Explorer: Untethered Real-Time Gas Main Assessment Robot System

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ABSTRACT: With funding from the NorthEast Gas Association (NGA), the U.S. Department of Energy (DoE) and NASA, Carnegie Mellon University (CMU) has developed ***Explorer***, a long range, un-tethered, modular inspection robot for the visual inspection of 6" and 8" natural gas distribution system pipelines. The robot can be launched into the pipeline under live conditions utilizing a commercial no-blow system via a specially designed attachment, and can negotiate diameter changes, 45-deg and 90-deg bends and tees, as well as inclined and vertical pieces of the piping network. The modular design of the system allows it to be expanded in the near future to include additional inspection and/or repair tools. The range of the robot is an order of magnitude higher than present state-of-the-art inspection systems and is expected to fundamentally alter the way gas utilities maintain and manage their systems. A prototype system has been built, and is undergoing extensive laboratory system testing prior to scheduled field demonstrations, expected for the summer and fall of 2003. This paper will describe the overall engineering design and functionality of the design, as well as present preliminary laboratory testing demonstration (a video of the system in operation will be shown at the conference).

KEYWORDS: gas pipeline, robot, inspection, wireless, untethered, segmented, modular, live operation.

1. BACKGROUND

US gas companies spend over $300 million annually detecting and repairing gas leaks in the urban and suburban distribution network settings. The current approach is one of above-ground leak detection and pinpointing, followed by excavation, repair and restoration. The major cost incurred is typically that of digging and restoring the excavation site. A tool capable of providing real-time and long-term inspection capabilities that would allow for rapid and pre-planned inspections and repairs wherever needed, would allow utilities to better manage and allocate their operating and repair budgets, potentially reducing costly emergency repairs.

2. STATE OF THE ART

In the area of in-pipe inspection systems, there are many examples of prior-art robotic systems for use in underground piping (transmission-pipeline pigs excluded). Most of them however are focussed on water- and sewer-lines, and meant for inspection, repair and rehabilitation (Pearpoint, Beaver, KA-TE, etc.). As such, they are mostly tethered, utilizing cameras and specialized tooling, etc. (see Figure 1).

Figure 1 : Prior art in in-pipe inspection systems

Three of the more notable exceptions are the autonomous *Kurt I* system from GMD (Germany) used for sewer monitoring (not commercial nor hardened), the (albeit tethered) cast-iron pipe joint-sealing robot (*CISBOT*; developed by Enbridge & Consolidated Edison of NY), which is deployed through a bolt-on fitting and injects anaerobic sealant into the leaking jute-stuffed joint, and *GRISLEE* (developed by the Gas Technology Institute, CMU & Maurer

Technology, Inc.), a coiled-tubing tether deployed inspection, marking and in-situ spot-repair system. These systems are shown in Figure 2:

Figure 2 : Tethered gasmain (CISBOT - right; GRISLEE - bottom) and untethered autonomous (Kurt I) robots developed to date by industry and universities

3. SYSTEM OVERVIEW

In order to explore this possibility, NYSEARCH, the reesearch committe of the NGA, DoE (current) and NASA (past), are funding a program at Carnegie Mellon University's (CMU) Robotics Institute (RI) to develop an advanced remote and robotic inspection system, capable of multi-mile long-duration travel inside live gas mains for in-situ assessment. Under this program, CMU has developed ***Explorer***, a real-time remotely controllable, modular visual inspection robot system for the in-situ inspection and imaging of live 6- and 8-inch diameter distribution gas-mains (see Figure 3 for an image of the prototype in a test network setting). ***Explorer*** is capable of locomoting through straight pipe segments and sharp bends, elbows, Ys and Ts, using a combination of its on-board driving-arms and steering-joints. The system is sealed and purged (and thus can safely operate in natural gas environments) and capable of negotiating wet and partially-filled (water, mud, etc.) pipes.

Figure 3 : Explorer - Pipe Inspection System

The architecture of the robot is simple and symmetric. A 7-element articulated body-design houses a mirrorimage arrangement of locomotion, battery-, support and computing electronics in purged and pressurized housings (see Figure 4). Each module is connected to the next through an articulated joint; the joints connecting the locomotor-module(s) to the rest of the 'train', are pitch-roll joints, while the remaining (four) joints are only pitch-joints. This allows the locomotormodules to articulate in any direction, with subsequent rotation-plane alignment of the remaining joints to enact a turn in any plane. The system is capable of multi-mile travel inside pipes using custom on-board battery-packs, which can use any desired chemistry depending on desired range and cost.

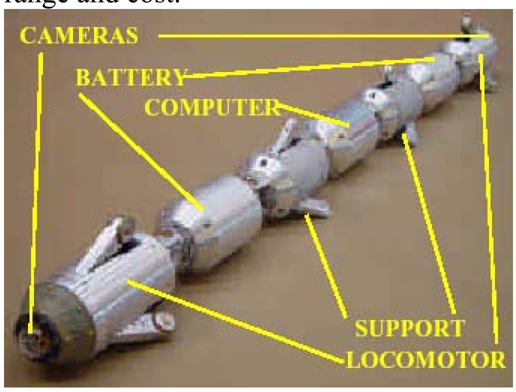

Figure 4 : Overall modular layout of Explorer

The locomotor-module contains the forward-looking mini fish-eye camera, -lens and -lighting elements, as well as dual drive actuators. These actuators allow for the deployment/retraction of a set of three 'arms', at the end of which are a set of custom-molded wheels used for pulling/pushing the train through the pipe; sustained speeds of up to 4 in/sec. are achievable (see Figure 5).

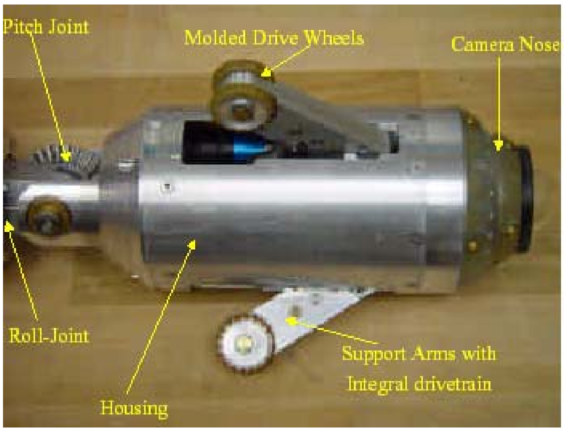

Figure 5 : Locomotor Module

The battery-module(s) contain custom battery packs to allow for a full 10-hour mission with all systems consuming maximum power. This module is the only one that is pressure-sealed due to battery-chemistry concerns at elevated methane pressures (see Figure 6).

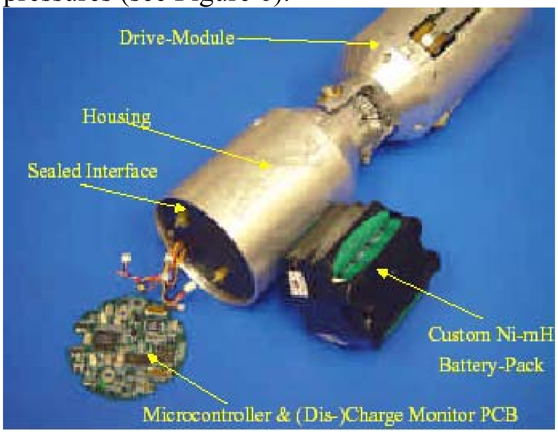

Figure 6 : Battery-Module internals

The support modules also have extendable 'arms', with the principle behind self-centering being identical to that of the drive-module, further easing turning and launching. The wheels at the end of the arms are passive and have embedded magnets with hall-effect encoding, allowing the system to determine position via dead-reckoning ,note that there are 3 wheels per support-module and 2 support modules, allowing for averaging out errors over distance - see Figure 7 for detail:

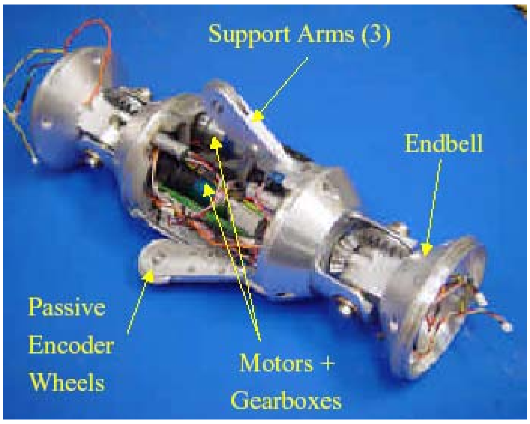

Figure 7 : Support Module Prototype Hardware (covers and end-modules removed)

The computer-module contains the custom-packaged 32-bit low-power (< 1 Watt) processor and support hardware for control and communications, as well as power-conversion and -conditioning (see Figure 8).


Figure 8 : CPU & Housing for Electronics Module

Articulation of all modules occurs through an innovative roll-pitch joint arrangement. On the inside edge of each of the drive modules are two roll joints that allow the whole train to rotate about its longitudinal axis. Each dually-interconnected module has an active pitch-joint, enabling successive joints to be rotated to allow the joints to rotate in a plane controlled by the orientation set by the roll-actuators; this is the approach used to make turns in pipes, given that cork-screwing for non-gravity locomotors is a given fact of free-moving braced locomotors in pipes (Figure 9 shows the combined roll/pitch joint prototype hardware).

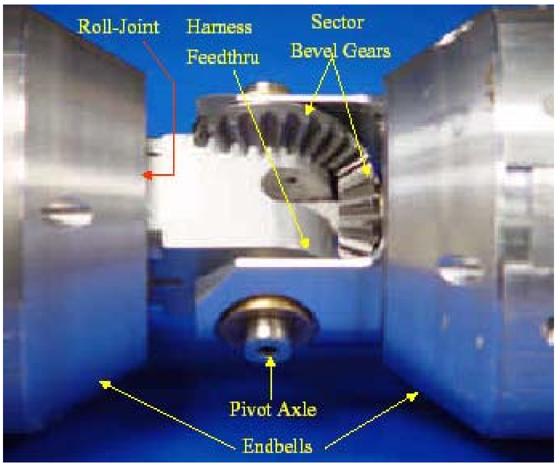

Figure 9 : Roll-/Pitch-joint hardware

The overall electronics architecture, shown in Figure 10, depicts the on-board scheme of using a central high-MIPS low-power CPU to communicate with a set of I2C-connected microprocessors to achieve all control, data-gathering and I/O functions over a customized wireless ethernet backbone implementation. A custom-developed 32-bit lowpower central processor controls all the locomotion and steering functions based on real-time operator control commands. All on-board functions are served through a network of distributed 8-bit microprocessors communicating over an internal I2C-bus. Real-time external communications is through a wireless 802.11b implementation of UDP, using the pipe as a waveguide
for long-range communications.

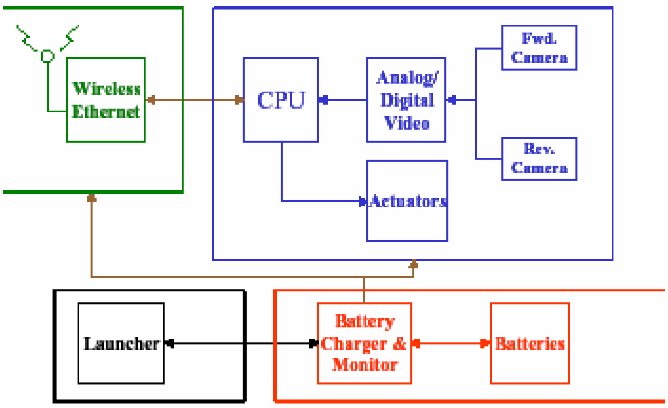

Figure 10 : Explorer overall electronics architecture

The system carries with it fish-eye cameras on either end, capable of imaging, dewarping and mosaiquing pipe-internal imagery at frame-rates with a combination of edge-finding and laplace-operations performed on image-slivers), and displaying these remotely at the operator console (see Figure 11).


Figure 11 :Fisheye and dewarping imagery user interface

The imaging hardware setup is based on a digital CMOS imager (640 x 480), coupled with a miniature fisheye lens illuminated by a set of 36 PWM white near & far focussed LEDs, delivering frame-rate imagery over an LVDS interface to the main CPU, allowing it to be broadcast wirelessly - the prototype setup is shown in Figure 12:

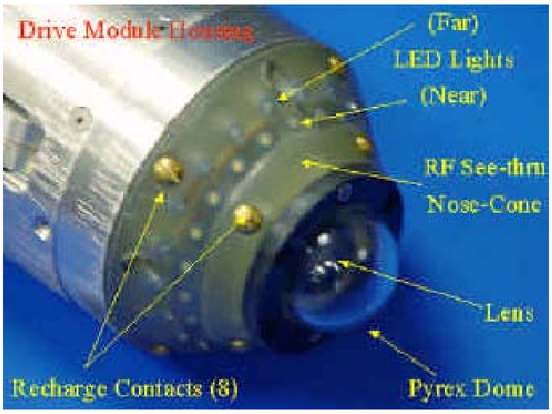

Figure 12 : Explorer Fisheye Imager setup

4. DEPLOYMENT

The system is launched through a live installed vertical launch-chamber (see Figure 15), after a hole has been dug in a 'low-cost' location selected by the utility, where custom antennaes are used to link the operator console to the robot. An operator controls the robot using a simple forward/reverse joystick interface,

Figure 13 : View of the test pipe-network setup at CMU (inside yellow box)

while the on-board computers generate all the individual joint-steer and driving commands (see Figure 14). Turns are possible by positioning the robot at the proper place in the pipe, identifying the direction of the turn on the touchscreen monitor, and engaging an automated scripted routine to coordinate the turning and driving motions to allow for a turn through a nonstraight section of pipe.

Figure 14 : View of the launching and control setup

5. PRELIMINARY EXPERIMENTS

The project team is currently experimenting with all the different types of 'obstacles' (bends, Ts, Ys, elbows, verticals, etc.) to be encountered in the field, in a separate laboratory pipe mock-up setting shown in Figure 15:

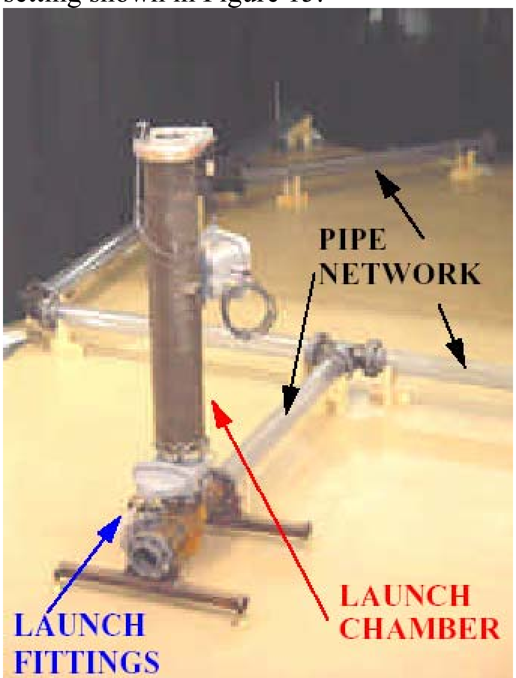

Figure 15 : Indoor Pipe Mock-up Test-loop setting

The access-method being used revolves around a vertical launch, using commercially-available fittings and valving, with a custom-developed pressurized and actuated launch-chamber. This method minimizes excavation costs and makes maximum use of existing OEM products the gas utilities are comfortable with in every day use. The launch-chamber and the robot shown in mid-launch (pipe removed for clarity), are shown in Figure 16:

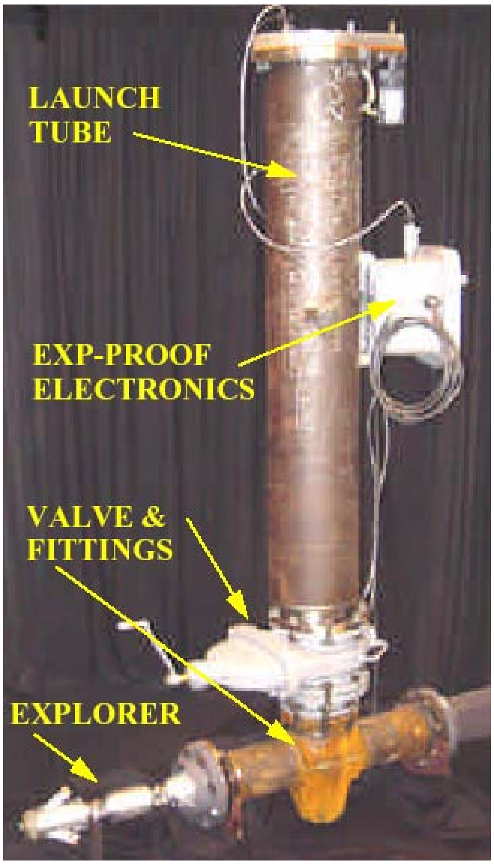

Figure 16 : Launch-chamber and pipe setup

Results to date have shown that the system can drive at 4 inches/sec. as required, with a typical obstaclehandling time of 10 to 15 minutes per occurrence. Launching has been timed at 45 minutes, with vertical pipe-climbing and retrieval still having to be tested.

6. CONCLUSIONS

The development of a segmented and modular robottrain to navigate almost all types of pipe-internal geometries has been shown to be feasible. Challenges remain in the areas of power-density and communications bandwidth to maximize the profitability of such a system in commercial applications. As part of commercialization it will be critical to tailor the early prototype(s) development to a subset of inspection tasks so as to ensure successful deployment and overcome the typical early-adopter reluctance to field unknown and limited track-record systems.

7. FUTURE PLANS

Challenges remain in the area of computer-executed script development, as well as simplified user interface development to allow operators to readily and easily control the robot around obstacles and out-of and into the launch chamber. Said work is in progress and is expected to be completed by the late fall of 2003, including endurance testing in the outdoor pipenetwork specifically built for the purposes of this effort at CMU (Figure 13). Live gas main field-trials are scheduled for the 2003 pre-winter season in New York State. Patents are pending, with licensing completed and commercialization efforts well underway.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] Ives, G., Jr., "Pipe Ruptures", PipeLine & Gas Industry Journal, Vol. 83, No.9, Houston, TX
[2] Staff Report, "New Optical methane detector improves gas leak surveys", PipeLine & Gas Industry Journal, September 2000
[3] Porter, C., Pittard, G., "Magnetic Flux Leakage Technology for Inspecting 'Live' Gas-Distribution Mains", GTI Technical Report # GRI-99/0199, Oct. 1999, Chicago, IL
[4] Schempf, et al., "Robotic Repair System for Live Distribution Gasmains", Field and Service Robotics Conference., FSR 2001, June 11 - 13, Helsinki, Finland.
[5] *Guidance Manual for Operators of Small Natural Gas Systems*, US Department of Transportation, Research and Special Programs Administration, August 1997.
[6] Schempf, et al., *"GRISLEE: Gasmain Repair & Inspection System for Live Entry Environments*", CLAWAR'01 Special Issue of the International Journal of Robotics Research, March-April, 2003, Vol. 22, Nos 3 and 4.