Robotic Repair System for Live Distribution Gasmains

Hagen Schempf hagen+@cmu.edu Edward Mutschler edm@rec.ri.cmu.edu Vitaly Goltsberg vitaly@rec.ri.cmu.edu

William Crowley crowley@ri.cmu.edu Brian Chemel doog@cmu.edu

Carnegie Mellon University Robotics Institute 5000 Forbes Ave. Pittsburgh, PA 15213

I. ABSTRACT

US gas companies spend over \$300 million annually detecting and repairing gas leaks in urban and suburban 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. The Gas Research Institute (GRI) and the National Aeronautics and Space Administration (NASA) are funding a program at Carnegie Mellon University's (CMU) Robotics Institute (RI) and Maurer Engineering (MEI) to reduce the cost of repairing gas distribution mains using advanced remote and robotics technologies to provide up to 50% cost savings over conventional repair methods. Under this program, CMU has developed GRISLEE (Gasline **R**obotic Inspection System for Live Entry Environments), а remotely controllable, modular leak-detection, inspection, surface-preparation and repair robot system for the real-time in-situ spot-repair of live 4-inch diameter distribution gas-mains. The system is capable of repairing 2 or more leaks per day from a single excavation over a 2,000 foot length under live conditions (i.e. without downtime in the gas main). The prototype system has undergone laboratory testing and proven the feasibility of its modular inspection, sensing, preparation, and repair technologies and systems. Field-trials with multiple utilities are planned for 2001.

II. INTRODUCTION

Currently, between 800,000 to 1,000,000 leak-repairs are carried out per year in the US, at a (national-average) cost of between \$750 to \$1,250 each, including leak-detection and -pinpointing, excavation, repair and road-restoration (costs are highly variable). The process usually involves the use of sensitive gas-detection equipment to locate, pinpoint the leak [1], mark, and excavate the site around the pipe, verify the leak, apply an external patch (clamp or weld-on), verify the seal, and then restore the excavation/ street/sidewalk. Most of these steps (excluding locating and pinpointing) are pictorially rendered in Figure 1.



Figure 1 : Conventional leak-repair method

The main issue with manual leak-repair centers on the costs of excavation and the repair-system. If a gas main section is to be relined or replaced there might be the need to shut off gas-flow to customers on the local grid. In highly urban areas, especially in larger cities with high population densities, the number of inconvenienced customers during the outage, coupled with the need to plan the outage and notify residents, etc. can become a burdensome undertaking for distribution utilities.

GRISLEE is intended to provide an alternate approach to line-repair and thus extend their usable life or Mean-Time-Between-Repairs (MTBR), providing a potential alternative to relining and complete replacement.

In order to reduce the restoration and multiple-excavation costs during each repair job, a program was conceived to develop a remote repair system, capable of entering a live gas main without requiring gas-flow interruption and capable of inspecting and locating leaks and also repairing them from a single excavation with a substantial reach (\leq 1,000 feet in either direction). It is expected that such a system would drastically reduce repair-costs and -frequency, as potentially provide for a preventative maintenance-tool as part of the inspection for gas-distribution utilities.

III. BACKGROUND

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 waterand sewer-lines, and meant for inspection, repair and rehabilitation (Pearpoint, Beaver, KA-TE, etc.). As such, they are mostly tethered, utilize cameras and specialized tooling, etc. (see Figure 2).



Figure 2 : Prior art robots in use in the sewer industry

Two of the more notable exceptions are the autonomous *Kurt I* system from GMD (Germany) used for sewer monitoring (not commercial nor hardened), and the (tethered) cast-iron pipe joint-sealing robot (*CISBOT*; ConEd), which is deployed through a bolt-on fitting and injects anaerobic sealant into the leaking jute-stuffed joint. These systems are shown in Figure 3:



Figure 3 : Tethered gasline (right) and untethered autonomous (Kurt I) robots developed to date by industry and researchers

IV. COST BENEFIT

As part of the program, a preliminary review of a gasutility's repair-records, generated relevant data as to the number, frequency and spacing of spot repairs in a suburban distribution network in the Northeastern US. The results are shown in Table 1:

Total # of 1999 Repairs Average Repairs per Cluster	60 2.6	110
Average Cluster-Spread [ft] Max Cluster-Width [ft]		118 225
	a . =a.	323
% of Clusters with 1 repair:	21.7%	
% of Clusters with 2 repairs:	43.5%	
% of Clusters with 3 repairs:	4.3%	
% of Clusters with 4 repairs:	17.4%	
% of Clusters with 5 or more repairs:	13.0%	
	100.0%	

Table 1 : Spot-repair data from gas-utility

It was found that over a period of one year, repairs carried out in specific areas, tended to result in multiple repairs within certain lengths of pipe. More than 75% of these repair-jobs patching 2 or more leaks within less than a 325 foot separation between leak-locations. Based on preliminary cost-estimates for live robotic gas main repair, it was determined that if more than 2 repairs can be carried out from a single excavation within a 2,000 foot distance around the excavation, live robotic repair could compete with conventional manual methods based on clamp-on/ weld-on sleeves emplaced through open-hole excavation methods.



Figure 4 : Payback cross-over for live internal repair

The repair-data and cost-estimates summarized in Figure 4 for both external clamp- and weld-on manually-applied repair sleeves show the payback cross-over point. In addition, the more 'suspect' areas can be repaired from a single excavation, the more cost savings can be realized by a utility in the long-run due to preventative maintenance benefits.

V. PROJECT OVERVIEW

CMU is teamed with Maurer Engineering, Inc. (MEI) to utilize GRI's live-pipe access and coiled-tubing deployment system (CT) to deploy GRISLEE. The CT system is a spooled-up steel-pipe with internal cabling, used extensively in the off-shore oil-industry for sensordeployment and well-treatment over thousands of feet in depth. The CT system allows one to access live gasmains, insert GRISLEE through a welded-on accessfitting, and 'push-pull' GRISLEE through the gas main for distances of up to 1,000 feet in either direction (limited by CT buckling loads and the extent of pipe-bends). GRI and Gaz de France (GDF) had previously funded the development of the CT system (developed through MEI [2]) and the magnetic flux leakage (MFL) flaw-detection sensor-head (developed through TuboScope Vetco Pipeline Services, Inc.). The team was tasked to develop a set of robotic/remote modules, that would allow a repair crew to: (i) detect wall thinning and/or leaks in the pipewall using the existing MFL-sensor, (ii) clean the pipe to prepare the affected pipe-area, and (iii) emplacement of an expandable metallized epoxy-sleeve to reinforce and/or seal the leak under live gas-pressure, without affecting the continued gas-flow inside the main line.

As part of the program, CMU was tasked to develop a simple, rugged, yet effective repair robot system that can be deployed in a modular fashion and perform the detection, preparation and area repair/reinforcement of a leaking live gas main. The robot system included several modules:

- a camera module to determine obstacles and joint locations in the gas mains,
- a magnetic flux leakage module to locate and measure remaining steel pipe-wall thickness,
- a marker module for marking and locating identified pipe defects,
- a brush module for cleaning a localized area at the defect or joint location, and
- an improved sleeve module to repair leaks in live pressurized gas mains.

A design-study revealed that for many technical, operational and logistical reasons, these modules should be made interchangeable and deployable as individual 'trains', rather than having all modules hooked into a single train inside the pipe.

VI. PERFORMANCE REQUIRE-MENTS

In order to develop the most appropriate system to repair leaks in live gas-mains, it is imperative that the complete system's performance requirements be spelled out as quantitatively as possible. Towards that end, a complete list of requirements was developed and compiled:

- Faster, cheaper and more convenient repair method than is possible with current methods.
- Access and work within live gas-mains from a single excavation and allow maximum travel from a single entry-point in both directions.
- Fit into and pass through 4-inch I.D. steel gas-mains
 Reasonable negotiate bends, debris & protruding
- taps • Operate safely within a natural gas environment
- Identify, mark, acquire, clean and repair the defective area(s)
- Install a reliable sealing-patch
- Guaranteed system retrieval under worst-case system failure
- Modularly interchangeable with existing/future deployment and sensing components
- Easy to operate with minimal and manual operator interactions

VII. SYSTEM SPECIFICATIONS

Based on the above performance requirements imposed on the design, and an iterative concept development and evaluation process, the CMU development team implemented the following set of system specifications:

- System to be designed as a multi-module exchangeable work-head system capable of viewing, inspecting, marking, cleaning and repairing pipeleaks.
- Unit to interface to existing coiled-tubing (CT) deployment system from MEI [2].
- The hard module-diameter not to exceed 3 inches O.D.
- Inert materials (SS) with internal purging and nitrogen pressurization to 100 psig, as well as potting and immersion to be used as safing techniques.
- The repair-head to have a forward-looking live-video camera monitoring system
- The system to have an independent visual flawmarking emplacement (coupled to MFL-head) and detection (on repair head) system.
- The system to be able to fine-position itself using the CT-unit to within +/- 1 inch or better.
- The internal pipe-surface to be cleaned mechanically.
- The frontal cleaning-head and repair-modules to be interchangeable.
- The operator controls to be integrated with existing CT, MFL and camera controls.
- The system to be deployable in the same manner as the current camera and MFL inspection systems.

VIII. SYSTEM OVERVIEW

The *GRISLEE* system consists of several independent modules, which are deployed utilizing the CT system through a live-access weld-on gate-valved sleeve on the gasmain. A topside operator monitors a computer/video

display that relays MFL-data and video imagery from the modules. Depending on the task at hand, the proper arrangement of modules is attached to the flexible whiphose at the end of the CT, and then inserted through the access fitting and pushed to the proper location utilizing the CT system. Once in place, the system is remotely controlled from above ground to perform its task, after which said module-train is retrieved, and replaced with the proper arrangement of modules to perform the next operation. The proper arrangement of the system architecture is depicted in Figure 6 in an iconic fashion.

Before deploying **GRISLEE**, the launching apparatus needs to be put in place. This requires (i) the excavation of the pipe-segment in question, (ii) exposing the pipe (~ 5 to 10 ft.) to allow human access, (iii) installation of the access-fitting, and (iv) installation of the CT-unit and the launching hardware. GRISLEE is then launched in a predefined sequence, including: (i) attaching the videoinspection train to inspect the pipe for obstructions, (ii) deploying the sensing and marking module-train to utilize the MFL to locate flaws and then mark them with the marking-module, (iii) insertion of the mechanical brushing system to remove loose scale around the defect-area, (iv) deployment of the spot-repair -sleeve, and finally (v) reinsertion of the camera-module to confirm the proper installation of the sleeve. This process is repeated until all detected and marked flaws are repaired. The same can be done in the opposite direction with a reversed fitting welded to the pipe.

USER INTERFACE

IX. TECHNOLOGY DESCRIPTION

The overall system is best described in terms of its main elements, which are the (A) deployment and access system, and the operator interface, and (B) the robotic inspection/mapping/marking/preparation/repair module trains. The robotic modules are best broken down into their different trains, namely those used for (i) video inspection, (ii) MFL sensing and marking, (iii) surface preparation, and (iv) spot-repair. The electronics, software and user interface are described separately.

• Access and Deployment System



Figure 5 : CT deployment & connector system

The access and deployment system developed by MEI under separate GRI and GDF co-funding, consists of a diesel-hydraulically powered coiled-tubing (CT) cable-spool, wound with mild-steel hollow piping, within which is seated a multi-conductor tether in a pressurized inert nitrogen atmosphere (see Figure 5).



Figure 6 : GRISLEE and CT system architecture

The CT piping is terminated at the spool-end through a multi-conductor slip-ring, that carries data, video and control signals to and from the control panel; at the distal end, a flexible composite-material whiphose (see Figure 5) is terminated with a strain-relieved connector.

The access-fitting that is used to allow the CT to be deployed into the live pressurized main, is a two-part welded-on steel-clamp, that has an angled fitting with a valve mounted to it. A hydraulically-powered hole-saw drill is manually deployed to cut an elliptical hole into the top of the pipe to the full diameter of the gasmain, which is then retrieved. After drilling, a launch-chamber is attached to the fitting, which when opened, allows for the attachment of modules and their launch/retrieval without any release of natural gas (Figure 7).



Figure 7 : Live gasmain access and launch fitting

• Tooling Module-Trains

The tooling module-trains, as depicted in Figure 8,



Figure 8 : CAD view of module-trains

clearly illustrate the modular nature of the system - for each task, a separate set of modules is attached to the basemodule to perform the task. Each module is internally pressurized above ambient pressure and internally monitored with a hardware-thresholded pressure-sensor. In addition, each module has a unique precision-resistor on its PCB for module identification. A pictorial rendering of all prototype modules is shown in Figure 9.



Figure 9 : GRISLEE prototype modules and assemblies

The base-module contains the DC power-supply, embedded CPU and serial communication electronics on custom-built circular PCBs that control each moduletrain, communicate to the topside controller and perform in-situ module-detection and safety-checking. Each modules' hardware safety-line and module-ID line are tied to two separate pins, so that the base can perform a simple fault-checking and module-ID before allowing any controls signals to be sent.

The video-inspection train is simply a combination of the base-module with a ruggedized camera-module. The camera-module consists of a high-resolution lensed color board-camera with an internally-mounted high-intensity white LED light-ring behind protective optical-quality glass-windows. The light-intensity is varied and synched to the video-signal. A view of the combined video-inspection train is shown in Figure 10.



Figure 10 : Video-Inspection Train: Base & Camera

The marking-train consists of the base-, marker- and MFL-modules, allowing the operator to view a computergenerated screen that depicts the metal-thickness and identified areas of metal-loss at the above ground operator control station. The operator can then mark the affected area using the marker-module. The marker-module uses internally-pressurized paint through a set of nozzles to mark the inside of the pipe with a visible paint-ring. The goal is to leave a visible mark in the pipe for an optical sensor to detect the mark in later passes so as to allow the preparation and repair modules to be accurately positioned without relying solely on odometry-data from the robot or the CT spool.

The pipe-preparation train consists of the base-, sensor and brush-modules, allowing the operator to go back into the pipe, locate and position the train over the sprayed-on marker, and then brush an operator-selectable length of the inside section of the pipe, thereby removing scale to maximize adhesion of the repair-patch. The sensormodule contains the electronics and sensors necessary to detect the sprayed-on paint-ring mark on the side-walls of the pipe. False-positives are avoided through a customized hardware setup and software algorithm.

The brush-module contains the electronics and drivers to activate the motors that power the mechanical surfacetreatment brushes. The driven shaft is designed to allow operators to externally exchange brush-module halves. An internally-mounted camera and light section allows viewing of the prepared area and repeated brushing if needed. The appropriate brushing media depends on the conditions within the pipe, and can thus be selected accordingly based on existing technologies and techniques.

The repair-train consists of the base-, sensor- and patchmodule. The base-module monitors the sensor-trigger to alert the operator to the proper position of the modules, and controls the valving to inflate and release small amounts of compressed nitrogen into the setting-bladder on the patch-module; the sensor-module is similar to that used on the preparation-train.



Figure 11 : Commercially-available spot-repair patch

The patch-module consists of a compressed-nitrogen chamber at 300 psig, valved through a regulator to inflate an elastomeric membrane on a setting-pipe. The setting-pipe is hollow, to allow gas-flow during the setting-process. The spot-repair patch that was used for the *GRISLEE* system is a substantially-modified version of a

commercially-available spot-repair system developed for repair of out-of-service gas mains. The notion behind spot-repair, is the ability to deliver a minimal level of sealing and reinforcement to a highly-localized area, so as to repair the pipe-section and extend its useful life. This approach allows utilities to <u>avoid</u> the use of costlier repair and rehabilitation methods, such as excavation and section-replacement, relining, or outright abandonment of a lengthy section of pipe and replacement with plasticpiping. A view of the commercially-available sleeve, prior to substantial modification, is shown in Figure 11.

The intermodule connector is used throughout each train to electrically/pneumatically interconnect each module. The connector was designed to withstand push and pullloads up to 3,000 lbs., while retaining flexibility and selfcentering capabilities. A specialized connector-pair internal to each mounting-flange, provides for the necessary interconnectivity.

• User Interface

The user interface developed for the *GRISLEE* system has been split between the hard controls used for the valve-control of the CT-unit, allowing one to control the spool and the levelwind. The module-trains are all controlled from a single rack-mounted panel-box. The video-signal is overlaid with the spool pay-out countervalue and displayed on a monitor as well as recorded with a VCR.

The control box consists primarily of a custom-built CPU that performs all communication tasks with the basemodule via serial communications, and all associated power-regulation from AC to DC for the base-unit. All buttons are read in over a digital I/O card, and status messages are displayed on a serial LCD display. Binary outputs control status lights and relays for power, as well as video-switching and safety shut-offs. Both the control-rack and the control-box are shown in Figure 12.



Figure 12 : Control-rack & control-boxes

• Electronics and Software

The overall system architecture for the control of *GRISLEE* is simple (refer to Figure 13 & Figure 14).



The system is based on a tethered communications and power backbone that goes through the CT piping and the sliprings, and splits signals for control, MFL-data, video, overlay and control/data into separate conductor-pairs.



Figure 14 : Data, signal and power diagram

Signals are either processed topside (counter video overlay, operator inputs, base feedback) or in the basemodule (topside commands), or as in the case of the MFL, passed straight through to the dedicated MFL processing unit's CPU (not shown in the figures).

The software architecture is based on an interrupt-driven events-table scheme. The topside (control-box CPU) and bottomside (base-module CPU) controllers monitor local events and trigger actions based on these processed readings. A simplified graphic of the architecture is seen in Figure 15.

The base-module CPU monitors module-ID values, pressure-sensor thresholds, diffuse-light trigger values, and in return executes digital and analog command sequences for the surface-cleaning motors, light-controllers and valve on/off signals. The topside controlbox CPU monitors the feedback coming from the bottomside CPU, as well as buttons and switches, and updates outputs to the LCD screen, the video-overlay board-set and all other button and status indicator lights.



Figure 15 : Software event input architecture

X. SYSTEM EVALUATIONS

The *GRISLEE* prototype modules/trains and the CT access and deployment system, were demonstrated in an above-ground 100-foot long pipe-network set up inside a CMU testing highbay laboratory-setting (see Figure 16).



Figure 16 : Prototype-testing setup & deployment

The network consisted of several 20-foot steel pipe sections coupled into a 100-foot test-loop, which was pressurized and flow-simulated using compressed air. The demonstration showed the viability of the live-access and deployment system, the use of the camera- and MFL sensor heads, the marking and locating modules, as well as the surface-preparation and patch-setting modules. Two patches were set in pre-drilled leaking pipe-sections and joints. These flaws were located, marked, prepared and patched by a trained operator.

The step-by-step repair-sequence, the associated infrastructure and logistics, throughput and timing, indicated that to repair multiple flaws in a live gasmain without flow interruption from a single excavation could be exploited under realistic field conditions. System field-trials in southern and northeastern US utility field-environments are planned for 2001.

XI. SUMMARY & CONCLUSIONS

The *GRISLEE* and CT systems that were developed for live-access of gasmains and in-situ flaw-detection and spot-repair, were proven in the laboratory-environment. The method of live-access and CT deployment were shown to be reliable, simple and of high throughput with adequate safety margin. The modular *GRISLEE* design and its ability to assemble dedicated module-trains was proven to be effective in terms of allowing optimal design and achieving desirable performance, allowing piece-part improvements and future expansion. The use of paintmarking and subsequent positioning via sensor-driven stripe-detection was shown to be adequate. The system also seemed to indicate that mechanical cleaning was an appropriate method for joints and pipes in certain conditions.

XII. FUTURE WORK

The *GRISLEE* and CT systems are currently being readied for a sequence of utility-sponsored field-trials at a few locations within the US. Detailed design documentation and operating and maintenance manuals are being completed. The system is expected to complete more extensive field-trials in 2001.

XIII. ACKNOWLEDGEMENTS

The *GRISLEE* system was jointly funded at Carnegie Mellon University (CMU) by NASA under research-grant #NCC5-223, and a contract from the Gas Research Institute (# 5097-290-6029). We wish to further acknowledge the prior development of the MFL sensing technology (by TuboScope Vetco Pipeline Services, Inc.) for distribution gasmains through a jointly-sponsored GRI/GDF project, as well as separate funding of MEI by GRI under a separate contract, for the development of a modified and upgraded CT deployment system for accessing and deploying *GRISLEE* into a live gasmain.

The *GRISLEE* system and process have been submitted for patent-protection and have a patent-pending status.

XIV. REFERENCES

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