedicated analog video lines. The software was reviewed and accepted by the Project Advisory Group in late January 2001.

Operations

The issue of pipe-access and pipe-internal navigation and positioning during inactive or failure conditions was addressed as part of the design. Several options for live- access already exist (Mueller, IPSCO, etc.). In terms of positioning and navigation internal to the pipe, available sondes (for aboveground detection in failure-cases), odometry and INS systems represent the span of options to design into the system, depending on what the required accuracy is. In addition, the issues of recharging the batteries and introducing antennas in the pipe network to maintain wireless communication with the robot as **EXPLORER** moves, are being considered. Actual hardware to accomplish these tasks will not be built until successful completion of the present effort and the identification of a commercialization partner. These issues are being reviewed periodically by the Project Advisory Group.

Safety

In order to operate in a safe mode inside the pipe, the system needs to be designed to meet NFPA standards. **EXPLORER** will not have power-levels sufficiently low to qualify as an intrinsically-safe system. The notion of designing the system to be explosion-proof is also not realistic, as the required sizes, material- thicknesses, etc. result in a design that is far too large (diametrically and/or longitudinally), not to speak of the weight of the system. The adopted approach, akin to the one used in *Neptune* and GRISLEE (other products developed for pressurized structures), is to evacuate the oxygen-containing atmosphere from the insides of any enclosed bodies, purge these volumes with inert gas and then pressurize them with the same inert gas to a pressure slightly above the ambient pressure in the gas-main with built-in check-valves for pressure equalization.. Such an approach would suffice for Class I, Division 1, Group D environments based on previous experience with other remote systems currently

in commercial use (*Neptune* and others). This approach was reviewed and approved by the Project Advisory Group in May 2000.

EXPERIMENTAL

During the period of October 1, 2003 to March 31, 2004 the efforts of the project focused on:

- Explorer robot electronics upgrade
- Control software development
- Battery recharge system upgrade
- Demonstration of robot to potential commercializers
- Acceptance demonstration for NETL/DoE managers

Each of these areas will be discussed in further detail next.

- *Electronics Upgrade*

The EXPLORER electronics team continued the upgrade cycle, primarily focusing on issues of video camera performance and unwanted system interactions. The original camera board provided a frame rate of one frame per second, which is deemed marginally adequate. Consequently, the electronics were upgraded and as a result a higher frame rate was achieved; four frames per second without data compression, and more than ten frames per second with compression are expected. On another front, the robot was experiencing for a number of months automatic resets during operation of unknown origin. The CMU team finally determined that these resets were due to static electricity build up on the robot due to its operation in the plastic pipes of the indoor network. No such resets are experienced when operating in the outdoor cast-iron/steel network. CMU has implemented solutions to avoid this problem during testing in the future.

- *Control Software Development*

Software development is nearing completion. All turning routines for operation in 8" pipe have been optimized and validated. All turning routines for operation in 6" pipe are nearing

completion and optimization. The routines for launching the robot in low pressure systems have been developed and optimized also. The only routines remaining to be developed are those of launching using the high pressure vertical launcher developed in this program. They are to be completed by end of May 2004. In addition, the Graphic User Interface has also been updated to better serve the needs of the field demonstrations.

- *Battery recharge system upgrade*

Until recently the batteries had to be removed from the robot in order to be recharged. During this period, CMU developed and implemented the system that allows in-the-robot battery recharge, a feature necessary for optimum robot deployment.

- *Robot Pressure Testing*

The robot was tested in an 124 psig air environment, successfully passing the test, indicating that all electromechanical components are able to survive and operate in such pressures

- *Demonstration of robot to potential commercializers (November 2003)*

CMU demonstrated the EXPLORER robot prototype and low-pressure launcher in a demo to two companies that have submitted proposals for commercializing the technology. The robot operated off the batteries and was controlled by the operator via wireless connection. A number of turns were demonstrated successfully and flawlessly, to the satisfaction of the representatives of the companies present. Only an indoor demonstration was conducted.

- *Acceptance Demonstration of robot to NETL/DoE (December 2003)*

An acceptance demonstration was held at CMU in order to demonstrate EXPLORER to the management of NETL/DoE. The robot was first launched in the indoor loop (transparent

plastic pipe with cast-iron bends and turns) where its operation in a variety of scenarios was successfully demonstrated. The robot operated off the batteries and was controlled by the operator via wireless connection. Then the robot was taken into the outdoor steel loop where it was also successfully operated off batteries and via wireless connection to the operator.

Major Remaining Issues

Major Remaining Issues - prior to June 2004 field demonstrations

- Development and refinement of turning routines associated with the vertical launcher.
- Final adjustments to the user interface display for more intuitive operator control.
- Testing of full system in a test-pipe at Keyspan under lower CI-like pressures for operation in natural gas environment prior to field demonstrations.
- The capability of launching and recovery needs to be tested and accomplished prior to the higher-pressure steel field-trials.
- Software to allow the robot to be driven under complete computer-control off a simple visual interface and GUI with unskilled button-pushes will be optimized.

Upcoming Events/Milestones

1. CMU expects to carry out a low-pressure natural gas test of the platform at Keyspan's test-facility in Brentwood, NY, on May 6, 2004, prior to field-trials.
2. A field-demonstration, with the support of one or more NGA member utilities for live gas testing and evaluation of the prototype system, is expected to occur during the first week of June 2004. The demonstration originally planned for late 2003 was not carried out due to weather imposed constraints.
3. A second field demonstration at the live network of another NYSEARCH member utility is planned for the last week of June 2004. At this point in time the project will be completed and a final report will be submitted to NGA and NETL/DoE by CMU.

PROJECT STATUS BY TASK

As per March 31, 2004

Task 1: Research Management Plan	Completed
Task 2: Technology Status Assessment	Completed
Task 3: Design Extension	
Subtask 3.1: Mechanical Power Charge Interface	Completed
Subtask 3.2: Wireless Communication	Completed
Task 3.3: Power Re-charge Circuitry	Completed
Task 3.4: Miniaturized Fish-Eye Imager	Completed
Task 3.5: High-Tension Design Issues	Completed
Task 4 Internal Design Review and Release	Completed
Task 5 Design Detailing	Completed
Task 6: Procurement	Completed
Task 7: Test-Circuit Establishment	Completed
Task 8: Fabrication	Completed
Task 9: Assembly	Completed
Task 10: Software Development	In-progress
Task 11: Subsystem & Integration Testing	Completed
Task 12: Operational Lab-Testing	In-progress
Task 13: Acceptance Demonstration at NREC	Completed
Task 14: Field Trial #1 Preparation	In-progress
Task 15: Field Trial #1 in downstate New York	Not initiated
Task 16: Evaluation and Preparation for Field Trial #2	In-progress
Task 17: Field Trial #2 in upstate New York	Not initiated
Task 18: Final Reporting	Not initiated

Bold indicates change of status from last reporting period.

RESULTS AND DISCUSSION

The project progressed very well during this reporting period. A number of major tasks were completed successfully. The turning routines were optimized for 8" operation, while optimization of those for 6" pipes are nearing completion. The electronic system received a last upgrade and all systems are now operating at maximum performance levels. The robot has accumulated tens-of-thousands of feet of operations and has undergone dozens of turning routines without any problems. The graphic user interface (GUI) has been upgraded/updated to meet the needs of the field demonstrations. The routines for the new low pressure launcher fitting, adopted by the Advisory Group for low pressure applications in order to minimize cost of operations, were developed and successfully tested.

The robot has been operating during the winter months of 2004 with no problems and is accumulating miles and hours of operations thus increasing our confidence in its ability to transition by the end of May 2004 to its first field demonstration, being planned for the first week of June 2004.

CONCLUSION

At the end of the first thirty months of this project, the design of **EXPLORER** has been completed and finalized, fabrication and assembly of the robot has been accomplished, design and construction of a vertical launcher has been completed, and endurance testing was initiated and continues in the laboratory and in the outdoor pipe-network facility. In addition, fully automated routines have been developed and successfully tested.

The efforts of the project are now focused on endurance testing prior to the two field demonstrations planned for June 2004.

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