

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

Semi – Annual Report

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ABSTRACT

The goal of this program is to construct and 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 system, which was designed in an earlier effort, is built in a modular fashion in order to accommodate various components intended to accomplish different inspection, repair, sample retrieval, and other in-pipe tasks. The prototype system to be built under this project will include all the basic modules needed by the system, i.e. the locomotion, 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 been designed, constructed and tested in the earlier effort. In the current effort, the full prototype system will be tested in the laboratory followed by two field demonstrations in real applications in NYGAS member utilities' pipes.

The purpose for EXPLORER is to be able to access live gas mains, insert the system in the piping network, and remotely 'drive' it within the gas main and its laterals through distances of five to ten thousand feet. Its adaptable locomotion system allows the robot to function through varying diameter pipes (150 - 200 mm or 6- to 8- inches) and is powered via on-board battery-banks. The presence of fish-eye cameras in both ends of the robot allows the operator to view the forward and circumferential views of the internals live using an above-ground TV. Communication takes place via wireless link between the robot and the launch-chamber used to insert/retrieve the system. This link is based on commercial technology presently employed in wireless telecommunication networks. Communication over long distances as well as battery re-charging will be accomplished without retrieving the robot but through the use of auxiliaries, to be developed in a follow-on phase, that will allow insertion of additional antennas and battery recharge plugs into the pipe under live conditions through inexpensive keyhole sized excavations.

The proposed system 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 New York Gas Group (NYGAS; a trade association of the publicly owned gas utilities in New York State), 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 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 the first six months since funding from DoE commenced. The project has achieved its goals for this period as outlined in the report. Currently the fabrication of the prototype is in progress and it should be completed by late-summer 2002. Testing of the prototype in the lab is expected to be completed by November 2002, to be followed by two field demonstrations in early 2003.

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EXECUTIVE SUMMARY

During this reporting period the project has finalized the re-design of the entire robot system, due to launching incompatibilities identified during the Milestone II meeting in June 2001, resulting now in a 7-module train as compared to the initial 5-module train. The final design went out to fabrication in late January 2002. Most of the electronic systems are being pre-prototyped to ensure that they operate as desired, and have experimentally verified that the distributed microprocessor architecture over CAN bus is feasible. A low-cost, off-the-shelf commercial fisheye camera was identified for integration in the robot, while the drive-modules were completely re-designed to incorporate this lens (which was experimentally determined to have substantially equivalent optical in-pipe performance as the larger high-cost version originally planned). 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. The project is progressing in a timely fashion as per project timetable.

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 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 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 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. It 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 the Project Advisory Group in May 2000.

EXPERIMENTAL

During the period of October 1, 2001 to March 31, 2002 the efforts of the project focused on:

- Detailing the Design
- Electronics Design, Prototyping and Debugging
- RF Antenna Testing & Evaluation
- FisheEye Camera Development
- Initiation of robot fabrication
- Launcher design

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

- *Detailing the Design*

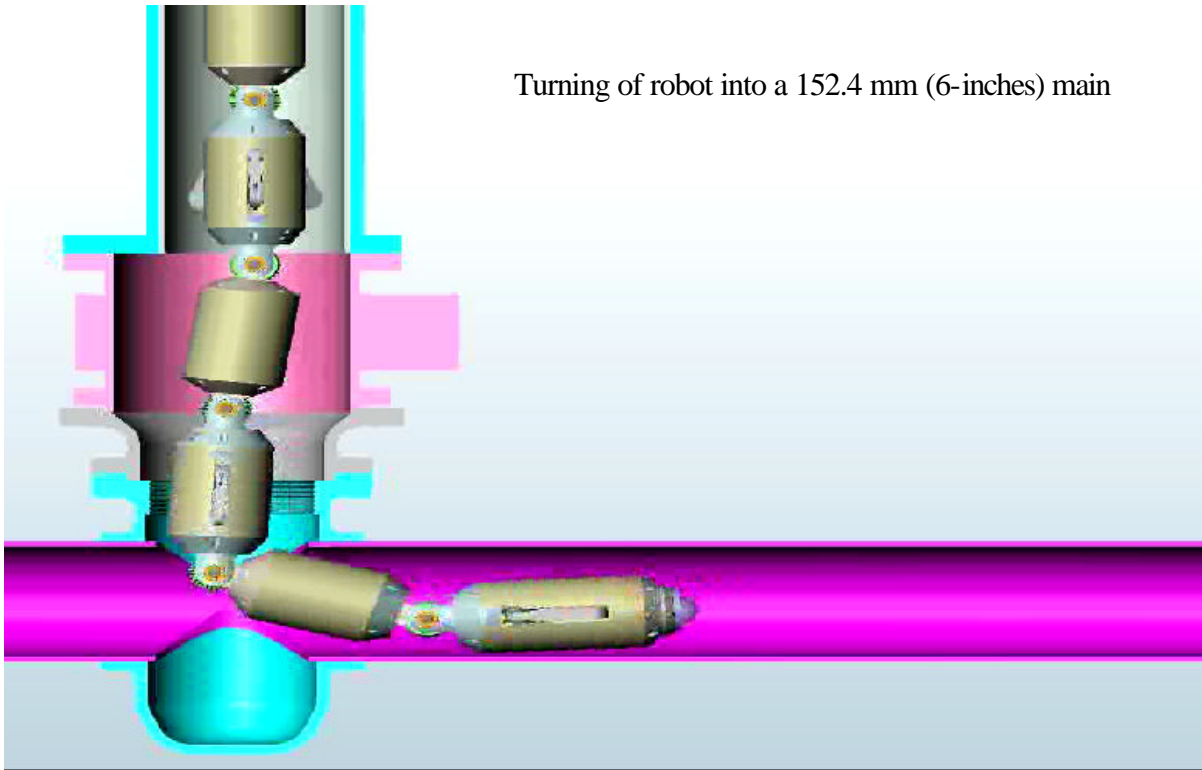
During the June 2001 Milestone II review meeting it was discovered that the initial design would result in a robot unable to be launched or retrieved from a 152.4 mm (6-inches) commercial vertical launcher due to size-constraints and pipe-diameter variations. A redesign effort was initiated which resulted in a new robot design that features an additional two modules, termed *support modules*. These additional modules lengthen and better support the robot, while providing better packaging for the support-legs. Thus, the new robot now has a total of seven (7) modules. A new design and simulation video have since been produced and shared with DoE. This re-design (incl. the new fisheye lens - see below) was completed by the end of November 2001. Machining drawings were produced during December 2001 and January 2002. Several vendors were given bid-packages to quote and CMU picked a combination of vendors to make and deliver parts on a timely, quality-conscious and cost-effective basis. Most parts were delivered by end of March 2002.

Original Design



Final Design





- *Electronics Design, Prototyping and Debugging*

The electronics design continues along its path of design, prototyping and testing. The project's efforts during this period focused in various areas:

(a) Distributed Multiprocessor Design: It has conclusively proven that the distributed multiprocessor design developed earlier is a feasible and doable architecture. Three processor boards were prototyped, and communications software was written that allowed three of them to talk asynchronously. Following this success, the PCBs for the final form-factor were designed. Six separate boards were produced for the six different modules and are currently in testing

(b) Central Processor Development: The software testing has been completed and the necessary hardware changes listed for the Version-6 prototype. The digital camera data-

acquisition, compression, and wireless transmission and reconstruction were implemented. This was a major accomplishment for it is the basic and most important attribute of the Explorer sensor system. A JBIG compression scheme is being used with a maximum of 10 full frames per sec., which is digitally smoothed out to avoid image-flicker at the operator console. Version-6.0 of the CPU board (not to the final form-factor yet) was built in February 2002. It was still being tested and certified for form-factor design at the end of this reporting period. All the software development is done on this unit, while Version-7.0 will have the final form-factor and be used for all software debugging on the prototype unit, and is slated to see development starting in May 2002

(c) Motor-Driver Electronics: A layout and fabrication of a motor-test board was completed. The purpose of this board was to experiment with the performance of all brushless DC and stepper motors to appear in the robot. The intention was to qualify the electronics and motor combination, as well as the hardware commutation scheme, prior to developing the final board-sets for each module and acquiring all motors. This work was completed in January 2002, and was followed by the building of all motor controller and other boards. Presently they are undergoing testing.

- *RF Antenna Testing & Evaluation*



Following the first RF antenna test in Toronto, Canada, at Enbridge Consumers Gas service territory, a second test was conducted in New York City in October 2001. In Toronto it was established that sufficient communication range can be obtained in a pipe segment with joints that were cast-iron and concrete-filled. In NYC (Keyspan Energy service territory) several holes were dug up in various distances from the “starting point” along a complex segment of the distribution system, which included cast iron lead-packed joints and several 45-degree offsets and non-conductive couplers. Communication was established at 11 Mb/sec between two

excavations at distances exceeding operator expectations. Hence it is clear now that a sufficiently large area of the network can be covered from a single launching point, while repeater-antennas would greatly extend it.

- *FisheEye Camera Development*



Following a meeting with a custom optics manufacturer in Florida in August 2002, the project was within days of issuing a purchase order to them for the design and construction of a custom lens. However, CMU uncovered another manufacturer well known to CMU and DoD, has under DoD funding developed a miniature fisheye lens for mini-board cameras, like the one we intend on using; the cost of this camera is \$250 retail in single unit volume. One lens was acquired and tested against the costly large unit that has been our reference lens since project inception. The results were that optically the small lens is not as light-sensitive and optically-perfect at the edges, but when two video-streams from the low- and high-cost versions were compared, the image-quality difference was undetectable to the human eye inside a pipe-environment. A VHS-tape comparing the two was developed. The re-design of the front/rear cone of the robot, to integrate this new lens into the design, was completed.

- *Initiation of robot fabrication*

Robot fabrication was initiated in early March and will proceed through June 2002, at which point in time all elements of the robot pertinent to the cornering routine testing should be assembled. The launch-chamber will be built and the launcher turning-software tested with a utility-supplied access system later in the summer of 2002, and also demonstrated to the utilities (expected in August 2002). Other parts of the robot, such as the camera system, will be integrated into the system after the turning routine has been tested and the ability of the

robot to be launched through a 152.4 mm (6-inches) fitting has been established. Launching into an 8-inch pipe is deemed very feasible, but launching into a 6-inch diameter main needs to be tested due to the tight clearances determined from the simulation effort to date.

- *Launcher Design*

The design of the launcher system was initiated in February 2002, and should be completed in May 2002 for approval by the Project Advisory Group in June 2002. The design will not be fabricated until the assembly of the robot is complete and experimentation and demonstration of its cornering capability are completed in June 2002. Thereafter, it will be fabricated and the launching routines demonstrated in late summer 2002 and featured in the outdoor network testing and demonstration in late Fall of 2002 (expected November 2002).

PROJECT STATUS BY TASK

As per March 31, 2002

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 2.2.4: Miniaturized Fish-Eye Imager	Completed
Task 2.2.5: High-Tension Design Issues	Completed
Task 4 Internal Design Review and Release	Completed
Task 5 Design Detailing	Completed
Task 6: Procurement	In-progress
Task 7: Test-Circuit Establishment	Completed
Task 8: Fabrication	In-progress
Task 9: Assembly	In-progress
Task 10: Software Development	In-progress
Task 11: Subsystem & Integration Testing	In-progress
Task 12: Operational Lab-Testing	Not initiated
Task 13: Acceptance 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

RESULTS AND DISCUSSION

The project progressed well during this reporting period having met its objectives in a timely fashion. The usual problems encountered in this stage of a development project (such as late delivery of a few key OEM components, a few machining mishaps, and a few design omissions that were easily corrected) were realized here also, but in a manageable number. The design and development of the launcher and its testing remains the major uncertainty to date.

The turning routine for the robot through a vertical 152.4 mm (6-inches) launching chamber was developed in CAD during this period. The same chamber will be used for launching in both 152.4 mm (6-inch) and 203.2 mm (8-inch) pipes.

It is expected that a complete mechanical assembly will be available by the end of May 2002. The assembly and testing of the electronics on board has also been proceeding according to plan. Software development and testing will be conducted from May thru June 2002.

Several molds and test-jigs were developed to test subsystems (motors, gearboxes, etc.) as part of the fabrication and assembly process. Most of this testing will be completed by late May 2002, the time at which the mechanical assembly should be completed.

The main computer board is undergoing its final revision this month. It should be debugged by the end of May 2002.

The camera and wireless antenna board-set are not being manufactured yet. These two tasks will be undertaken and completed during the Summer of 2002, and will be incorporated into the final system for the in-pipe demonstration in late 2002.

Cornering and the overall robot system on a wired power- and data-link will be demonstrated to NYGAS and NETL/DoE by late June 2002, with a wireless and self-powered demonstration of the same under laboratory conditions for both launching and cornering,

being planned for late August 2002; thereafter preparations for the pipeline network testing and demonstration will be undertaken, culminating in the acceptance demonstration for NYGAS and DoE at CMU by late 2002.

CONCLUSION

During this first six months of the project the design of Explorer was completed and finalized, and fabrication and assembly initiated. The re-designed Explorer should be able to be launched through a vertical 152.4 mm (6 inches) launching chamber, which is now being designed. This is a major accomplishment, for it will greatly reduce deployment costs. It is still to be proven in the laboratory.

The efforts of the project are now focused on the timely integration of all mechanical and electrical hardware, and the successful development of the necessary software to operate the system and demonstrate its ability to negotiate obstacles and be launched through the 6-inches vertical launching chamber. The actual testing and demonstration of the prototype hardware and cornering is expected in June 2002, with the launching process expected to be demonstrated in August 2002.

REFERENCES

None.