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. This module, which incorporates technology developed by NASA, has already been designed, constructed and tested, having exceeded performance expectations. The full prototype system will be comprehensively tested in the laboratory followed by two field demonstrations in real applications in NGA member utilities' 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 DOE's contribution to this current phase of the project is $499,023 out of a total of $780,735 (not including NASA's contribution).

The present report summarizes the accomplishments of the project during its third 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 the last system integration issues and on software development for the turning and launching routines. Testing of the prototype in the lab is expected to be completed by Summer 2003, to be followed by two field demonstrations in early Fall 2003.

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EXECUTIVE SUMMARY

During this reporting period the project has finalized the construction of all subsystems and the assembly of the entire robot system. The launching system met a major milestone in December 2002 when the complete launcher was shown to and accepted by the funders. Minor design changes were suggested for the launcher, which were implemented during the first two months of 2003. 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, a 90-deg turn through a 6” tee. In addition the locomotor was launched through the actual launching chamber. The turning routines were successful, however the speed with which these turns are made were very low and not meeting the specifications set by the project’s Advisory Group. CMU will concentrate 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. This process has proven to be substantially more time consuming than originally anticipated and has resulted in some delay in the project. The entire assembled robot is undergoing extensive laboratory testing, electronic components and software being updated to obtain maximum performance. Experiments have yielded that the maximum wireless range in a cast iron (CI) lead-jointed pipe, including offsets, tees, etc., is adequate for field deployment of the robot meeting the minimum specifications set by the utilities.

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 for 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 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 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 rugge dized 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, 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.

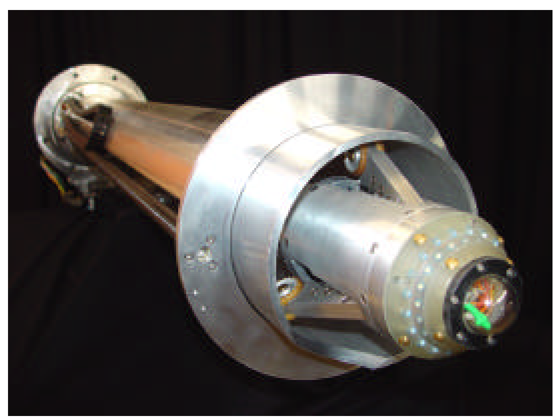
EXPERIMENTAL

During the period of October 1, 2002 to March 31, 2003 the efforts of the project focused on:

- Launcher fabrication and testing
- Electronics Upgrade
- Control software development
- Milestone V meeting for the demonstration of the turning and launching routines (March 2003)

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

- *Launcher Fabrication and Testing*



The launcher has been built to spec, including an upgrade for proper safety margin at 125 psig. The system is in operation and functioning properly. Launching has been tested and shown to work properly with the system hardware. Remaining tasks include the addition of vent and purge ports, testing under pressure, as well as any additional changes necessary for proper recovery, which might entail the installation of a camera and passively gimballing the nose-cone. Final potting and harness enclosing will only be carried out prior to a field-trial. Any future improvements are expected to be carried out between April and June 2003.

- *Electronics Upgrade*

The EXPLORER electronics have gone through a motor-driver hardware upgrade, but still require additional work related to start-up timing and proper full-torque generation. This effort is expected to carry on and be completed by June 2003, at which point proper speeds and torques will be demonstrated to the sponsors in order to perform faster turning and recovery and vertical climbing operations.

- *Control Software Development*

Software development has been hampered in its output by the unreliable hardware to date. CMU has been able to put together scripts that can launch and make the robot turn in Ts and 90-degree elbows reliably - they are however all manual and keystroke initiated - no automation, nor have computer-initiated automatic scripts been implemented or tried. It is expected that the software effort will focus in the next 3 months on the lower-level automation and computer-control of on-board robot functions, with a complete user interface and push-button control with automated scripting being in place in another 6 months.

- *Milestone V Meeting for the Demonstration of the Turning and Launching Routines (March 2003)*

CMU demonstrated their EXPLORER robot prototype and launcher in a demo to NGA and DoE on March 19th, 2003 at the REC indoor mock-up test facility. The review team from DOE and NGA witnessed in real time a launch of the robot system in a vertical MUELLER launcher, into a 6-inch steel pipe, with attached straight sections of see-thru pipe and cast-iron fittings. The demo was set up to demonstrate T-turns, 90-deg elbow turns as well as 45-degree Y-turns. The demonstration showed, albeit in a slow-speed mode, that the robot was able to launch vertically out of the launcher into the pipe, make a 90-degree turn in a T, as well as a90-degree turn through a swept elbow. The launch was performed under tether-power, as the charging system required for launching was not yet received by CMU for installation in the launch-chamber. Once launched, the tether was disconnected and the robot operated on on-board battery-power. All controls and data-communications were done over wireless link. The robot-video was transmitted and displayed at 1 frame per 2 seconds on the robot control screen. All turns and motions were scripted, but were executed manually. Parts of the demo were watched remotely on TV monitors in the meeting room due to the slow process of the demonstration. At key points in the demonstration, the group would proceed to the test-setup and view a live operation as necessary. The demonstration proved that the robot is physically able to perform the launching and turns in a T and a 90-degree elbow. However, neither a 45-degree Y-turn, nor recovery nor a vertical could be demonstrated at this time.

Major Remaining Issues

1. The speed of turning was very slow due to the inability to properly control the motor-driver chip to date. CMU has two solutions they will pursue that will involve software fixes to this issue. The intent will be to speed up all obstacle-handling motions by at least a factor of two, resulting in a T/elbow turn of no more than 15 minutes, and a vertical launch-time of 45 minutes or less. It is expected that this effort will be completed by end of April 2003.

2. The power-supply system for the launcher needs to be received and installed to allow for completely untethered operations during launching. It is expected that this effort will be completed by end of April 2003.

3. The wireless communications link only operated at 1 Mbps, while it is designed to run at 11 Mbps - further driver debugging needs to occur. It is expected that this effort will be completed by end of April 2003.

4. The camera needs to be tuned for proper gain and offset and color-schemes - its

granularity is currently not acceptable. It is expected that this effort will be completed by end of April 2003.

5. Routines for launching and turning in all these obstacles have to be rerun at higher speeds and completely wirelessly. It is expected that this effort will be completed by end of May 2003.

6. The capability of recovery and vertical climbing needs to be tested and accomplished. Certain modifications to the launch-chamber in terms of gimballed nose-cone and internal camera may need to be implemented. It is expected that this effort will be completed by end of June 2003.

7. Several electronic upgrade items still remain on the TBD list and will need to be accomplished for the robot to operate properly for full-fledged software development - this will be an ongoing effort but will mostly be completed by end of May 2003.

8. 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. It is expected that this effort will be completed by end of August 2003.

9. Testing (purging and pressurization) of the launch-chamber will need to be accomplished prior to field-trials. It is expected that this effort will be completed by end of August 2003.

Upcoming Events/Milestones

1. The CMU team expects to demonstrate the launching & retrieval sequence as well as horizontal turning (T, elbow & Y) as well as vertical climbing during the

NYSEARCH/NGA meeting on June 25th, 2003.

2. CMU expects to carry out an acceptance demonstration for DoE and NGA in their pipe network sometime in August/September 2003, subject to not being subjected to further delays due to technical difficulties.

3. A field-trial is expected to occur in the late fall of 2003 with the support of one or more utilities for live gasline testing and evaluation of the prototype system. If this date is missed due to delays, etc., a field-trial will not be possible before May 2004 due to weather constraints.

PROJECT STATUS BY TASK

As per March 31, 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	In-progress
Task 12: Operational Lab-Testing	**In-progress**
Task 13: Acceptence Demonstration at NREC	Not initiated
Task 14: Field Trial Preparation	Not initiated
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 faced some of the typical problems encountered in this stage of a development project. The launcher and the robot, operating using the fisheye camera, wireless link, and on-board batteries, were demonstrated to NGA and NETL/DoE in March 2003. However, one significant issue that persisted from the last reporting period was that of the time needed to develop and optimize the software for the launching as well as various turning routines to be built within the Explorer. CMU has realized that this effort will require additional resources and time. Additional resources are being put in place by CMU to address this issue so as to achieve the revised milestone schedule.

Launcher construction was successfully completed by early 2003.

The development of the optimized turning routines should be completed by June 2003. Thereafter preparations for the pipeline network testing and demonstration will be undertaken, culminating in the acceptance demonstration for NGA and DoE at CMU in late Summer 2003.

CONCLUSION

At the end of the first eighteen months of this project, the design of EXPLORER was completed and finalized, and fabrication and assembly have also been completed. EXPLORER will be launched through a vertical 152.4 mm (6 inches) launching chamber, which has been constructed and accepted by the funders. This is a major accomplishment, for it will greatly reduce deployment costs.

The efforts of the project are now focused on the timely integration and upgrading of all mechanical and electrical hardware, and the successful development of the necessary optimized software to operate the system and demonstrate its ability to negotiate obstacles and be launched via a vertical launching chamber into a 6-inch pipe. The demonstration of the launching and turning routines is expected in June 2003, while actual testing and demonstration of the prototype hardware in the CMU piping network will take place through August/September 2003. Field demonstrations are expected during the late fall of 2003.

REFERENCES

None.