PHASE I
STATE-OF-THE-ART REVIEW

submitted to
Department of Energy - National Energy Technology Laboratory

in compliance with

Contract # DE-FC26-04NT42264

focussed on the technologies for

In-Pipe-Assessment Robot Platforms

Document Number: REP-GOV-DOE-20041102

November 30th, 2004

submitted by

Carnegie Mellon University
The Robotics Institute
5000 Forbes Avenue
Pittsburgh, PA 15213

Technical Contact:
Hagen Schempf, Ph.D. (412) 268-6884, (412) 268-1893 FAX; hagen+@cmu.edu

1.0 Introduction - Pipe Robots

Internal pipe inspection and maintenance are not new concepts in such industries as sewer and water maintenance as well as transmission pipelines for oil and gas. Such systems typically are an integration of mechanical, electrical and software subsystems, supporting one or more sensory payloads for measuring the pipe's overall state and structural integrity (corrosion, ovality, etc.). One of the main subsystems in such inspection systems is the locomotor or mobile platform that carries the sensing and explorative end of the tool. This is the area this report will focus on as part of the state-of-the-art review contained in this report, by illustrating technical advances and deficiencies, by way of seminal platform examples (whether fielded, prototypes or in the design-stage). The intent will be to help support technology-developers and decision-makers in understanding how and where to provide technology innovation and where to allocate ones resources to see technical advances realized.

2.0 Background

The above-mentioned application-areas are discussed in brief detail below by way of an overview and a few of the salient examples and a comparative table condensing the comparative descriptors that one might use into a single graspable location. There are however substantial differences and presumptions that will remain to be clarified in order to understand the gradation in terms of capabilities and applications in this arena.

2.1 Water and Sewer Mains

This area is not intended to be elaborated on in any depth as part of this report. It is however worth noting that in-pipe robots, mostly self-powered units, have and are seeing their largest volume applications in this arena. All of these systems rely on a power- and (push-)pull tether to provide power and communications to the robot, and return information to the user. Most of this information is raw video-data, but can also include acoustic as well as laser-caliper dimensioning data. Efforts have been made in the past to also make these systems more autonomous by providing on-board battery power and 'cutting' the tether and relying on on-board smart software and guidance/navigation/imaging sensors to handle in-pipe locomotion decisions. However, due to the bulk and shear linear footage of water- and sewer-pipes in the world, and the relatively low barrier to entry (cost, operational infrastructure and relatively low operational hazard-level), this industry has seen substantial growth in the last decade and will continue to be the largest market for in-pipe robots in terms of revenue for near foreseeable future.

Some of the more salient images of the state-of-the-art in water and sewer pipe inspection and repair systems are depicted in the figure below:

BlackHawk

Beaver

Pearpoint

KA-TE

2.2 Oil- and Gas Pipelines

This application area has seen substantial work in the past 20 years. Most of the past and current effort has focussed on using passive flow-powered (pigs) platforms to carry an ever-improving array of sensors for integrity evaluation. New efforts in the past few years has begun to also look at actively powered platforms to access the unpiggable sections of these transmission mains. Both of these areas are covered further below.

2.2.1 Transmission Mains - Pipe Pigs

There are basically two types of pipe pigs; the simple mechanical version that is used for cleaning and flow passage surveys; and the more complex version that integrates the basic platform with other sensor-based elements intended for pipe inspection. These elements range from simple mechanical calipers to advanced electronics to optical based data storage. The evolution of the sensor-based platforms has resulted in a family of inspection tools commonly referred to as *Smart Pigs*. The simple mechanical pig is basically a piston moving through the pipe, being powered by the fluid flow and the associated pressure drop across the seals. Pigs require the internal pipe diameter to remain relatively constant and the pipe runs to be straight or only gradually curving to guarantee ‘safe’ passage. Since current sensor technologies accuracy depends on surface cleanliness (mostly), cleaning is accomplished through the mounting of bristle brushes and/or the use of hardened surfaces around the circumference of the pressure seals. The use of these types of pigs does require a means for removing the debris that accumulates in front of the pig as it moves through the pipeline; that is why an inspection run is typically preceded by one or cleaning-pig runs. A modern Smart pig is quite sophisticated in both configuration and inspection capability. Smart pigs include on-board power supplies, data recorders and storage, and sophisticated NDE sensors to measure pipe wall defects. Magnetic flux leakage (MFL) has been the most popular NDE technique employed on pigs. However, ultrasonic, eddy current and acoustic sensors are also commercially available for Smart pigs. A collection of such cleaning and sensing pigs offered by the industry leaders[1], are depicted in the figure below:

There are many physical obstacles within typical transmission pipelines that have (in the past) curtailed and/or restricted the use of these Smart pigs, many of which have seen technology improvements over the years. Despite these advances though, many deficiencies (physical and flow obstacles) remain with the current technology that will prevent the use of these devices in many miles of existing transmission pipelines, especially those belonging to local gas distribution companies.

---

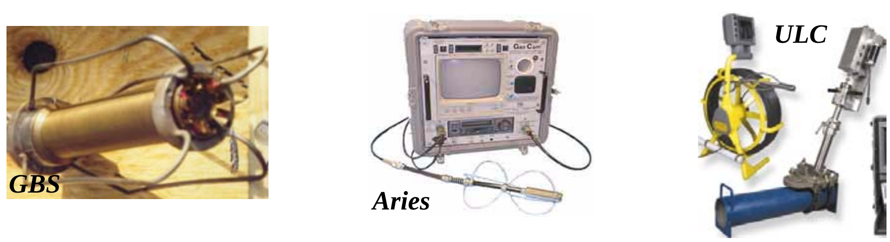
1. Integrated Full-Service Companies: Rosen, TDW, GE/PII, TuboScope, Baker-Hughes, CPIG, InvoDane, Enduro, etc.

2.2.2 Oil- and Gas-Wells - Tethered & Autonomous Robots

The use of robots to perform downhole operations (E&P: Exploration & Production - whether oil or gas wells) has been under consideration for about 10 years. Existing pieces of equipment are exclusively tethered by slickline (simple cable) or coiled-tubing deployed. There are hybrids such as the WellTec system that is powered over a cable, and the iTRobotics system which is autonomous but is only used for inspections of coiled-tubing itself. Prototypes such as Shell's Bore-shuttle and Baker-Hughes downhole robot do exist but have not yet seen full commercialization - these systems have no link to the surface and operate completely autonomously and using on-board power while travelling up and down the casing in an oil/gas well. Images of these systems are shown in the figure below:

2.2.3 Distribution Mains - Stick-Cameras

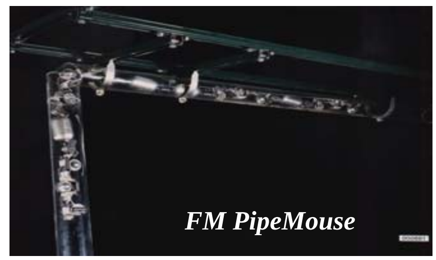
In terms of systems that have been used in live gas mains, particularly lower-pressure (< 100 psig) distribution mains, only a few video-inspection systems have come to the commercial market. they are able to be pushed/pulled into place using a tensile/power/data cable and are launched into a live main using specialty fittings and deployment systems. They provide only video but are commonly used for rapid inspection of critical/emergency areas. They vary in size, but the inspection-diameters of the pipes in question range from 4 to 10 inches in diameter and are almost exclusively in use in the natural gas industry. Three of the main systems in use today are depicted in the image below:



2.2.4 Distribution Mains - Pipe Crawlers

In the application of lower-pressure distribution mains for natural gas, several systems have been prototyped and fewer deployed for real-world inspection and repair in live natural gas mains. These systems are characterized by both tetherless and tethered operations over substantial long distances under live conditions. Advantica (R&D division of British gas) demonstrated the ability to perform RFEC inspection of steel pipes with a segmented robot, yet it has not yet been field-hardened. The FM PipeMouse is a tethered inspection system capable of traversing sharp geometries, yet it never was field-deployed. Explorer is the first robot to perform truly untethered real-time video inspection of live gas mains in real time while also being capable of traversing bends, Ts, junctions and vertical pipe-sections. A collage of these inspection systems is given in the figure below:


Advantica


FM PipeMouse


Explorer

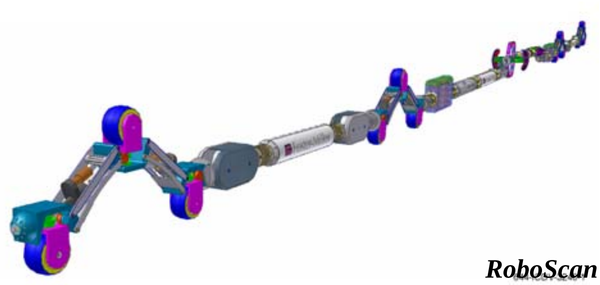
Other existing systems in use by the gas distribution industry revolve around pipe-inspection and repair. The two most notable ones are CISBOT and GRISLEE. The former is a tethered system capable of inspecting and repairing (via sealant-injection) cast-iron bell-and-spigot joints. The latter is a modular system to perform a visual and NDE MFL inspection, and perform an in-situ repair using composite repair sleeves - all while being deployed into and out of a main under live conditions using a coiled-tubing push-pull tether with internal power and data conductors. These two systems are depicted below:


CISBOT


GRISLEE

2.2.5 Other applications

Another noteworthy locomotion platform under development is the revival of the PipeMouse as the RoboScan platform for use in unpiggable transmission mains. This system will be self-powered and using autonomous control, while it scans the large-diameter transmission main for pipe-wall degradation using NDE sensor technologies.


RoboScan

3.0 Platform Comparison

The comparison-table depicted on the next page, attempts to provide detail on the different platforms locomotion characteristics as well as provide common and differentiating features amongst them.

In terms of pure locomotion, it seems clear that there are fully-tethered short-range system-solutions, as well as (mostly) untethered long-range systems capable of both video as well as NDE (development only) inspection. For those systems where power is provided on-board, using rolling locomotion is a clear preference. There seem to be different approaches to provide for traction but all rely on compressive-force against the pipe. Different geometries to achieve pipe-adaptation have been implemented, as well as different types of articulation and steering joints, all the way from purely passive, to fully articulated/powered. Geometries are clearly pipe-diameter dependent, as well as what types of obstacles they need to be able to handle such as sharp bends, elbows, plug-valves, etc. With the exception of one, all systems provide for real-time data through a dedicated copper or fiber-link/-tether. Even though on the drawing-board, there seems to be a clear lack of long-range inspection capability for both small and large diameter pipe-sizes under low and high pressure conditions, utilizing more than just video inspection but also coupling it with NDE-inspection.

To achieve inspection-ranges in the miles and perform the inspection in real time and under teleoperated or supervised/autonomous fashion, will require technology advancement in key areas such as battery-power and -recharge, communications, sensor-miniaturization and reliable control/autonomy software. The platform geometries and ability to locomote provides for different solutions which are typically driven by geometrical constraints as well as innovative preference depending on the development outfit as well as any relevant real-world deployment experience they may have accumulated over time - there is however no substantially superior architecture, locomotion or integration design that has yet been proven through field-deployments to be superior to its competitors, the main reasons being a real lack of competing varieties of platforms as well as a lack of real-world deployment data for all existing platforms or those still under development.

MARKET	CATEGORY	SYSTEM	SUPPLIER OR VENDOR	Pipe Market Segment [1]	Technology Maturity [2]	Design Architecture [3]	Obstacle Handling [4]	Locomotion Mode/Type [5]	Repair Capability	Inspection Capability	Sensor Type(s) [6]	Tethered	Power & Comms Type [7]	Range per launch
								[in]	[Y/N]	[Y/N]		[Y/N]		[ft]
Civil Infrastructure	*Water / Sewer Mains*	***Various*** BlackHawk, PearPoint, Beaver, KA-TE, Innuktun, etc.	Many - see previous	W/S	Comm	M, O	SPO, MC	FW, FT, PPT	Y	Y	V, UT	Y	LV, TL	< 200
Pipelines	*Pigs*	***Various*** Rosen, GE/PII, TDW, TuboScope, CPIG, B.Hughes, Halliburton, Enduro, etc.	Many - see previous	GT	Comm	M, S	SPO, MC, TSB	FP	N	Y	All; no V	N	BS, NL	Miles
Exploration & Production (E&P)	*Oil & Gas Wells*	Bore-Shuttle	AI/Shell	E&P	Prot	M	SPO, MC	FP, AW	N	Y	TBD; no V	N	BS, A	Miles
		Slick-Tool	BakerHughes	E&P	Comm	S	SPO, MC	PPT	N	Y	MFL, EC	Y	LV	Miles
		WellTractor	WellTec	E&P	Comm	M	SPO, MC	AW, PPT	N	Y	O	Y	LV, TL	Miles
		WellBot	iR/Halliburton	E&P	Field	M,S	SPO, MC	FW	N	Y	U	N	BS, A	U
	Coiled-Tube	InspectorBot	iTRobotics	E&P	Field	S	SPO, MC	FW	N	Y	MFL, EC	N	LV, NL	Mile+, U
Gas Pipelines	*Pipe-Cameras*	PipeCam	GBS	GD	Comm	M	SPO	PPT	N	Y	V	Y	LV, TL	<1000
		GasCam	Aries	GD	Comm	M	SPO, MC	PPT	N	Y	V	Y	LV, TL	<200
		HP Gas Camera	ULC	GD	Comm	M	SPO, MC	PPT	N	Y	V	Y	LV, TL	<200
	Pipe-Crawlers	RFEC Inspector	Advantica	GD	Field	S	SPO, MC	FW	N	Y	EC	N	BS, U	U
		PipeMouse	FosterMiller	GD	Prot	S	All; no V	AW	N	Y	V	Y	BS, TL	U
		Explorer	CMU/NGA	GD	Field	S	All	AW	N	Y	V	N	BS, W	>1000
		CISBOT	ConEd	GD	Comm	M	SPO, MC	PPT	Y	Y	V	Y	LV, TL	<250
		GRISLEE	CMU/MEI/GTI	GD	Field	S	SPO, MC	PPT	Y	Y	MFL, V	Y	LV, TL	<1000
		RoboScan	FM/NGA/DoE	GT	CAD	S	U	AW	N	Y	TBD	U	BS, TL	U

1 Water (**W**), Sewer (**S**), Gas Distribution (**GD**), Gas Transmission (**GT**)
2 **CAD** (Low), **Prot**otype (Lab only), **Field**ed (Real-world Proven), **Comm**ercial (Mature, Reliable & Cash-Generator)
3 Monolithic (**M**), Segmented (**S**), Other (**O**)
4 Straight-Pipe-Only (**SPO**), Minimal Curvature (**MC**), Tights Smooth Bends (**TSB**), Sharp bends Elbows and Ts (**SBET**), Verticals (**V**)
5 Flow-Pressure (**FP**), Fixed-Wheel Crawler (**FW**), Fixed-Tracked (**FT**), Articulated-Wheel (**AW**), Push-Pull-Tether (**PPT**)
6 Video (**V**), Ultrasonic (**UT**), Magnetic Flux Leakage (**MFL**), RF Eddy Current (**EC**), **EMAT,** Caliper-Tool (**CT**), Other (**O**), Unknown (**U**), **TBD**
7 POWER: Line-Voltage (**LV**), Battery Supply (**BS**) COMMS: Tether-Link (**TL**), Wireless (**W**), Autonomous (**A**), No-Link (**NL**)

4.0 References

[1] www.pearpoint.com

[2] KaTe System AG; http://www.ka-te-system.com/html/homee.html

[3] http://www.foster-miller.com/t_robotics.htm

[4] *"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.

[5] "*Explorer: Untethered Real_time Gas Main Assessment Robot System*", 1st International Workshop on Advances in Service Robotics, ASER'03, Bardolino, Italy, March 13-15, 2003

[6] http://www.ariesind.com/gascam.html

[7] http://itrobotics.ath.cx/Products/Products.htm

[8] http://www.advantica.biz/

[9] http://www.ulcrobotics.com/

[10] http://www.maurertechnology.com/Engr/Products/MFL.asp

[11] www.netl.doe.gov/scngo/Reference%20Shelf/ tsa/tsa-videoinspect-0202_1.PDF

[12] www.bakerhughes.com/pmg

[13] CISBOT - Company: ConEd – Enbridge Product: Cisbot: Contact: Terry Whitehead, Enbridge Contact Phone Number: 416-496-7147

[14] http://www.nygas.org/M-2002-015.htm

[15] http://www.welltractor.com/

[16] "Method and System for moving equipment into and through an underground well", Pat.# 6,675,888

[17] http://www.bakerhughes.com/bot/service_tools/index.htm

[18] www.tdwilliamson.com

[19] www.roseninspection.net

[20] http://www.gepower.com/prod_serv/serv/pipeline/en/index.htm

[21] www.blackhawk-pas.com

[22] http://www.ais.fraunhofer.de/BAR/kurt.htm

[23] http://www.netl.doe.gov/publications/press/2004/tl_oilgas_bbfa.html

[24] http://www.netl.doe.gov/scngo/Natural%20Gas/Projects_n/TD&S/T&D/T&D_C_41645RobotPlatform.html