Design, Construction and Field Demonstration of EXPLORER:

A Long-range Untethered Live Gasline Inspection Robot System

Semi – Annual Report

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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 retreival, 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 form 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 fourth six-month period. The project has in general achieved its goals for this period as outlined in the report. The fabrication of the prototype is complete and is now been tested in the laboratory mainly focusing on endurance testing and testing of launching procedures. Testing of the prototype in the lab is expected to be completed by Fall 2003, to be followed by two field demonstrations in Winter 2003-2004.

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EXECUTIVE SUMMARY

During this reporting period the project has concentrated in the development of the fully automated turning routines and the debugging of the robot's electric system and software. As reported previously the locomotor system met a major milestone in March 2003, when it demonstrated its ability to perform a 45-deg and a 90-deg turn in a 6-inch pipe, and a 90-deg turn through a 6" tee. However, the speed of the turning routines was low and not meeting the specifications set by the project's Advisory Group. CMU concentrated its efforts during the April to June, 2003, period in optimizing these turning routines in order to minimize the time needed to perform such maneuvers. The accelerated routines were demonstrated to the funders in June 2003, during the Milestone VI meeting. The entire assembled robot is undergoing extensive laboratory testing focusing on eliminating problem areas and improving performance. A new fitting for launching the robot in low pressure cast-iron pipes was adopted at the June 2003 meeting. At the end of this reporting period the robot has been accumulating operating hours without any operational problems. Launch-testing is still to occur based on the pending delivery of the fittings. Additional endurance testing is however required prior to releasing the system for field demonstrations.

INTRODUCTION

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. <u>Modular design.</u> 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 retreival tools (for retreiving 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, initited in Janaury 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 that 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 April 1, 2003 to September 30, 2003 the efforts of the project focused on:

- Explorer robot electronics upgrade,
- Control software development, and
- Milestone VI meeting to review turning routine development

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

- *Electronics Upgrade*

The EXPLORER electronics team continues their debugging and upgrade cycle, primarily focusing on issues related to electrical noise, heat-sinking, and unwanted system interactions. The main effort over the summer months was focused around the replacement of all feed-through lines with new ones to enable the LVDS lines (carrying video) to be shielded and grounded as the video system was not reliable and noise-free enough for the electronics to decode them properly. The wireless drivers had to be re-written in order to optimize speed and reduce overhead to improve on heat-generation and bandwidth throughput. The battery monitoring and charge circuit was also improved to allow for no memory-loss upon battery power-cycling; inherent in this switchover was also the logical inversion of the on-off button to avoid accidental short-circuiting (which caused a number of failures of boards in the past).

- *Control Software Development*

Software development had been hampered in its output by the unreliable hardware up until late August 2003. As of this point though, the electronic hardware is stable enough for software development and debugging to be carried out with high intensity. T-turn and elbow turns were demonstrated in fully automated fashion only by the end of the reporting period.

Before that, turning routines were carried out in semi-automated fashion and without the needed reliability. This was especially the case in late June 2003, when DOE and NGA representatives participated in the Milestone VI meeting at CMU and the system actually ceased to function mid-turn. Since then watchdogs and timers were implemented to allow the system to reset itself and communications to be re-established to avoid system hang-ups. It was also discovered that operating off batteries is very different to tethered operations, as the voltage varies dramatically, with a substantial impact on drive-leg expansion and power, which severely impacts turning performance. A new user interface with camera video overlay and camera-controls has been developed and is in use. The camera works well now, albeit only at 1 frame per second, due to the fact that the cache on the SH4 CPU board is not useable with the old CAN-chipsets. As a result the SH4 design is being upgraded and should have a revised board built, debugged and as a replacement by late 2003 - this will greatly impact on-board throughput (increased video-rate, etc.) and limit heat generation in the SDRAM. The main hurdles that remain are to address the issues related to turning under realistic and uncontrollable conditions - meaning without manual and visual assistance inside a pipe using only video and referencing pipe-internal features! Finally it was determined that the white-blue LEDs on the robot do not generate as color-rich an image as natural light. CMU is exploring the option of false-coloring the image by adjusting the RGB-content of the camera-signals (hopefully before fall 2003) to address the issue.

- *Milestone VI Meeting for the Demonstration of the Turning and Launching Routines (June 2003)*

CMU demonstrated their EXPLORER robot prototype and steel-main launcher in a demo to NGA and DoE on June 25th, 2003 at the REC indoor mock-up test facility. The review team from DOE and NGA witnessed in real time a wireless self-powered horizontal drive with a T-turn. The system failed (loss of communication and hang-up) during the T-turn, requiring delay of the demonstration until the system was extracted and re-started. The rest of the demonstration was shown with a remote video link to the conference room where discussions on field-trials and other issues continued. The funders requested that a list of pre-demonstration tests was developed. These tests would need to be passed prior to being allowed into transitioning to field demonstrations. In addition, the prototype would have to be tested under pressure (a few psi first, before going to 125 psig), and also tested at a special test-pipe setup at Keyspan for operations in natural gas. The Project Advisory Group agreed to a low-pressure cast-iron pipe demonstration in late fall of 2003, and a high-pressure steel pipe demonstration in late spring of 2004. The late-fall demonstration required CMU to have an OEM design and deliver a simpler lower-cost angled clamp-on fitting, which ConEd volunteered to test and certify prior to allowing a field-demo on their system in NY (Westchester county). These fittings and drills were ordered and are in the midst of being produced and delivered. It is likely that the larger-sized (8-inch) fitting will be used, which requires the validation of turning-routines developed for 6-inch pipe in an 8-inch test setup. Furthermore, new launching routines/scripts need to be developed and tested for this new fitting, prior to going into the field for real-world testing.

Major Remaining Issues

Major Remaining Issues - prior to Fall 2003 demonstration

- Development and refinement of all turning and driving routines; particularly validation in a real steel/CI main with real Ts and elbows (not clear pipe with cut-open fittings).
- Refinement of the user interface display for more intuitive operator control.
- Development and testing of the new low pressure cast iron (CI) launcher fitting.
- Setup and testing of 8-inch mains and fittings in highbay for 8-inch deployment.
- Design/building and testing of the currently undeveloped launcher-tube - awaiting drawings form manufacturer prior to proceeding.
- Development of launching routines for the new CI fitting(s).
- Testing and validation of driving/turning/launching routines for 8-inch CI mains (will be the same for steel).
- Testing of the entire robot under low pressures (a few psig; before low pressure CI demonstration) and higher pressures (125 psig for high pressure steel demonstration in 2004)
- Checking for full operability.

- Carting and testing of full up system in a test-pipe at Keyspan under lower CI-like pressures for operation in NG-environment prior to late-fall demonstration.

Major Remaining Issues - prior to Spring 2004 demo

- The capability of launching and recovery as well as vertical climbing needs to be tested and accomplished after the fall 2003 demonstration and during the winter 2004 period.
- Certain modifications to the launch-chamber and internal camera may need to be implemented.
- Several electronic upgrades will need to be performed for the robot to operate properly for full-fledged software development.
- Software to allow the robot to be driven under complete computer-control off a simple visual interface and GUI with unskilled button-pushes will need to be implemented and tested.
- Testing (purging and pressurization) of the launch-chamber will need to be accomplished prior to field-trials.

Upcoming Events/Milestones

1. The CMU team expects to demonstrate the inclined-angle launching & retrieval sequence as well as horizontal driving, turning (T, elbow & Y) in the indoor and outdoor piping network, in late November 2003.

2. CMU expects to carry out an acceptance demonstration for NGA and DoE in their indoor and outdoor pipe network sometime in early to mid- December 2003, subject to not being subjected to further delays due to technical difficulties.

3. CMU expects to carry out a low-pressure natural gas test of the platform at Keyspan's test-facility in Brentwood, NY, sometime in late November, immediately prior to

field-trials.

4. 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 in December 2003 at the latest - if this date is missed due to delays, etc., a field-trial will not be possible before May 2004 due to weather constraints. A second field demonstration is scheduled for May 2004.

PROJECT STATUS BY TASK

As per September 30, 2003

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: Acceptence Demonstration at NREC	Not initiated
Task 14: Field Trial Preparation	**In-progress**
Task 15: Field Trial #1 in downstate New York	Not initiated
Task 16: Evaluation and Preparation for Field Trial #2	Not initiated
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 well during this reporting period having completed many important tasks. The robot, operating using the fisheye camera, wireless link, and on-board batteries, was demonstrated to NGA and NETL/DoE in June 2003. While the turning routines were performed as per specifications, the fact that the robot stalled during operation, demonstrated the fact that additional work is needed in debugging the system and ensuring proper levels of reliability.

A new launcher fitting was adopted by the Advisory Group for low pressure applications, in order to minimize cost of operations.

The robot has been operating during the month of September with minimal problems and is accumulating miles and hours of operations thus increasing our confidence in its ability to transition by the end of the calendar year to its first field demonstration, hopefully by December 2003.

CONCLUSION

At the end of the first twenty four 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 has been initiated and is under way in the laboratory. In addition, fully automated routines have been developed and successfully tested.

The efforts of the project are now focused on final debugging of the system, the timely development and testing of the newly adopted low-pressure fitting/launcher, and optimization of the user interface. The acceptance demonstration for the system is anticipated in December 2003, assuming no major technical issues surface during testing. The first field demonstration is expected in December 2003, again assuming no major technical issues surface during endurance testing.

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2. D'Zurko, D., *"Explorer: Untethered Real-Time Gas Main Assessment Robot System"*, NETL/DoE – GTI Distribution Technologies Workshop, Chicago, IL, October 15, 2003