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Distribution Gasline Robotics and Automation

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Explorer: Long-Range Untethered Real-Time Live Gas Main Robotic Inspection System

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II. ABSTRACT

Under funding from the Department of Energy (DoE) and the Northeast Gas Association (NGA), Carnegie Mellon University (CMU) developed an untethered, wireless remote controlled inspection robot dubbed *Explorer*. The project entailed the design and prototyping of a wireless self-powered video-inspection robot capable of accessing live 6- and 8-inch diameter cast-iron and steel mains, while traversing turns and Ts and elbows under real-time control with live video feedback to an operator. The design is that of a segmented actively articulated and wheel-leg powered robot design, with fisheye imaging capability and self-powered battery storage and wireless real-time communication link. The prototype was functionally tested in an above ground pipe-network, in order to debug all mechanical, electrical and software subsystems, and develop the necessary deployment and retrieval, as well as obstacle-handling scripts. A pressurized natural gas test-section was used to certify it for operation in natural gas at up to 60 psig. Two subsequent live-main field-trials in both cast-iron and steel pipe, demonstrated its ability to be safely launched, operated and retrieved under real-world conditions. The system's ability to safely and repeatably exit/recover from angled and vertical launchers, traverse multi-thousand foot long pipe-sections, make T and varied-angle elbow-turns while wirelessly sending live video and handling command and control messages, was clearly demonstrated. Video-inspection was clearly shown to be a viable tool to understand the state of this critical buried infrastructure, irrespective of low- (cast-iron) or high-pressure (steel) conditions. This report covers the different aspects of specifications, requirements, design, prototyping, integration and testing and field-trialing of the *Explorer* platform.

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LIST OF ACRONYMS

FOV - Field of View
MEI - Mirier Engineering, Inc.
GRI - Gas Research Institute (now GTI)
GDF - Gap de France
CT - Coiled-Tubing
MFL - Magnetic Flux Leakage
RF - Radio Frequency
MIPS - Million Instructions Per Second
LAN - Local Area Network
DOF - Degree of Freedom
w.r.t. - with respect to
RG&E - Rochester Gas & Electric
NYPUC - New York Public Utility Commission
NYSEG - New York State Electricity and Gas
NGA - North East Gas Association
DoE - Department of Energy
LVDS - Low Voltage Differential System
LED - Light Emmitting Diode

III. EXECUTIVE SUMMARY

The design, prototyping and demonstration efforts of the joint NETL/DoE and Northeast Gas Association (NGA) funded Explorer project have been successfully completed. The project entailed the design and prototyping of a wireless self-powered video-inspection robot capable of accessing live 6- and 8-inch diameter cast-iron and steel mains, while traversing turns and Ts and elbows under real-time control with live video feedback to an operator.

The Explorer robot system specifications led to the design of a segmented actively articulated and wheel-leg powered robot design, with fisheye imaging capability and self-powered battery storage and wireless real-time communication link. The prototype went through a lengthy testing and evaluation period both in the laboratory and an above ground pipe-network, in order to debug all mechanical, electrical and software subsystems, and develop the necessary deployment and retrieval, as well as obstacle-handling scripts. In addition, the test-period included the honing of the safety design and -procedure for launching and retrieval.

An early in-air pressurization test indicated that the system was capable, as designed, to withstand pressures up to 120 psig, and was tested during launching and operation at those pressures in the laboratory. The next step of in-gas operation proved that pressurized natural gas, and the associated procedures related to safe launching/retrieval and operation in such a medium, were valid and acceptable. As part of the final field-demonstrations, the Explorer robot was shown to be capable of operating in low- and high-pressure natural gas mains. In addition, the capability of performing scripted and manual launches, both vertical and angled, elbow (short and long) turns of varying degrees, as well as Ys and Ts, clearly demonstrated the systems' design-capabilities.

At the end of the field-trials, the system had logged at least 10 miles of operation in the laboratory and the test pipe-network, performed at least 50 elbow/Y/T-turns, and around 50 launches and recoveries in angled and vertical launchers. Real-world footage included around 1.5 miles of travel and 12 obstacles with 15 launches and recoveries under live conditions. The Explorer robot is undergoing continued evaluation, testing, demonstration and commercialization efforts. Additional field-data collected through this process will hopefully come to benefit any future developments.

The Explorer robot design, with its compact and active articulations (steering, centration and driving), was clearly shown to be a viable and successful implementation of an inspection system for launching, operation and retrieval in 6- and 8-inch diameter natural gas distribution mains. The use of the wheeled leg-design, with passive centration- and support legs (including odometry), was shown to be capable of providing the needed drive and articulation to optimize fisheye pipe-inspection. The battery-power source was shown to be more than reliable for full-shift operation. The wireless communications link and associated Graphical User Interface (GUI) was clearly demonstrated to be the backbone of the system and not limit its operation, especially in steel mains. The simplified angled launching system for cast iron pipes and the vertical launcher for steel pipes proved to be very successful in the field. The developed safety design and operational safety procedures for launching and retrieval were well motivated, executed and proved themselves to provide a safe operating system.

The test-results were collected over a lengthy evaluation period and included a large number of tests. Laboratory testing for launching/retrieval and obstacle handling successfully uncovered electro-mechanical issues that were resolved as part of the integration phase of the program. In addition, long-term driving in the outside (above ground) test network allowed for the run-in and endurance testing and long-term failure-mode evaluation. Compressed air testing validated the operation of the specialized purging and ventilated enclosure design and certified operation to 125 psig. In-gas pressure testing provided proof to the utilities of the safety procedures and safety-design and endurance of the materials and systems to natural gas exposure (including mercaptan).

The conclusions that can be drawn from the two low- and high-pressure cast-iron and steel main field trials are fairly general and powerful. It is clear that deployment and retrieval into live gas distribution mains is very feasible and can be performed safely given the Explorer design and procedures. The ability to make turns in elbows and Ts was clearly shown in repeated settings as was the ability to find, view and visually analyze features (joints, debris, taps, feeds, etc.) using the operator GUI and the digital fisheye camera video. Endurance and wireless control range were shown to be well beyond that possible with current tethered pushrod camera systems.

In combination with all the previous features, Explorer was shown to best existing camera inspection systems by at least an order of magnitude in range from a single excavation and be able to not be subject to straight-pipe deployments, and drastically reduce the inspection costs of underground pipe-sections by limiting the number of excavations by at least an order of magnitude over its closest competing technical alternative (tethered pushrod inspection-camera).

It would seem that Explorer has not only a future in live-main video-inspection, but also in corrosion-inspection of higher-pressure steel mains should it be desirable to add an NDE sensor capability to the platform.

1.0 Introduction

1.1 Setting the Stage

Gas distribution utilities nationwide continually search for new and improved means to maintain, upgrade and efficiently operate their underground natural gas distribution and delivery system. To do so, these utilities use a substantial array of technologies to monitor, inspect, repair, rehabilitate and replace their underground mains. With these mains ageing rapidly, the biggest needs in the industry is to perform in-situ inspection using a vast array of inspection sensors, so as to ascertain the state of the main prior to making decisions as to what maintenance steps to take. Performing such inspections under live conditions, with minimal excavation and without considerations as to pipe-internal layout, has been an unattainable goal with existing technologies. This goal is now becoming reality with Explorer.

1.2 Vision

The vision that utility companies have of how to maintain and manage their gas distribution network, is based mainly on their short- and long-term needs, and the state of technology and its potential to offer novel solutions in the near to mid future. The vision centers heavily on information of the state of the network, both in terms of structure (pipe-integrity, corrosion, cracks, leaks, etc.), as well as process properties (pressure, flow, humidity, etc.). A major part of the management plan relies on having sufficient high-density in-situ data of the pipe-internals, so as to be able to ascertain parameters such as leak-paths, water-intrusion, corrosion and cracking, etc. Such data is typically only available after a local inspection survey is performed, either visually via a camera, or through other pipe-structure sensor systems (MFL, UT, eddy-current, etc.). Based sometimes on this, but mostly on no concrete data, managers have to make a decision as to whether to repair, reline or replace (typically with plastic) their mains. Their need thus for comprehensive, detailed, real-time data as to the internal state of a line, would be immensely helpful to them to make a decision as to what course of action to take.

The vision that would make this need a reality, centers around a sensor-probe, capable of single and low-cost pipe-access and traverse of live gas mains of varying pipe-sizes, during 24 hour operations, without any human tending. This system would provide continuous data, initially purely visual, to a central control location, where data could be viewed live or off-line. Over time this (or more) unit(s) would have traversed most of the network and amassed a complete record of the system for operators to review. Such a system should ideally be capable of operating autonomously, rely on its own power and communicate its data back live for storage, viewing and post-processing.

Even though this might seem to be an unattainable vision if assumed to be required in its entirety, the utilities are eager to even utilize technology that extends their current inspection-cost, -time and -range, beyond what is currently in use within the field. Utilizing this concession, and surveying the technical state-of-the-art, it would thus seem that the need for systems capable of accessing the underground network from a single point and travelling on their own, untethered and without requiring topside tending but relaying data in real time, constitutes a major step towards realizing at least the up-front portion of the detailed vision.

1.3 Motivation

The use of untethered inspection systems is expected to radically improve gas line inspection and repair. More and more piping needs to be inspected due to the age of the existing urban gas-pipeline distribution network. Currently, little to no internal inspection is performed on a line that is known or assumed to be leaking in one or more locations, with at least one of them being major to warrant immediate action. The operating company has to make a decision as to whether to spot- or section-repair the line, reline it or completely dig it up and replace it - these decisions are typically made based on in-situ evidentiary data (maps, historical repairs, leak surveys, corrosion data, etc.) to help the operator make a safe and cost-effective decision. Due to logistical and financial considerations, repairs and line replacement is only performed in the case of multiple-location or single-location leaking sections of pipeline. Most of the time though, the decision to replace and/or reline an existing gasline is not always supported by physical evidence that the line to be replaced actually needs to be replaced along its entire length, rather than just in certain stretches or maybe even only in certain spots.

The overall assessment and repair process can thus be extremely costly without the ability to judge the most cost-effective repair approach. In the US alone, over $650 million per year is spent to repair leaks of all types - giving the utilities the tools needed to make the decisions for cost-effective repair-method selection would have a drastic impact on their operations. Possible savings are hard to estimate, but if one assumes that up to 50% of the currently section-replaced/relined or completely replaced pipelines could have been repaired with the next-'cheapest' repair method, savings may be on the order of 25% to 50% over conventional replacement techniques, saving the gas industry tens of millions of dollars annually.

The ability to have continuous video footage of the condition within miles of piping of any distribution network, provides the information to the maintenance division of any utility to decide upon the location, repair-method and scheduling of repairs (if any). Such a system would be able to detect (i) water infiltration, (ii) accumulated debris, (iii) abandoned and live service connections, (iv) locate main reducing fittings and offsets, (v) verify location (counting joints and reset-measuring and adding pipe-lengths) and path of main (by use of a sonde), and (vi) provide a visual evaluation of pipe-internal condition (primarily for corrosion-detection in cast-iron gas-mains).

The availability of such a long-range and easily deployable tool will greatly enhance the diagnostic and maintenance budgeting for existing gas operators (i.e. as a job-planning tool), with the potential to save large costs in terms of providing the data to make decisions as to which repair/replacement method (spot/local/complete-line replacement/relining) to utilize. In addition, such a system could also be used as an emergency maintenance tool, by assisting in (i) the location of water infiltration into a low pressure gas main (thus eliminating or reducing the duration of costly main-outages), (ii) the location of cracked cast-iron gas mains and damaged steel mains, and (iii) the location of water pools and obstructions due to the presence of foreign material in the pipe.

Since the system is insensitive to which material the pipe is made of, it is actually applicable to 100% of the (ferrous - thereby excluding plastic pipe) pipeline market, in sizes bigger than 4 inches - this excludes only the feeds between these lines running under the streets/sidewalks and each individual residence (typically 1-2” ID). In the future, additional corrosion-detection and corrosion-loss measurement sensors could be added to give an even more detailed picture of the non-visible piping-condition within the network if so desired and technically and operationally feasible.

2.0 Technology Description

2.1 Prior Art - Relevant OEM Systems

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.). They are mostly tethered, utilizing cameras and specialized tooling, etc. (see Figure 1).

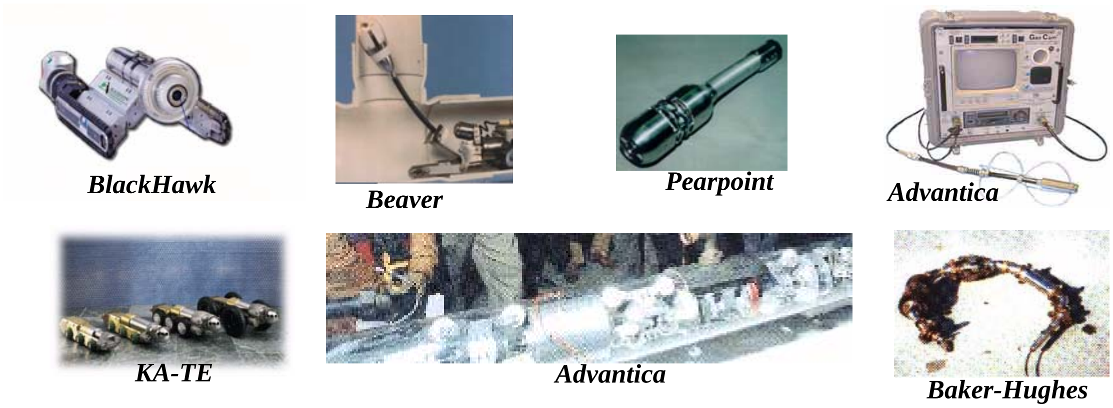


Figure 1: Prior art in in-pipe inspection systems

Three of the more notable systems in use for gas distribution network inspection, 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*; ULC Robotics), which is deployed through a bolt-on fitting and injects anaerobic sealant into the leaking jute-stuffed joint, and *GRISLEE (GTI, CMU & MTI)*, 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; GRISLEE) and untethered (Kurt I) robots

The Explorer system varies from existing systems by virtue that it is not limited by the length of a hard-connection (tether or pushrod), that can be dragged or pushed down a pipe. Hence the ability to provide power from on-board and communicate imagery and data back wirelessly open up a whole new realm of possibilities. Additionally, the system is launched through a vertical access-port, and is thus also able to access pipe that is beyond sweeps, bends, junctions, Ts, etc. - all other systems are not able to access pipe that in any way substantially curved, with corners, Ts, etc. The ***Explorer*** system is thus completely untethered and capable of operating in more deviated/lateral mains and perform visual inspections over longer ranges and periods of time - all operations are viewable and controllable in real time from a single console by a single operator outside the main, plugged into the system only by virtue of a cable to an antenna sticking into the main. Hence the variety of pipe types and sizes, and the range-capability of Explorer is what will set it apart from all the other competing systems. To get a sense of the state-of-the-art in current video-inspection systems, whether for gaslines or not, we have briefly described the current systems available for sale or service below:

- **GasCam^{R} - Aries, Inc.**
  This system was funded by Niagara Mohawk and allows visual inspection of a variety of sized low-pressure gasmains under live conditions. The lipstick-sized camera is capable of entering a main through a keyhole (sized according to pipe-diameter), where it is then pushed with a composite pushrod with embedded power and video-lines through the main. The system can access only mostly-straight and slightly swept mains, due to its flexure-limitation in the pushrod and the inability to push farther due to friction-buildup and pushrod buckling. The range of the system is no more than 250 feet in either direction from an inclined launch-point installed by way of tapping into the main inside of a full-excavation hole.
- **GRISLEE^{TM} - GRI/NASA/CMU/MEI**
  The GRISLEE system jointly funded through NASA and GRI, and developed by CMU and MEI, is a set of interchangeable modular elements to perform visual and MFL inspection of a live gasmain, and deliver a patch-repair module into a live main to repair a weak, leaking or joint-section inside a 4-inch steel live gasmain. The system is launched through an angled chamber welded (high-pressure) to the pipe inside an oversized excavation-hole, with a fitting to a coiled-tubing (CT) spool, where a steel and composite pushrod connected to the end-module on the train, allows for the push/pull deployment of these systems. The maximum distance, given an almost perfectly straight pipe with minimal bends, can be in the 500 to 1,000 foot range from a single hole in the pipe (the range can be doubled by using a fitting welded on pointing in the

opposite direction).

- **PipeCam - GBS, Inc.**
  GBS developed a standard FOV camera for use with MEI's CT-unit to provide visual inspection of a main prior to launching the MFL-head jointly funded through GRI and GDF, and developed by TubaScope Vetco, Inc. (MEI developed the CT-unit under that program). The camera has again limited capabilities by virtue of the deployment access and progress-method (CT pushrod), and its inability to perform only straight main-main visual inspection with a standard FOV (60 to 90 degrees) camera-and-lighting system; deviated mains and elbows, Ts, miters, bends are not accessible with this system.

- **ScanCam - VIT Everest, Inc.**
  This camera was developed for use in larger sewer-mains, to not only perform visual downpipe but also high-resolution lateral and side-wall inspection. The system has a forward and a separate articulated side-looking camera and lighting system. The system is sized and hardened for sewer use and is either deployed by way of pushrod, or atop a tethered mobile platform. The range of the unit and access into deviated or side-mains is again limited by the tethered connection and the mobility platform used by the contractor. The unit has not been ruggedized nor packaged for use in gasmains, and it would seem to be of substantial length, necessitating again an inclined launch-chamber, implying a larger and costlier hole, were it to be used in the gas-industry.

- **SewerCam - CORE, Inc.**
  This system was developed by a Japanese consortium and is being marketed in the US through CORE. The system is basically an environmental housing within which sits a wide-angle camera-and-lighting system, capable of high-resolution imaging of forward and sidewalls inside of sewer-mains. The system is deployed only atop a tethered or pushrod deployed crawler. Images are also dewarped and mosaiqued, and packaged into a report and video for the sewer-utility to review. The system is impressive in terms of its camera-resolution and imaging software, yet it also suffers from similar size- and range-limitations due to the geometry and deployment-method of the same. The system has also only been used in larger-diameter sewer-mains.

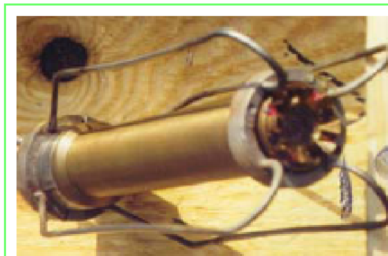
- **Articulated LateralCam - Aries, Inc.**
  Finally, another available system, again from Aries, Inc., revolves around a crawler-deployed camera-head, with the ability to have its 'neck' extended and 'poked' a short distance (<1 foot) into a lateral of slightly smaller size. The notion is to provide sewer operators an image of laterals connecting to a main, as it is here where connections tend to wear and fail over time. The unit thus offers value to sewer-operators, but again due to its size and deployment-method, would

have a limited range, costly and cumbersome launching requirements, and only work in larger-sized pipes, assuming it could be made safe to operate in live gasmains.

- Aries GasCam[R]

+ Works in Live Line!
+ Small DIA. (4”+)
- Tethered
- 250’ Range (pushed)
- No elbows

- GBS PipeCam



+ Works!
+ Medium DIA.
- Tethered
- 1,000’ Range
- No elbows
- Tied to CT-unit

- VIT ScanCamera

+ Works!
+ Inspects Main Pipe only
- Tethered
- Limited Range
- Large Pipe (>6”)
- Sewers only – possibly sealable

- GRISLEE

+ Works!
+ Inspects Main Pipe only
- Large & complex launch setup
- Increased Range +/- 500/1,000 ft.
- Straight Pipe only
- No elbows, Ts, etc.

- CORE SewerCam

+ Works!
+ Mosaiques Pipe
- Tethered
- Limited Range
- Large straight Pipe (>10”)
- Sewers only!
- Needs a locomotor

- Aries Art. Camera

+ Works!
+ Inspects Lateral
- Tethered
- Limited Range
- Large Pipe (>6”)
- Sewers only!

2.2 Technology System Concept

The ***Explorer*** system is intended to be a long-range untethered live in-pipe inspection system for use by the gas utilities in distribution mains ranging in size from 6 to 8 inches ID. The system differs from previously designed (see Section on Prior Relevant Work), developed and tested systems in that it is far simpler, cheaper to build, deploy and operate, while providing at first live video feedback (e.g. no sampling, no repair, no corrosion sensing, etc.), at complete power-autonomy and at a higher speed, range and duration than is currently possible with tethered systems - all this from a single 4 ft. W x 15 ft. L x Pipe-Depth excavation.

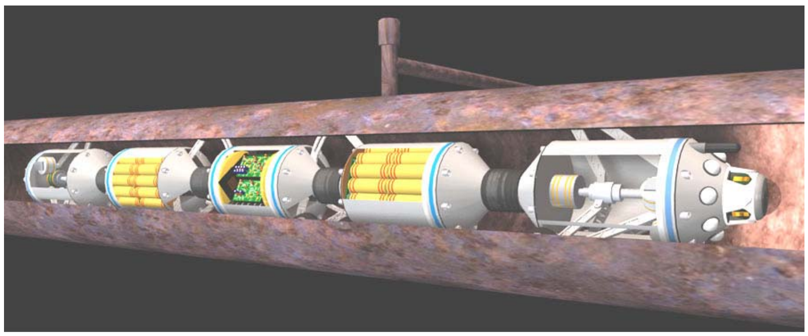


Figure 3: Original Explorer Concept

2.3 Operational Setting

The system operational specifications and characteristics can be summarized as detailed here and depicted in Figure 4. The system is deployed through a Mueller welded-on launch-chamber sleeve-system on an excavated underground gasline into the live environment. The system adapts its geometry and locomotors to the encountered gas-line ID, thereby driving against the pipe, and locomotes down the pipe with speeds up to 4 inches per second by extracting power from its battery-bank. The system carries an on-board frontal fisheye lens camera to collect live imagery. The system communicates live TV and teleoperator control to the system via RF using the pipeline as a waveguide. The system can reconfigure itself to access 90-deg bends, negotiating 1.5D bends, with reduced travel and comm-link range. The system could travel in either direction from the insertion point, subject to communication-range and power-drop - deployments could last longer and go further depending on the number of access-points, etc. Location and navigation of the system, as well as emergency- and failure-retrieval will be accounted for in the system design. The simplest and most accurate ‘navigation’-approach to use will be to visually count joints and software-reset the on-board odometer at each joint, measure each pipe-section individually and accurately, thereby generating a non-drifting estimate of longitudinal displacement within the pipe (presumes accurate human decision on whether a feature is a joint, which should be very easy to detect). The safety approach will rely on evacuation, inert-gas purging and pressurization and pressure-differential monitoring during the deployment, rather than attempting to design the system to intrinsic-safety (unlikely to succeed due to required power-levels) or explosion-proof (unlikely to be small enough to fit in the target pipe-range) standards.

2.4 Critical Technologies

Based on the description of the envisioned Explorer system, it is important to list, detail and analyze those technologies that were envisioned to be critical at the onset of this effort. Additionally, it was also important to identify those features that are inherently critical to the mission-profile, and make sure they were properly addressed during the design-phase. The intention was to address most of these early on in a feasibility evaluation, and others during the final design-phase, prior to proceeding into prototyping. A list of both these categories is provided below in tabular form:

CATEGORY	AREA/ENTITY	COMMENTS
Technology	***Wireless Communications***	Exploring the range and signal quality as a function of the amplitude and frequency of the RF-wave
	Power Source & Recharge	Exploring the use of on-board chemical storage cells/batteries with external docking for recharging in-line
	Wide-angle Visual Pipe View	Exploring the utility of providing a wide FOV lens, lighting and camera arrangement with software to dewarp and mosaique the pipe-wall imagery for real- and off-line review

CATEGORY	AREA/ENTITY	COMMENTS
Feature	***Modular Turn/Steer Geometry***	Exploring the size and diameter relation of individual modules to ascertain turning radii and lateral access. Additionally, the type of module-interconnection and centration scheme to be used to keep the train centered needs to be explored
	Packaging, Integration & Safing	Given the size limitations, exploration of packaging, integration and safing of the key electro-mechanical components in the system as the design evolves
	Computer Software & Hardware	Development of the architecture and associated processor-type and board-sets to support current and future missions. Issues such as distributed processing and minimal interconnect wiring through common power and data bus need to be considered, as does selection of CPU for current and future tasks, for both centralized and distributed tasks/processes

Figure 4: Overall Deployment Scenario

3.0 System Design

3.1 System Requirements Overview

The mission that Explorer was supposed to undertake can best be described as follows:

- ***The objective is to perform a teleoperated long-range untethered video-inspection of live distribution gas-mains.***
- ***The goal of the project team, in order to achieve the above objective, was set to be the development of a prototype 'crawler' system for live gas main access with wireless video & data communications utilizing on-board power sources.***
- ***The minimal target shall be defined as traversing 6- to 8-inch inside diameter piping, while able to crawl through elbows, mitered joints, Ts, climb and descend inclined and vertical sections, while safely operating in a medium-to-high pressure pure natural gas environment, allowing operators to communicate and receive live video in real time, including accurate navigation position-estimates.***

The performance requirements that can be derived from the mission scenario detailed above, are detailed in the bulleted list below:

- ***Access pipe through angled-to-vertical fittings***
- ***Operate in 6 to/or 8 inch pipe in horizontal, sloped, elbowed, T'ed and vertical sections***
- ***Operate on sequential single shifts***
- ***Maximize speed and reach while minimizing down-/recharge time***
- ***Provide for a wireless interface for real-time video feedback and assisted teleoperation***
- ***Smart recharging in the launcher***

The system that was being targeted for development was seen to be applicable to live gas mains (both cast-iron and steel pipe), allowing for a single entry-point to cover large distances in non-straight and convoluted piping-runs, relying only on on-board high-density chemical cells for power, allowing it to maintain a real-time data and video-link inside the pipes. The visual inspection data being considered for the system, was believed to be of most value in low- to medium-pressure gas mains (such as cast-iron, plastic and some steel) with the system performing long-duration pipe-survey/-sentry missions.

3.2 Subsystem Design

3.2.1 Overall Configuration

The overall system configuration given to the pipe-internal crawler was a function of its environment, operational regime and mission requirements. The decision to perform visual inspection and be capable of omnidirectional motion, placed the need to have one camera at either end of the system. The ability to make turns into Ts and elbows, limited the individual unit-length to a not-to-exceed length, requiring a minimal number of units due to packaging. The ability to climb/descend vertically drove the design to put drive-units on either end of the entire assembly, which at this point was defined as a self-centering collection of modules interconnected at the ends. The overall diameter of each module was directly linked to the module-length capable of making a turn (the larger the diameter, the shorter a module needs to be to make a turn), the need to stay as high off the bottom of the pipe due to deposits, and the need for a minimal diameter to package mechanics and electronics. Since we had to be able to make turns in any direction, it was deemed necessary to have a steerable joint after each end-module - the rest of the modules were deemed to only require a passive spring-loaded wheel-centered universal joint. The biggest electro-mechanical challenge came at the drive-module and steering-joints due to the need to package substantial elements into the unit. The power system was estimated to require two separate modules due to the energy needed for a complete days' mission.

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 5 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 5 : Explorer - Pipe Inspection System

The architecture of the robot is simple and symmetric - see Figure 6:

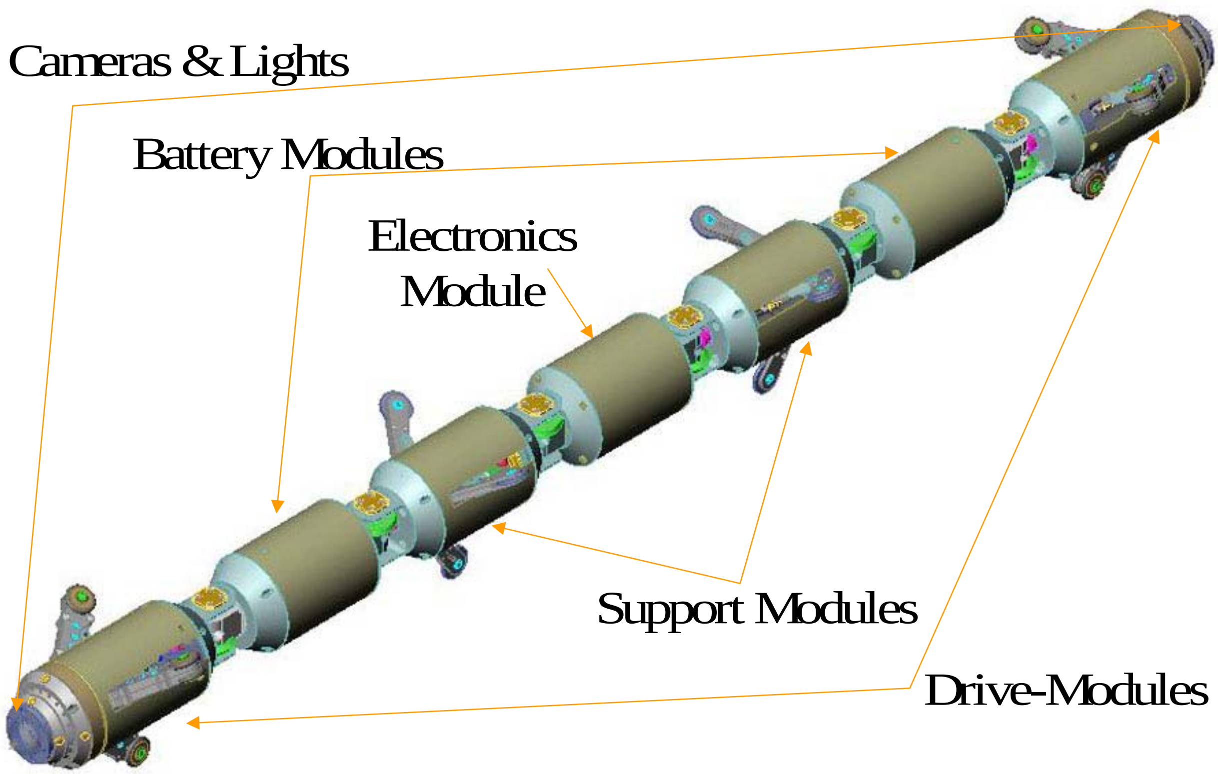


Figure 6 : Explorer Architecture CAD Design

A 7-element articulated body-design houses a mirror-image arrangement of locomotion, battery-, support and computing electronics in purged and pressurized housings (see Figure 7). 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 locomotor-modules 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 prolonged travel inside pipes using custom on-board battery-packs, which can use any desired chemistry depending on desired range and cost. 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. The battery-module(s) contain custom battery packs to allow for a full multi-hour mission with all systems consuming maximum power. The support modules also have extendable 'arms', but the wheels at their ends are passive and are used for accurate displacement-encoding. 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.

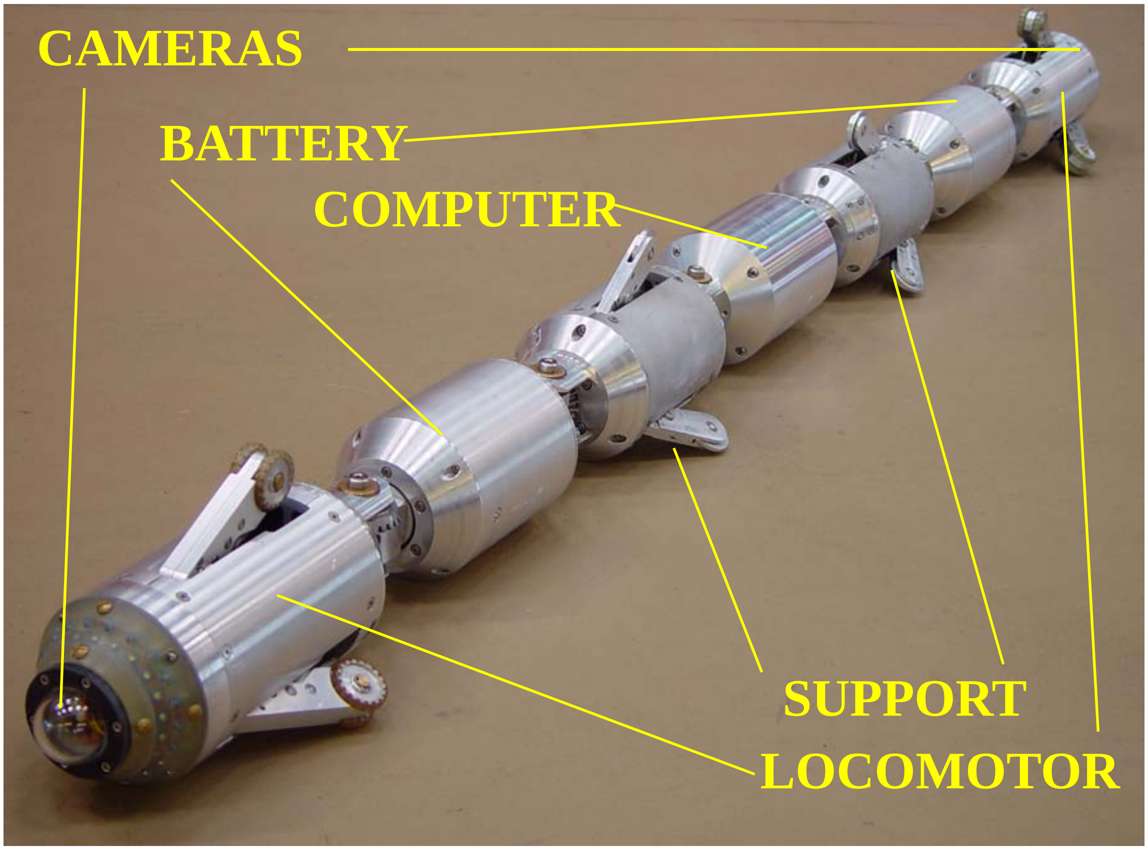


Figure 7 : Overall view of Explorer

The overall electronics architecture, shown in Figure 8, while the design of the distributed electronics architecture for on-board the robot is shown in Figure 9. Figure 9 depicts the on-board scheme of using a central high-MIPS low-power CPU to communicate with a set of bus-connected microprocessors to achieve all control, data-gathering and I/O functions over a customized wireless LAN backbone implementation. A custom-developed 32-bit low-power 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 multi-drop communication-bus. Real-time external communications is through a wireless radio-link, using the pipe as a waveguide for long-range communications.

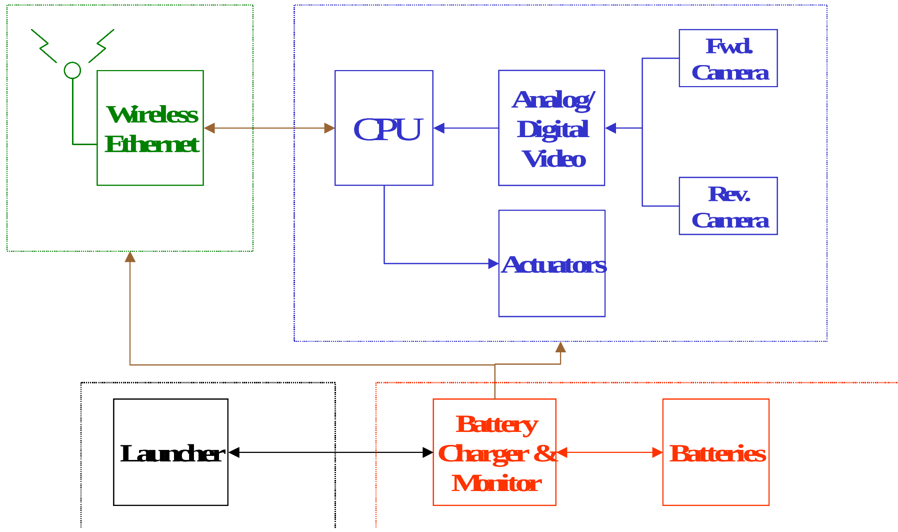


Figure 8 : Explorer overall electronics architecture

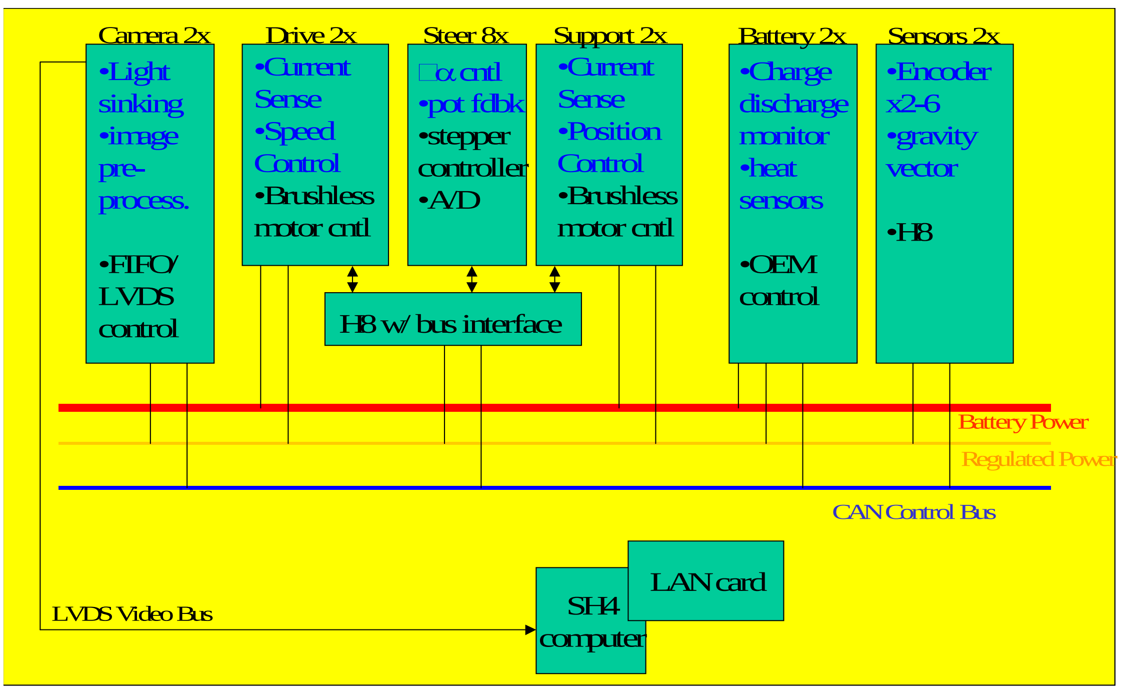


Figure 9 : On-board robot distributed electronics & functional architecture

3.2.2 Deployment Concept

The operational deployment was centered around accessing the live main in a low-cost and readily-reachable area free of other underground obstacles and buried utilities (such as parking lots, etc.). A simple utility-van would access the area after it was dug and the launcher was installed, and deploy the system using solely a computer interface with limited joystick control and semi-automated scripts. Obstacles were to be handled in a similar manner, utilizing manual driving control (speed-variations) with automated turn-scripts for elbows, Ts, Ys, etc. A view of the deployment-setting is shown in Figure 10.

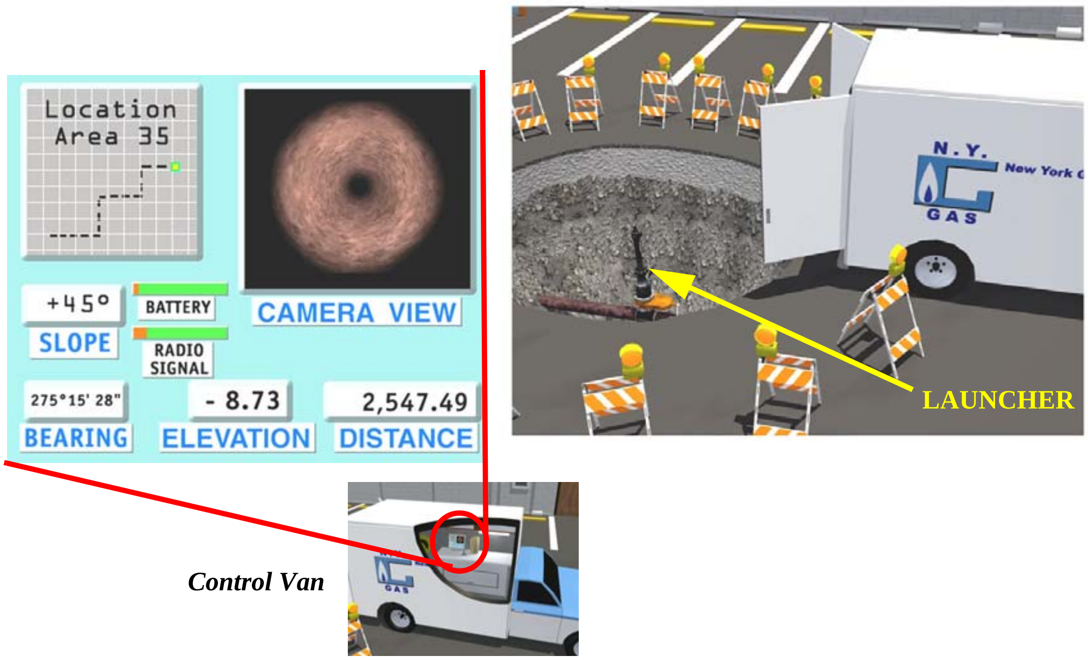


Figure 10 : View of the launching and control setup

3.2.3 Locomotion System

The locomotion system for Explorer is contained in its entirety in identical modules at the front and rear of the module-train. The locomotion mode that was decided upon, primarily due to the power-efficiency and combined progress travel-speed, combined a powered wheel-driven preloadable and adjustable hybrid-locomotor into a single unit. In order to allow the operator to see where the unit was headed, cameras were added to each module to look forward/reverse. The architecture of the module is such that the drive-module has the ability to collapse its articulated driven arms, allowing it to ride on the bottom of a pipe, but expand to self-center itself in a 6- and 8-inch ID pipe. The arms are powered by a single motor driving a spur-gear pass, powering a ballscrew, to which a nut is attached, which drives the three-bar linkage arrangement so as to extend/collapse the arms (an anti-rotation feature keeps the nut from rotating causing only linear travel). The wheels at the end of each arm are all synchronously driven by a single motor through a planetary gear-reduction, with a pass-thru gear-train inside each arm, which then powers a dual set of wheels at each arm. The wheel achieves traction due to the compression of the wheel against the inside pipe-wall.

A CAD internal view of the arm-deployment and -drive section is shown in Figure 11.

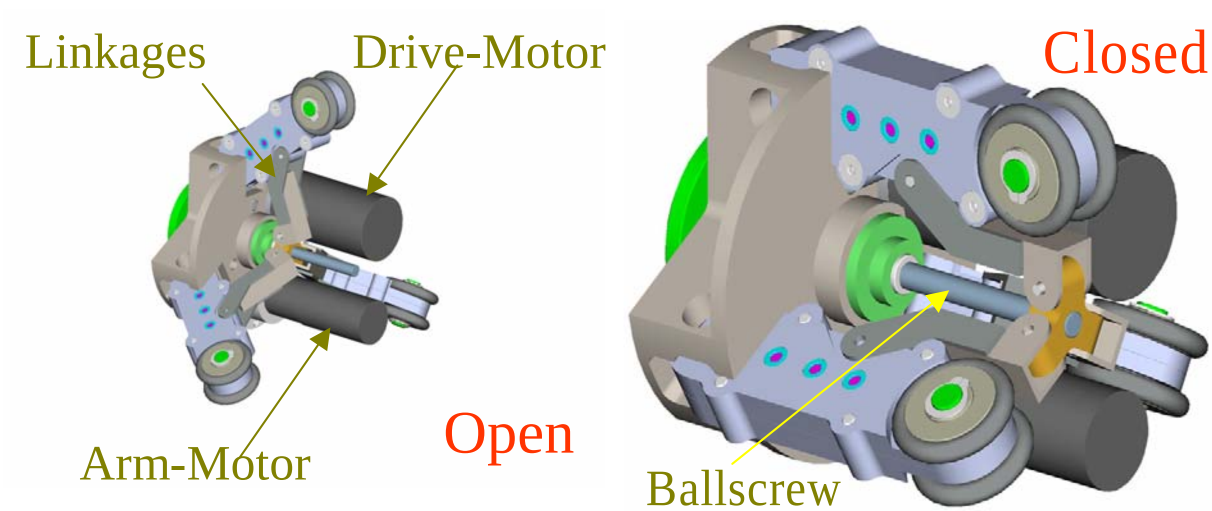


Figure 11: CAD internal view of arm-deployment and -drive system

The unit is sized and speced to allow full vertical ascent and descent inside of pipes, as well as sweeps, bends, Ts and mitered joints in any orientation. A depiction of the locomotion-/drive-unit is shown in Figure 12.

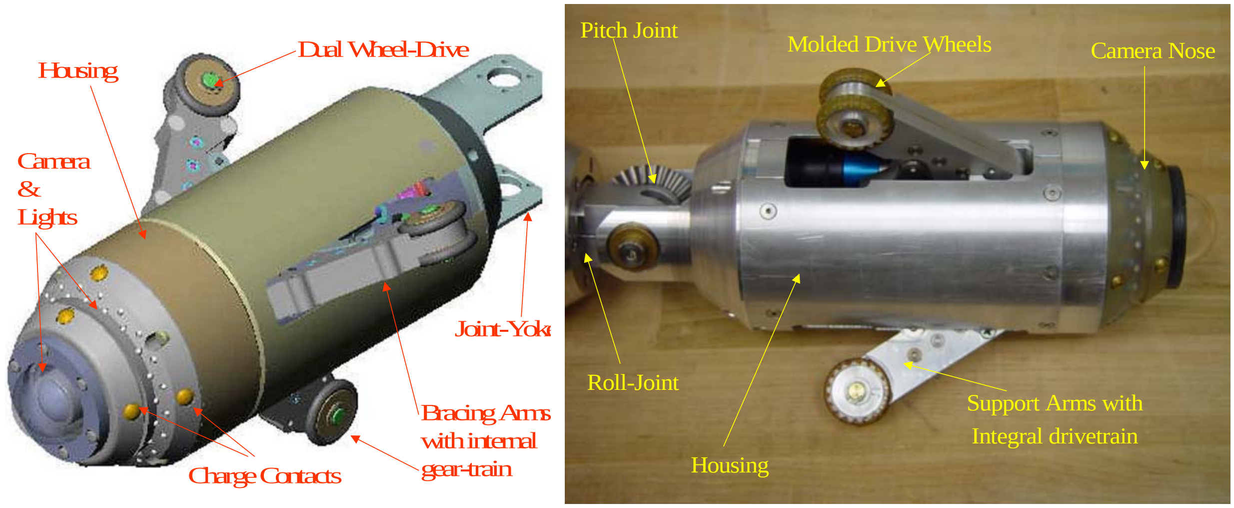


Figure 12: Explorer locomotor module design

3.2.4 Steering System

The steering system consists of two types: (i) a single roll-joint at each drive-module, coupled with a simple pitch-joint, and (ii) an actuated one- DOF pitch joint interconnecting all the remaining modules. The design is based on two endbells that house a brushless motor-gearbox combination, mounted off-axis, driving a bevel-gear through a shaft-mounted pinion. The central shaft mounted to the bevel-gear, has a hollow-shaft that penetrates the endbell, allowing wires to be routed through it, and hooks up with a bevel pinion-gear. Said pinion gear then engages a sector bevel-gear that is coaxial with the u-jointed bearing-supported shaft around which the axis rotates. The joint is capable of a 45-degree angle, limited by hard-stops in both directions. Such a seemingly limited angle though is sufficient to perform the 90-degree turns required of the system.

The system contains a ‘home’ switch, allowing the system to re-center itself during power-loss. A potentiometer provides analog position-feedback during operation, so as to enable accurate positioning even if power is lost. The motors are brushless commutated stepper-motors, with motor-step commands used as open-loop position estimates.

An image of the CAD-renderings for the steering joint, is shown in Figure 13:

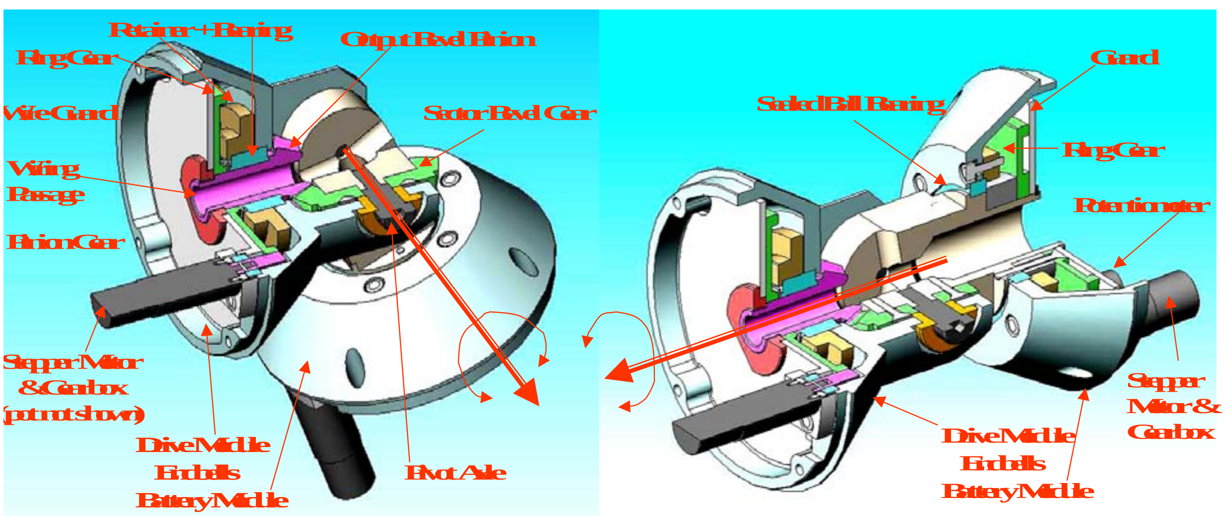


Figure 13: CAD image of the steering joint with cut-away view(s)

A view of the prototype joint is shown in Figure 14 below.

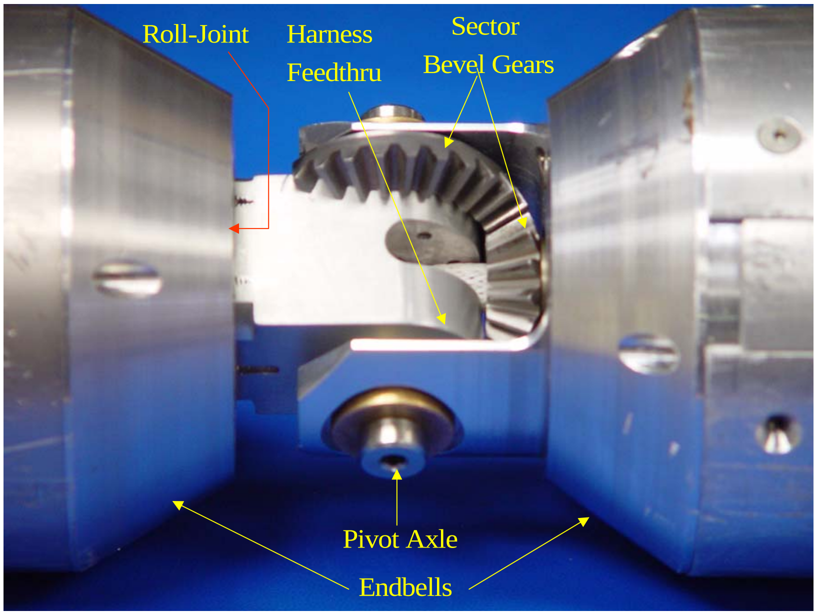


Figure 14: Explorer steering joint module design

3.2.5 Support Module

The support module is necessary to provide centration during launching/retrieval as well as climbing and turning to reduce friction and guarantee obstacle navigation. The design of this module is similar to that of the drive-module (without the camera-nose), in that it employs the same structure and leg-deployment drive-design. However it lacks the in-arm wheel-drive train and only provides for an arm with a free-wheeling wheel at the end. Said wheel however is encoded using magnets and hall-effect sensors to provide for a highly redundant position-feedback indicator used by the computer for odometry. On either end of the module are located the steering modules detailed earlier.

An up-close view of the support module, is shown in Figure 15:

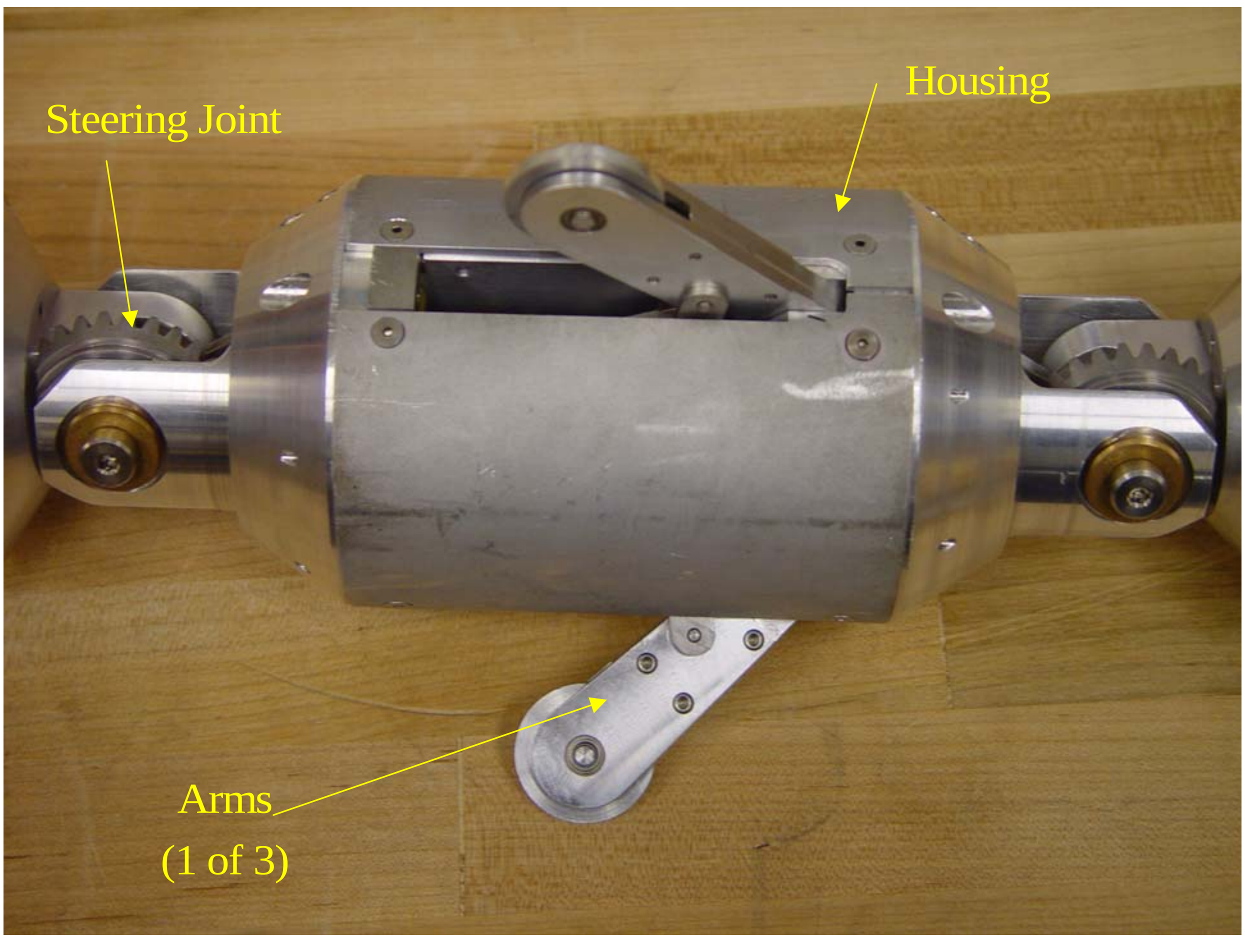


Figure 15: Support Module Design

A detailed set of views of the support module, including opened views for the same, are depicted in Figure 16:

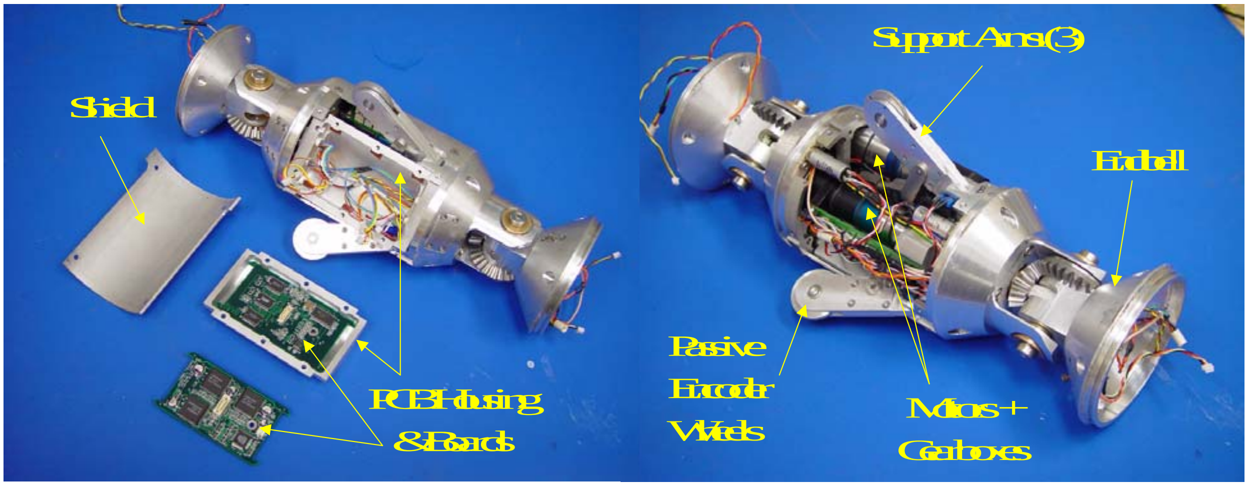


Figure 16: Overall and internal views of the prototype support module

3.2.6 Electronics & Control Module

The main brain and controller for the robot-train resides within the electronics module in the center of the train. The design is such that a central card-cage, carrying all the needed circuitry for communications and processing, reside within a bi-directional check-valve-protected enclosure (purged and vented with nitrogen), with identical steering joints attached to either end to connect it to the train.

An image of the module design and prototype hardware are shown in Figure 17:

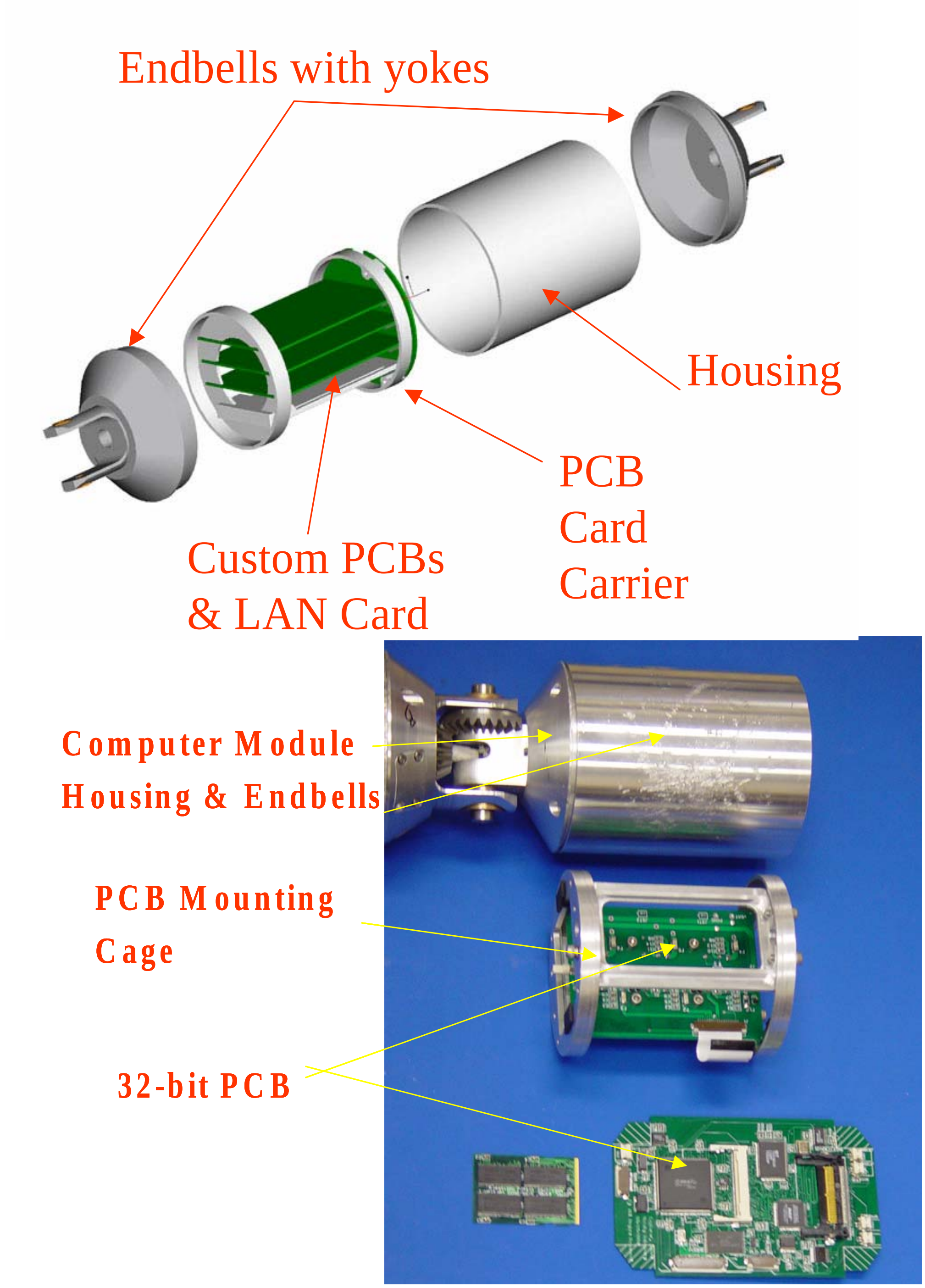


Figure 17: Explorer Electronics Module

3.2.7 Drive-Module Camera Section

The drive-module front-section on either end contains a set of electronic boards, RF antenna as well as LED lights and the fisheye camera section. The overall assembly of said section is depicted in Figure 18.

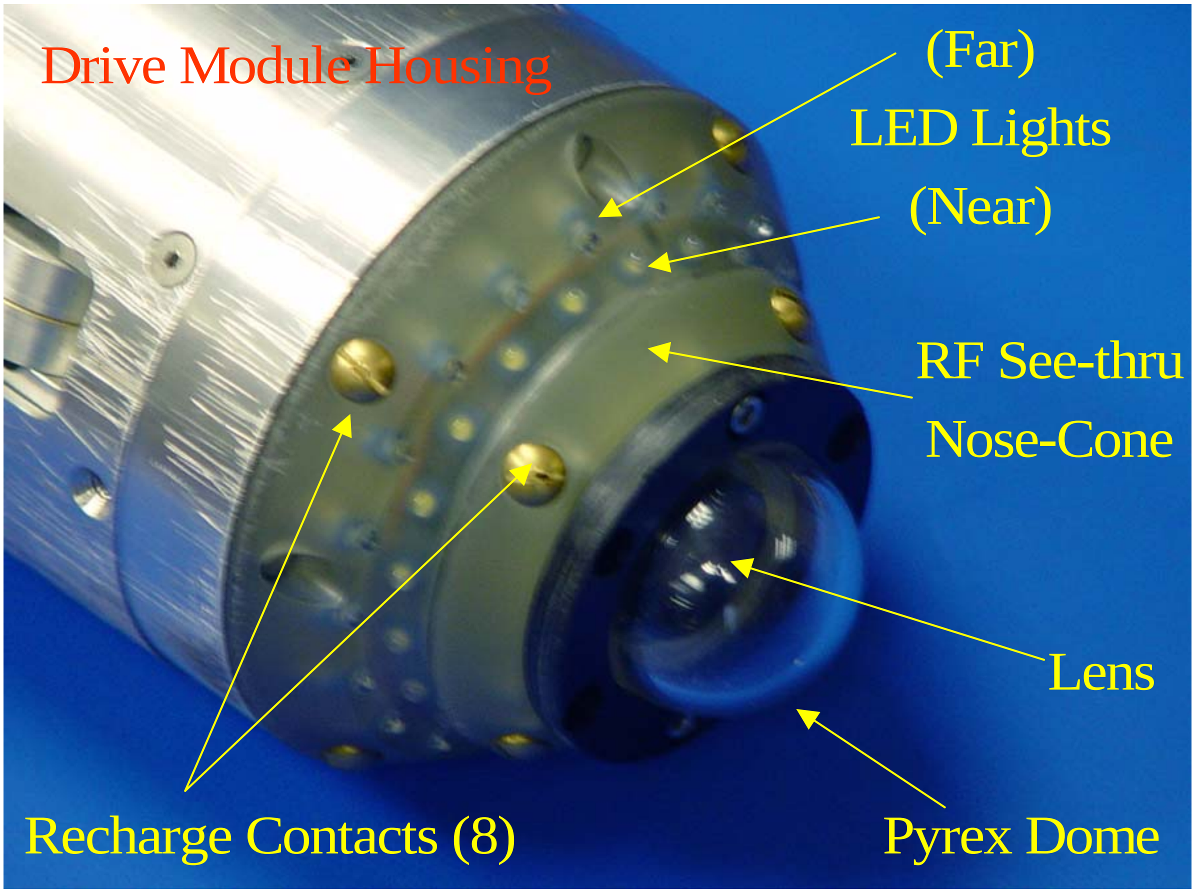


Figure 18:Drive-module frontal camera assembly

The protective pyrex dome protects the lens of the camera, which sits on a CMOS imager (640x480) which is connected to the main processor over an LVDS bus. Two sets of far and near focussed white LEDs are mounted in an RF-transparent dome, including a set of power recharge points. Surrounding the camera lens sits a custom antenna PCB, which is responsible for the wireless LAN connection. In behind the antenna-board, sits the 8-bit H8 microprocessor board responsible for controlling the drive-module as well as the camera-lighting and -settings.

An image of the module design and prototype hardware internal to the front dome, are shown in Figure 19 on page 27:

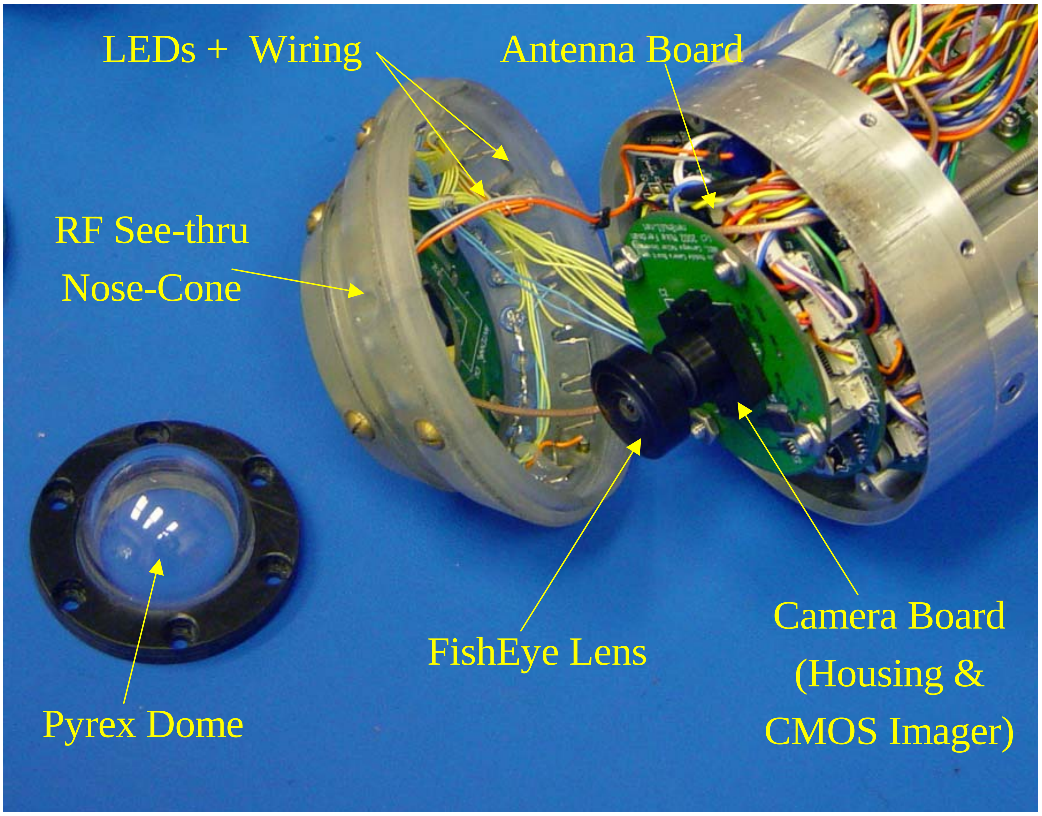


Figure 19: Explorer Camera-Nose internal assembly detail

3.2.8 Power System & Module

The power system for the Explorer robot is based on chemical energy-storage, namely batteries. The choice of the battery is driven by its use and energy and power-requirements. It was obvious that the system had to be reusable, and hence no primary cells were an option. Space was at a premium, and the need for long-duration usage and high-power short-termed draws necessitated the look at some of the more uncommon cell technologies. Tempered by the fact that the battery-pack had to be affordable and buildable by CMU or an OEM within reasonable time and expense frameworks, the selection was eventually limited to NiMh and Li-Ion.

Before a selection on the desirable chemistry could be made, we analyzed the necessary power and energy to comply with the single-day mission-scenario developed and agreed-to by the utility industry. The main assumptions that needed to be made revolved around the following:

- ***Weight: 35 lbs***
- ***Max. Speed: 4.5 in/sec.***
- ***Frequency or total distance of vertical travel over 2 mile horizontal travel: 1% or 110 feet; equates to (18) 3-foot rise-and-drops over 2 miles or a 3-foot-rise-and-drop (bypass) every 590 feet***
- ***Deployment Duration: 8 hrs.***
- ***Bus Voltage: 26 VDC***

The resulting power-draw table, including inefficiencies in the drivetrain (50%), the motor (80%) and the amplifier (85%), and accounting for all the hotel-load items (computing, cameras, lights, sensors, communications, etc.), results in a table as shown below:

Assumptions				
weight (lb)	35	**Max Discharge Current**	5.06	Amps
work day (hours)	8	**Max Discharge Current per battery module**	2.53	Amps
Nominal Voltage	26	**Max Discharge Current per cell-stack & cell**	0.84	Amps

Functional Block	**Device Power (Watt)**	**Duty Cycle (%)**	**Avg. Power (Watt)**	**Energy (Watt-hr)**
Drive Vert.	61.25	1	0.61	4.90
Drive Horiz.	12.25	99	12.13	97.02
Steer	8.00	1	0.08	0.64
Preload	42.00	1	0.42	3.36
Mech.Subtotal	**123.50**		**13.24**	**105.92**
CPU	4.00	100	4.00	32.00
Lights	0.24	100	0.24	1.92
RF	1.40	100	1.40	11.20
Support Elect.	0.50	100	0.50	4.00
Heat	2.00	100	2.00	16.00
Elect. Subtotal	**8.14**		**8.14**	**65.12**
Total:	**131.64**		**21.38**	**171.04**

Notice that using a 6-pack arrangement allows one to reduce the maximum current per cell (and thus pack) to a manageable number, allowing one to consider the cheaper, safer and easier-to-integrate NiMh cells. A comparison of the two chemistries, utilizing OEM cells, yields the table shown here:

	Nominal Voltage	**26V**	
	Chemistry-Type	NiMh	Li-Ion
cells			
dimensions	(mm x mm)	**17x67**	**17x67**
cell voltage	(V)	**1.2**	**3.9**
# of cells		**42**	**42**
configuration		**21s2p**	**7s6p**
weight	**(lb)**	**4.9**	**3.2**
capacity	(Amp-Hr)	7.6	7.5
	(Watt-Hr)	**197.6**	**195**
life	(hours)	8	8
charge time	(hours)	**15**	**2**

Notice that NiMh is a viable candidate over Li-Ion, except that it is 50% heavier as a pack, and takes 8 times longer to recharge. Hence if the cost, delivery or safety-concerns for the Li-Ion based power-system become an issue, the project can revert back to the NiMh technology and build their own pack.

The design of the respective power-module, of which there would be two, hence splitting the power-pack in two, can best be described as a set of packaged cells, connected to a monitoring (voltage, current, temperature, etc.) and charging circuit-board, all housed within the power-module in a pressure-enclosure. A view of the CAD assembly for the power-module and the prototype, are shown in Figure 20.

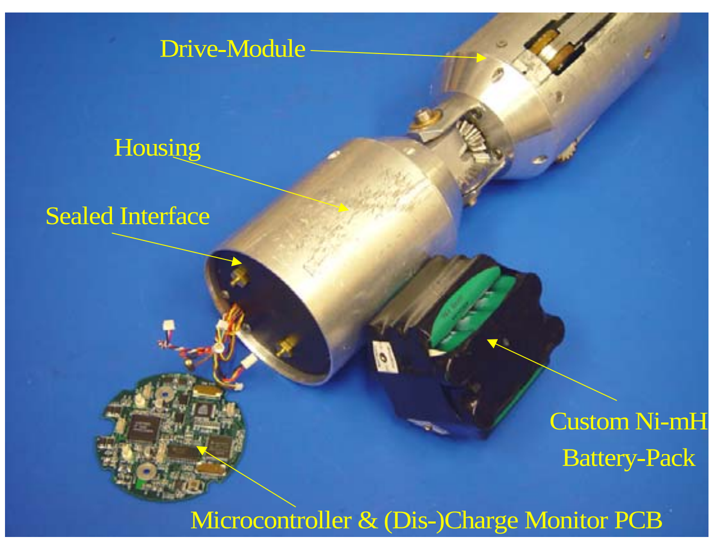


Figure 20: Image of the prototype Power Module

A cut-away CAD view of the battery module is shown in Figure 21:

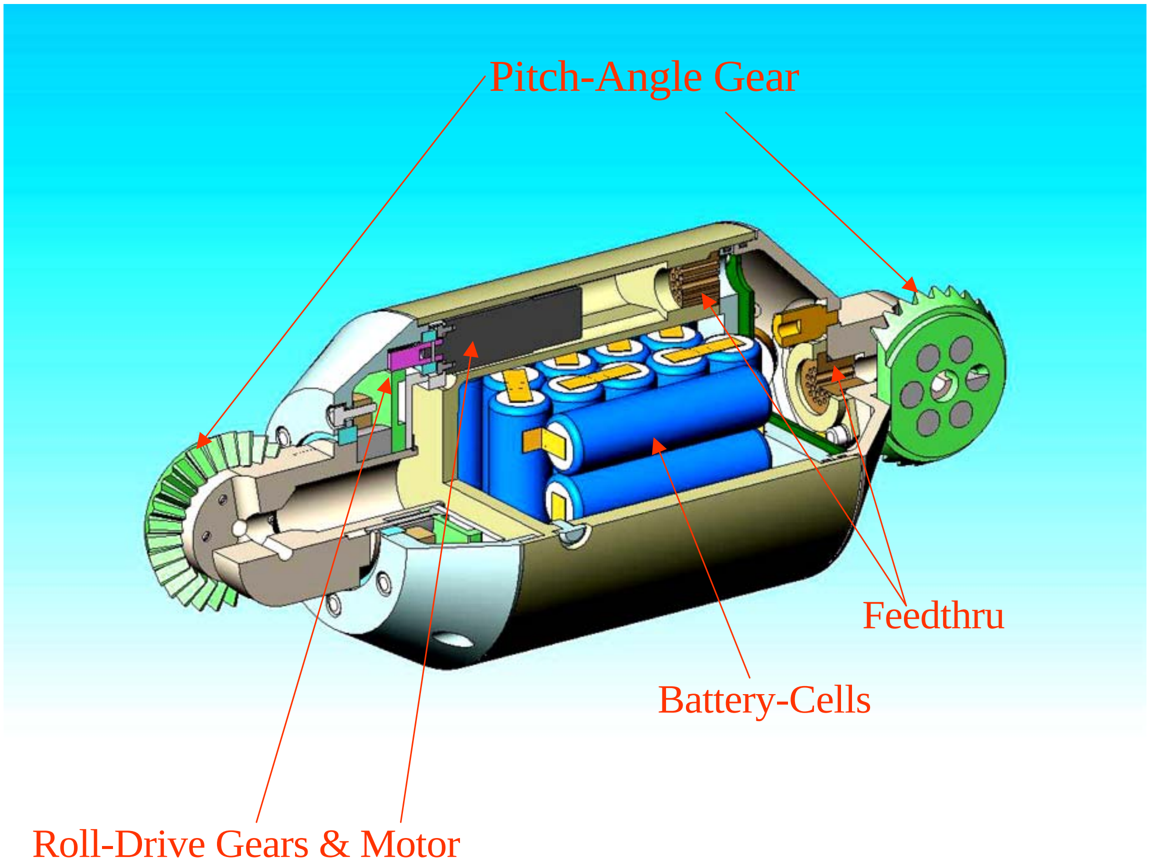


Figure 21: Cut-away CAD rendering of the battery-module

3.2.9 User Interface

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. A view of the prototype display, including graphical representations of the robot configuration and the raw fisheye imagery, are shown in Figure 22. The need for real-time dewarping of the fisheye image was deemed non-critical at this time, but rather relegated to a post-processing activity for ready archiving of digital in-pipe inspection data. Lighting controls are also included to allow the user to control reflections and saturation via camera-gain. All video-imagery also gets recorded in analog format on a VHS-tape as a backup.

Figure 22 :Fisheye and dewarping imagery user interface with hardware platform

3.2.10 Live-main Launching

Two different systems are used for robot launching into a live pipe. In the case of low pressure applications an off-the-shelf relatively inexpensive fitting by IPSCO is used, to which a specially designed launcher tube, carrying the robot, is attached. Different fittings are needed for 6” and 8” pipes. In the case of high pressure applications a specially designed vertical launch-chamber is used (see Figure 23) - both fittings were tested in a test-network (see Figure 23) at CMU prior to field-trial experimentation.

Low-Pressure Clamp-on Cast-Iron (CI)

High-Pressure Welded Steel

Figure 23 : Live-access launching hardware systems: Low-pressure CI and high-pressure steel

An image of the CAD details for the launcher design are shown in Figure 24:

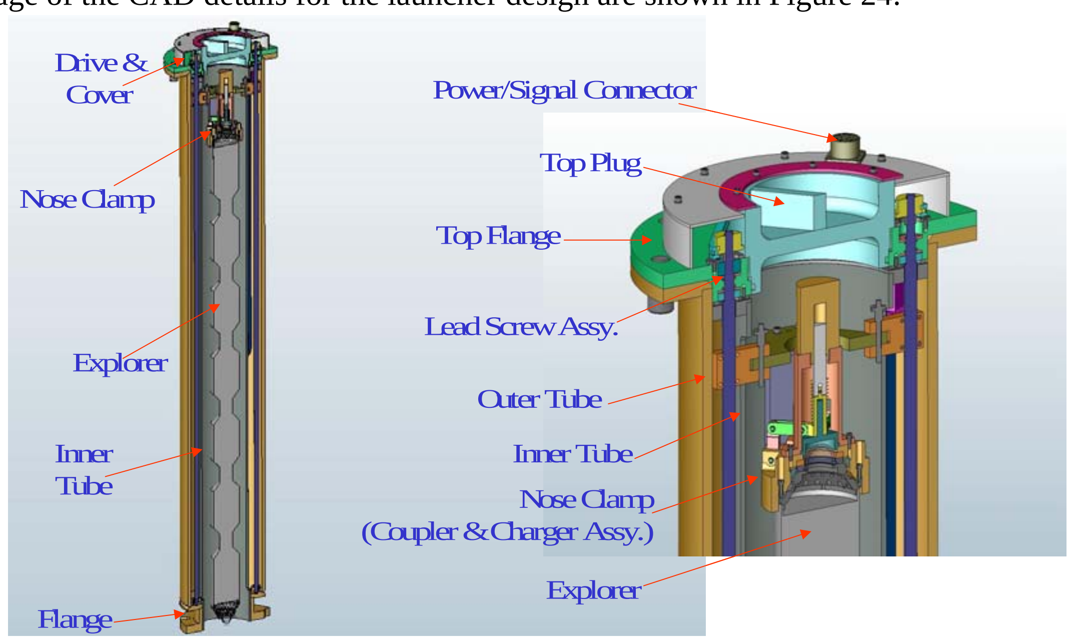


Figure 24 : CAD views of the high-pressure steel launcher

In both cases every effort is made for the excavation to be dug in a 'low-cost' location selected by the utility, where custom antennae are used to link the operator console to the robot.

An operator controls the robot using a simple forward/reverse joystick interface, while the on-board computers generate all the individual joint-steer and driving commands. 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 non-straight section of pipe.

3.3 Software Architecture

This section describes the software architecture employed on the Explorer robot. The diagram in Figure 25 depicts the high level components of the Explorer software controller(s).

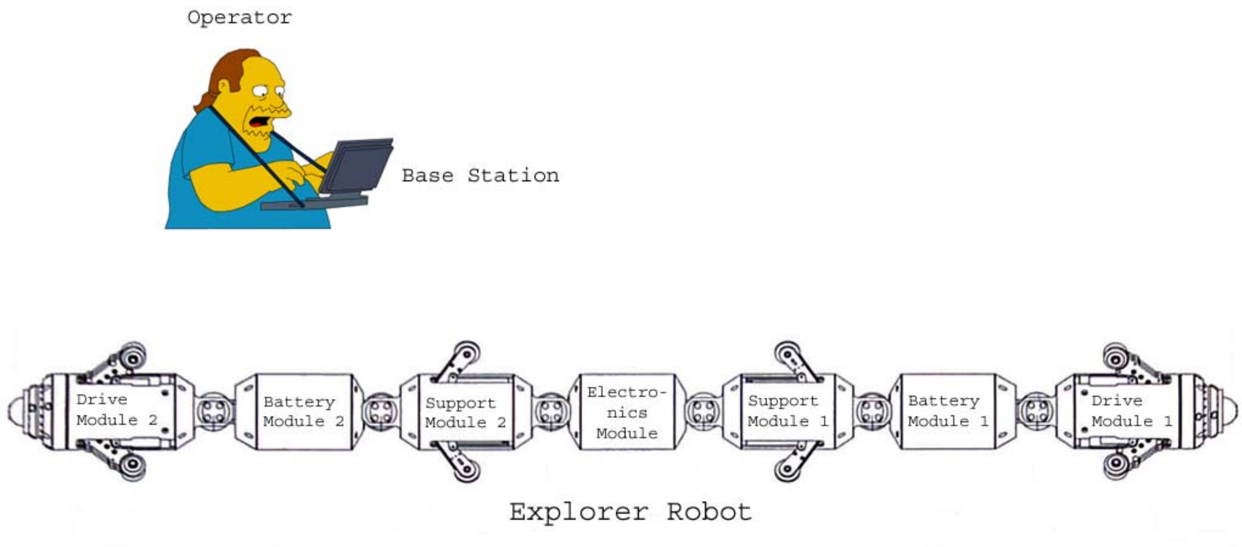


Figure 25: Overview of Explorer Software Split

The highest level is the human operator who sends commands using the graphical user interface on the base station. The base station interprets these commands and sends them to Explorer using a proprietary wireless ethernet protocol. Then comes the robot, which has seven modules. The ethernet messages are received by the Hitachi SuperH4 processor (henceforth referred to as SH4) in the electronics module of the robot. The SH4 relays the appropriate commands to the other modules in the Explorer robot over CANBUS to successfully complete the desired action.

Mechanically, the first side of the robot is symmetric with the other. That is, drive module 2 is the same as drive module 1, battery module 2 is the same as battery module 1, and support module 2 is the same as support module 1. Each of these six modules has an H8 micro controller which receives the CANBUS messages from the SH4 and, if the command is valid, performs the desired action. A more detailed description of each module is provided in the following sections.

The SH4 software architecture used is depicted in Figure 26. Notice that the software is written with a multitude of threads each servicing a particular task, such as communications, video-acquisition, wireless and CAN access, timer interrupts, etc.

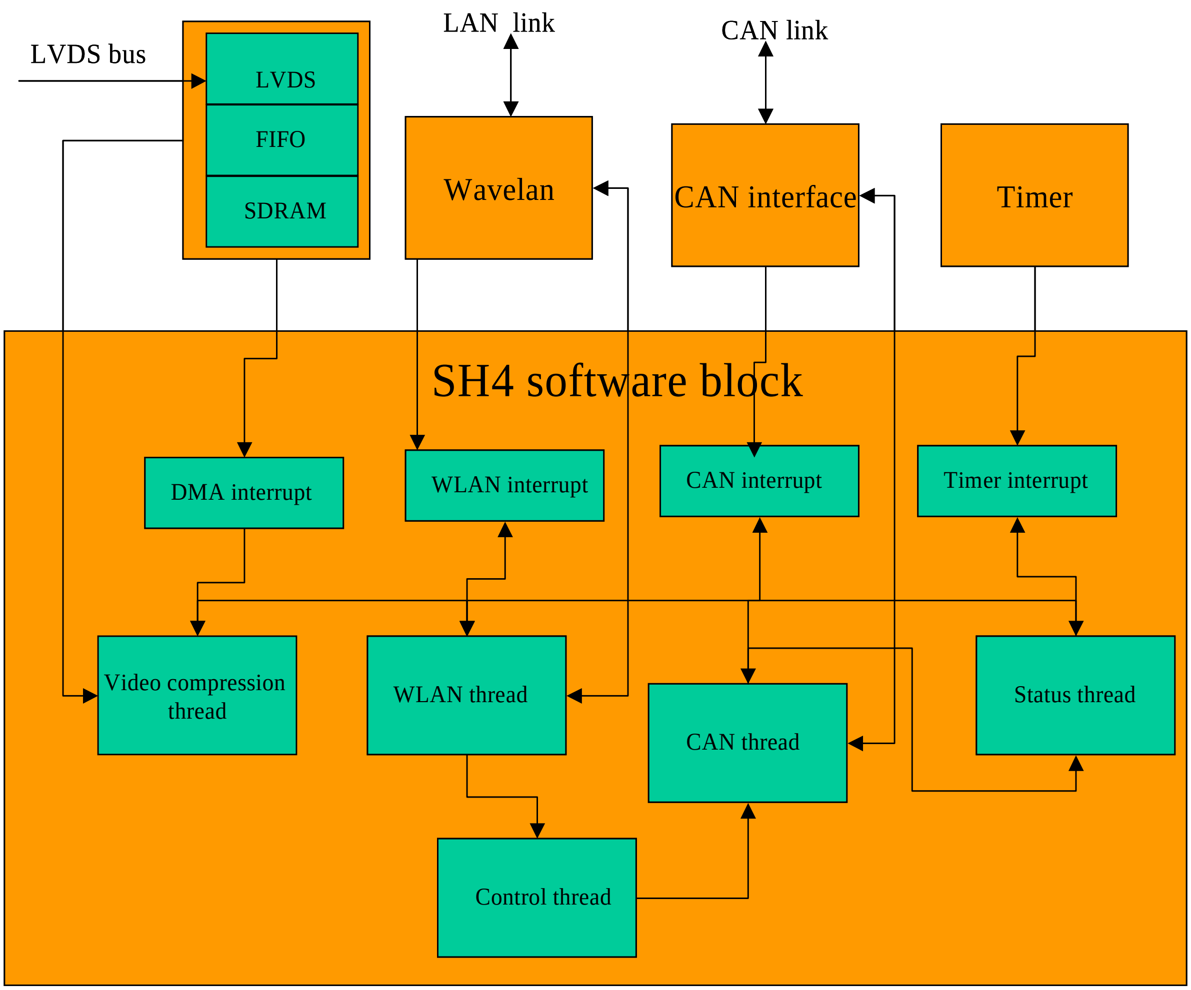


Figure 26: SH4 Software Architecture Diagram

The basic sequence in which the software on each of the microprocessors operates, is as follows:

- Receives commands from the control station wirelessly and controls 6 modules via CAN bus.
- Each communication type is handled by a separate driver/control thread (WLAN, CAN threads).
- Data from WLAN thread is interpreted by Control thread, which then is communicated to modules via CAN thread.
- There is a stream of image data from front/rear cameras, which is received via an LVDS bus, stored in a FIFO and is put into SDRAM via DMA. Video thread compresses the data and transmits it to the control station via WLAN thread.
- CAN thread receives status messages from the modules and updates a status table, which is shared with the Status thread and is periodically sent to the control station via WLAN thread.

The software architecture for the H8 microprocessors is as depicted in Figure 27:

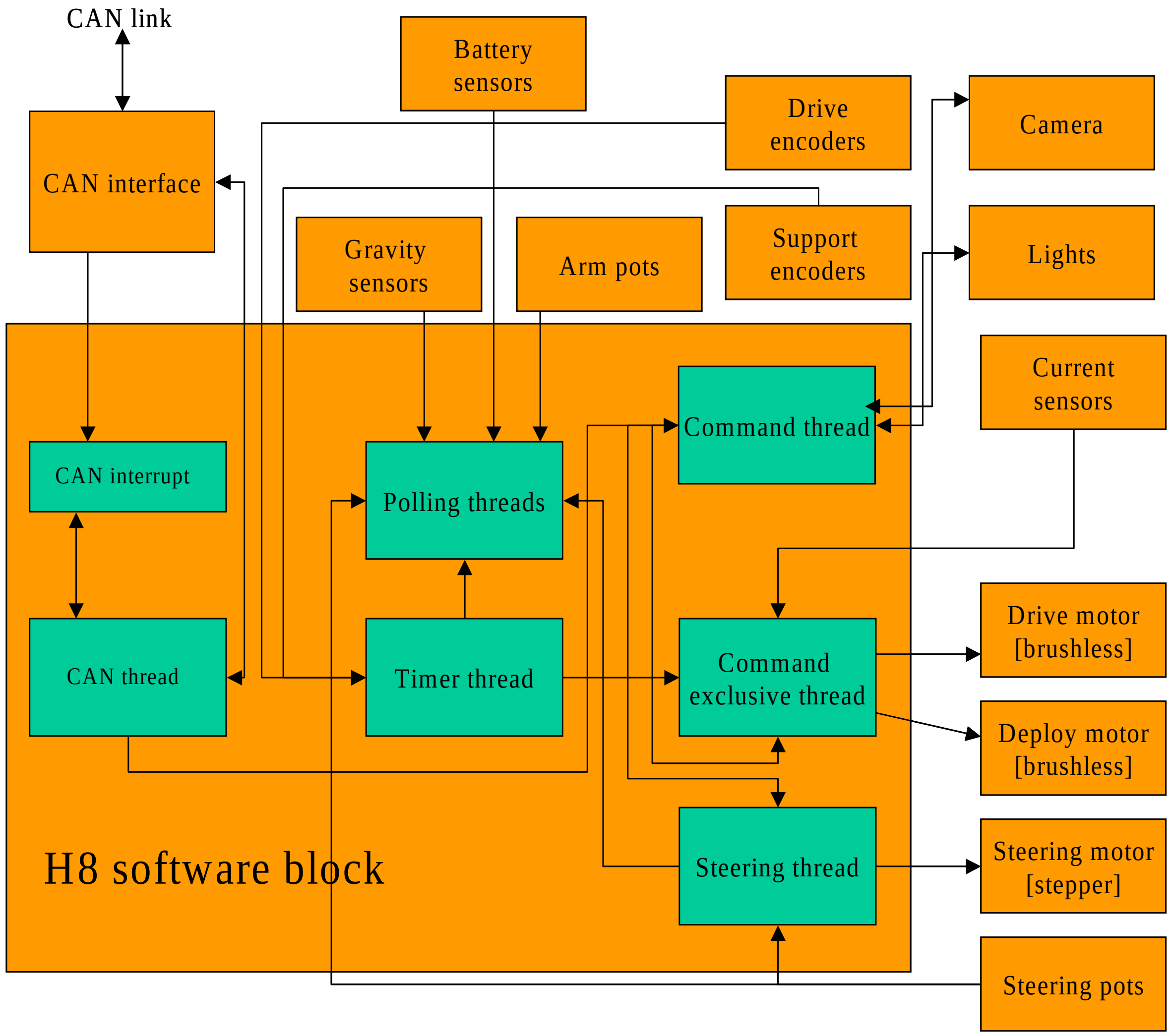


Figure 27: H8 microprocessor software architecture

The control software architecture diagram in support of the above architecture, operates a sequence of steps that can de delineated as follows:

- Receives commands from the SH4 computer board via CAN bus interface.
- Interprets the commands in the Command thread and executes them either immediately or via Command Exclusive thread, which controls Deploy and Drive motors, or Steering thread which controls the Steering motors.
- Updates values of potentiometers, encoders, gravity sensors, current sensors and battery sensors in the polling thread and sends them to the SH4 computer board via the CAN bus interface.
- Command Exclusive and Steering threads use the encoder and potentiometer values to monitor hardware task execution, detect stalls, etc. They also report to the SH4 success or error in the execution of a command via CAN bus interface.

The control station that the operator uses, has a built-in software architecture depicted in Figure 28:

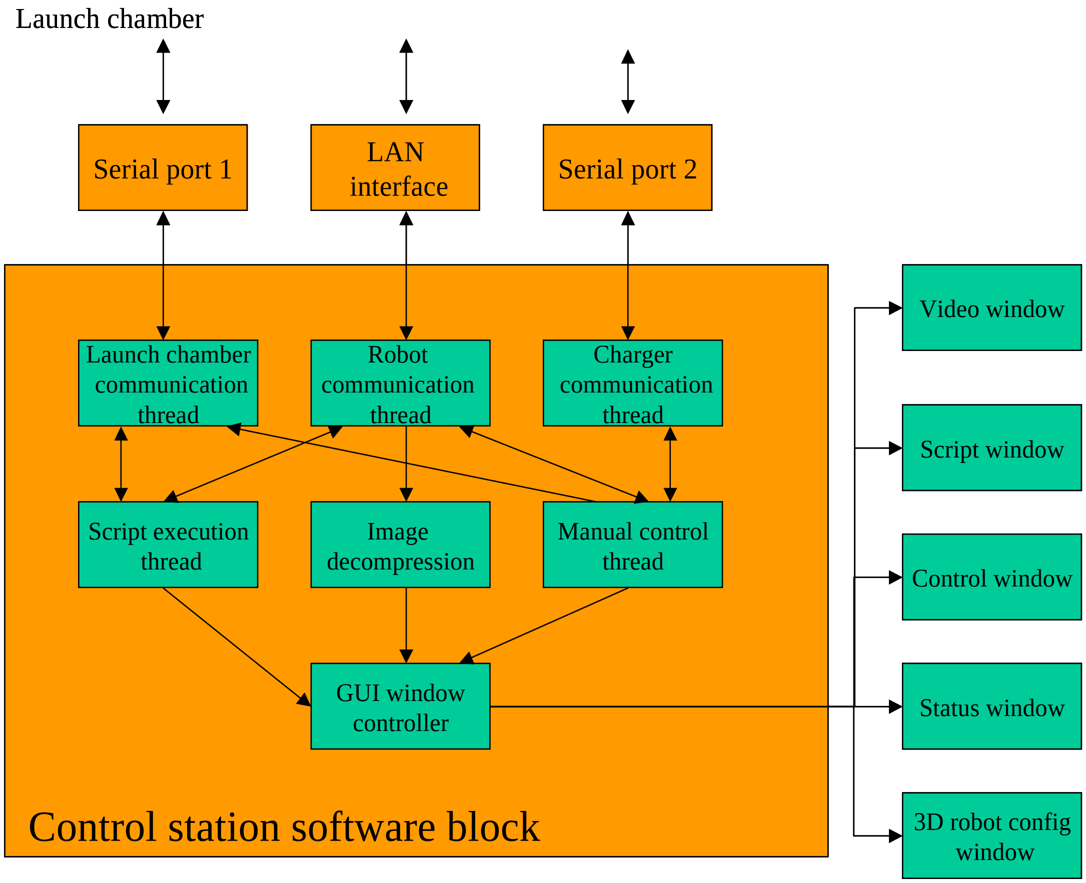


Figure 28: Microprocessor software control architecture

The stepwise operation supported by the above controller software, can be described as an infinite loop executing the following steps:

- Communicates with and controls Explorer (wirelessly), launch chamber and battery charger (via serial connections).
- Each communication is handled by a separate thread.
- The communication threads supply data to, and receive data from, the control threads – automatic (script) control and manual control.
- Data from the communication threads is used as feedback by the automatic control thread and is also reflected in the status and 3D configuration view windows.
- Explorer communication threads also supply an encoded video stream, which is decoded by the image decompression thread and displayed in the video window.
- Windows are handled by the GUI window control thread.

3.4 Health and Navigation Sensory Systems

The on-board processor-system is also responsible for monitoring the proper operation of all systems, determining the health of individual components and subsystems, as well as maintaining an estimate of navigational self-awareness. In each of these two categories, we implemented the following:

- **Health**

  The Explorer robot system utilizes several schemes to monitor its own operation on-board, its health and communication link with the topside operator. The following modalities and schemes are being utilized:

  - At the highest level within the Explorer system, the individual distributed processor boards within each module, communicate with the central processor over the common data-bus, acknowledging their presence and proper operation on a frequent basis - this is know as establishing and maintaining a ‘heartbeat’.
  - The ‘heartbeat’ concept is taken a further step by the central processor, in that it establishes a regular communications interval with the off-board wireless control-box utilized by the operator. The idea is to ensure that the Explorer does not drive out of communication range unexpectedly. This can be detected through the operator-interface computer sending a regular ‘heartbeat’ signal to the Explorer, which will be expected and answered by the same. Should it not receive the signal, the Explorer will stop.
  - In the case of the drive-module, the local processor monitors motor-current and voltage, establishing the baseline of operation. Depending on the mode in which the Explorer might be (horizontal vs. vertical, straight-vs.-turning), the local processor can safeguard the motor, but be overridden by the central computer. The localized three-DOF accelerometer signals also help qualify the system mode to allow the local processor to decide as to whether the current falls within the expected performance range.
  - A dedicated processor-board or task on-board the power-module local-controller is responsible for monitoring pack-voltage, -current and -temperature. This is not only important to safeguard the pack from improper operation (shuttled through a computer-controlled relay-bank), but to also allow the central computer to estimate the remaining battery-charge based on the open-loop voltage with a look-up table based on a discharge-graph of the cell provided by the manufacturer; a measurement that allows the computer to alert the operator and only allow motions that bring the system back to its deployment-point (under the current round-trip deployment model).
  - Safety-sensors that are included in each module include moisture-detectors and oxygen-monitors. Each of these are simple implementations that allow monitoring the module-internals for the concentration of oxygen within each module, and open-circuit pins that if short-circuited by water migrating into the module, will alert the system and alert the operator to retrieve the system and initiate a shutdown as soon as possible.

- **Navigation**

  The navigation scheme used for Explorer relies on the use of multiple sensing-modalities to generate an estimate of the actual robot position within the pipe network.

  - The simplest, yet most error-prone open-loop measurement is based on encoding the drive-motors by utilizing the hall-effect feedback to generate up/down counters that generate an estimate of progress-distance through gear-ratios and wheel-diameters. This measurement is inaccurate in that the wheels might slip w.r.t. the pipe-wall, and the OD of the wheel is not constant due to compressibility of its urethane rim.

- The next stage of encoding is based on the use of the centralizing wheeled-arms at each passive joint, to compute an 'averaged-out' estimate of travel along the pipe, utilizing their phased hall-effect encoders measuring distance as a function of wheel-rotation. This is especially important as the system makes turns and drive-wheels lose contact with the wall and we have to rely on rearward wheels and drives to update the position estimate.
- In order to qualify travel as a function of three-dimensional distance, the 'counting' of pipe-joints and identification of features inside the pipe by the operator using the live video feed, coupled with cross-referencing of the as-built plates, allows for a three-dimensional positioning check when deploying in the field.
- Lastly, each of the steering joints is encoded with a relative-position and absolute-position potentiometer, allowing the motions to further be resolved within pipe-coordinates by the computer.

The entire set of navigation sensors is 'fused' into a single estimate of position. There is furthermore no doubt that the operator will need to utilize a paper- or digital plate layout diagram of the network to chart the progress in absolute terms. Utilizing visual features and correlating them to an as-built plate, allows the operator to frequently 're-zero' the position-estimate of Explorer in order to reduce the potential of accumulating position error over time. This is important, as this impacts the ability of the utility to know the position of the robot in case of detection of an anomaly to be charted or even its recovery in case of failure or other abnormal operating condition.

3.5 Safety Approach

The explosive range for natural gas (NG), sits at about 5% to 15% natural gas (95% methane) by volume in an air-to-NG mixture. Operation outside of this arena, despite the presence of oxidizer and an ignition-source, will not cause combustion-onset. Arguments that even if a certain minimal amount of oxidizer were to be present and ignited, such as that brought in and contained within the module-train, if ignited, could not cause any harm to the structure of the pipeline to cause the reaction to continue, but rather self-extinguish as the oxidizer is consumed; the minimal pressure-surge and temperature-surge is highly localized and minimized due to the shear size of the 'reservoir' (the entire connected network). Given the above considerations, the project team decided to safeguard the Explorer robot in a unique yet simple fashion, described below. The method utilized, is based on reducing the overall system weight and size, purging and venting, and avoiding the use of pressurized enclosures wherever possible.

- In the case of the drive/locomotion module, this implies, especially due to the impossibility of sealing the system entirely, leaving the module 'open' to ambient conditions, and ensuring through seals and booting, that no foreign matter can get entrapped in the mechanism or water gaining access and allowing the short-circuiting of any electronics. Electronic elements at ambient pressure are pressure-tolerant (up to 125 psig), and capable of operating in a pure natural gas environment.

- The steering-joint is inherently unsealable, except for allowing a boot to seal out foreign matter. Again, all motors are capable of operating within the pressurized natural gas environment.
- All passive joints are only protected by a boot, but are pressure-equalized through a bypass port.
- The computing-module is hermetically-sealed to the outside environment, with the addition of two opposing one-way check-valves, enabling pressure-equalization to ambient conditions, with just a simple cracking-pressure differential inherent in the check-valve. Hence all internal components operate within a pressurized environment. The system is purged of all air, and has the contents replaced with nitrogen at atmospheric pressure prior to going into the field, to minimize any chance of entrapped oxygen within the module.
- The power modules houses the battery-packs within their own pressure enclosure, designed for operation in 125 psig differential pressure conditions. The system is also purged of all air, and has its contents replaced with nitrogen at atmospheric pressure prior to going into the field, to minimize any chance of entrapped oxygen within the module.
- The launching chamber is loaded with the Explorer module-train, sealed and also purged of all air and has its contents replaced with nitrogen at atmospheric pressure, remaining sealed until deployed in the field. Once mounted atop the launch-valve-head assembly, the pressures between the launch-chamber and the main are equalized manually, leaving no possibility of entrapping air in the launch-sequence. The use of nitrogen in the launch-chamber could be avoided, if shown that pressure-equalization and temporary bleeding of the same out the top of the launch-chamber, accomplishes the same goal - removal of air to the extent that the explosive-range environment is avoided prior to system power-up.

The approach used in Explorer is similar to that used by other robotic equipment, such as CISBOT, developed by ConEd and Enbridge/Consumers Gas of Toronto, in that the system in inherently not intrinsically safe, can not be built to be explosion-proof, but rather is purged of all oxygen-containing volumes, replaced with a nitrogen-blanket and then operates within the pure natural gas environment.

4.0 System Testing

As part of the prototype validation effort in this program, CMU engaged in a multi-step experimentation and testing program covering a four-step itinerary: (1) laboratory testing, (ii) pressure testing, (iii) low-pressure cast-iron main field-trials and (iv) high-pressure steel main field-trials. The events and results for each of these test-efforts are detailed in this section

4.1 Laboratory Testing

CMU has built a substantial pipe test-loop at their outdoor test-facility. This test-loop consists of 6- and 8-inch steel pipe with cast-iron fittings, including reducers, elbows, Ts, Ys, swept-turns, vertical runs, etc. The total length is near 1,000 feet and was used extensively for deployment-testing, endurance-runs and camera-imaging experimentation (see Figure 29 for a layout).

Figure 29 : View of the test pipe-network setup at CMU (inside yellow box)

This setup was primarily used to test for proper operation of all modules, wireless performance, launching and retrieval and overall endurance and sensor/video tuning. It is here where the acceptance demonstration was held prior to being allowed to proceed into field-testing.

4.1 Pressure Testing

The robot system was tested for operation and usage, as well as validation of the purging and safing procedure, at an in-ground test-facility on Long Island (owned and operated by Keyspan Corp.) in early 2004. The system was loaded into a test-pipe section that could be flooded with nitrogen and natural gas to varying pressures. The robot was proven to be capable of operating under these conditions, including operation (driving, communicating, etc.) at pressures up to 55 psig (limit of test-loop). An image-collage in Figure 30 shows the setting and deployment activities.

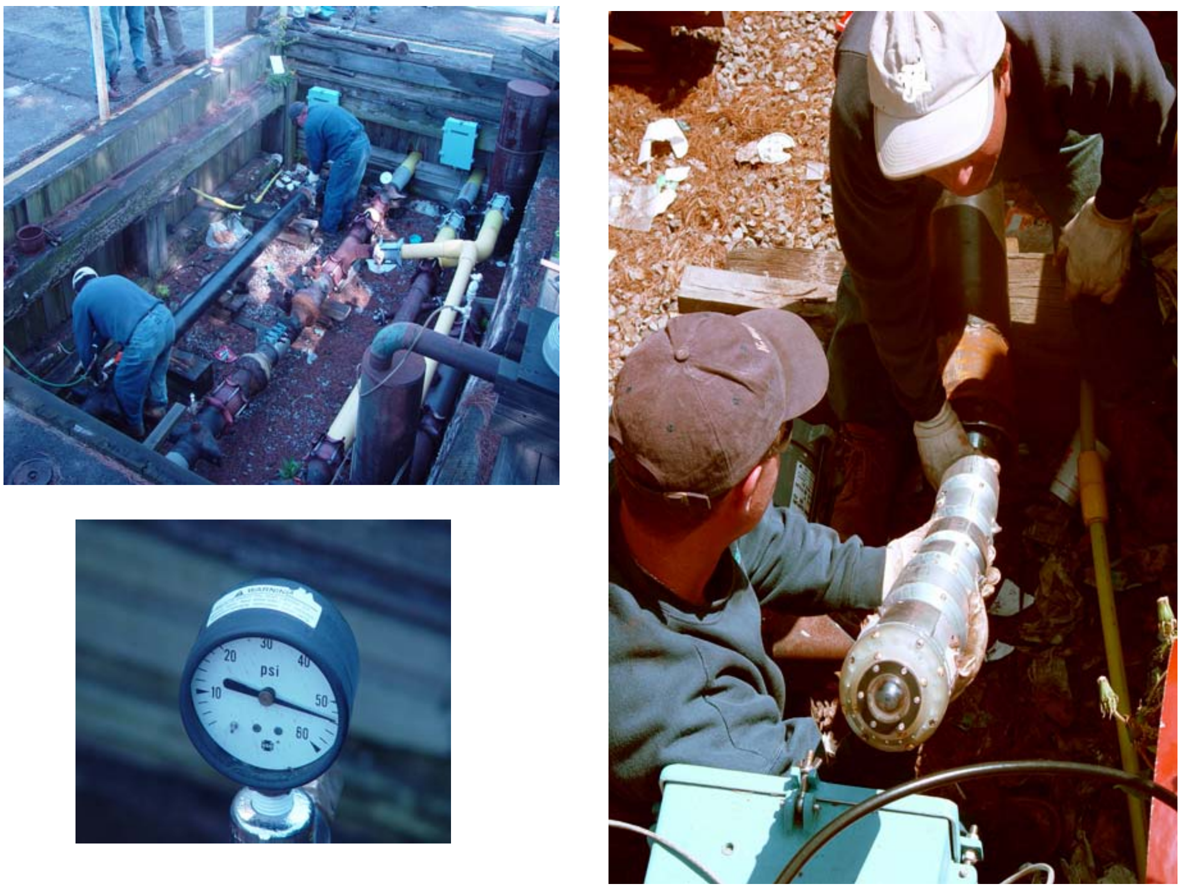


Figure 30 : View of the pressurized natural gas pre-deployment testing

4.2 Cast Iron Main - Field-Trial - Yonkers, NY - Consolidated Edison

The *Explorer* robot system was fielded into a live 8-inch cast-iron main (operated by Consolidated Edison of New York) installed in 1893. An excavation was made and a one-sided IPSCO-fitting and a purgeable/pressurizeable see-thru launch-tube installed. The robot was launched and recovered multiple times during the multi-day test-period (see Figure 31).

Figure 31 : Live CI New York Field-Trial setting

The step-by-step of the multi-day demonstration unfolded as follows:

- The demonstration was planned for the period of Wednesday, June 2 to Friday, June 4, 2004. The first two days CMU would deploy the robot and experiment with it. The third day utility and US DoE representatives were to witness the demonstration.
- Prior to the demonstration CMU developed a written robot launching and retrieval procedure, which was reviewed and approved by ConEdison.
- The site was in a residential area, the launching point being in the middle of an 800 ft, 8” cast iron main oriented in the north/south direction. The north end, about 380 ft from the launching point, was defined by a 90-deg tee into another 8” cast iron main. The south end, about 430 ft from the launching point, was defined by a replacement plastic section installed a few years ago.
- The low-pressure launcher was used in this first demonstration. It is a 6” plastic, transparent pipe with flanges attached to its ends. Purging valves are attached at the two ends of the launcher. The launcher is attached to an IPSCO fitting, which is a commercially available item.
- ConEdison excavated the site and installed the IPSCO fitting the week before the demonstration.
- CMU arrived at the site on Wednesday morning. It was realized that the access port on the fitting, used to deploy the gas-flow-stopper (bag), was undersized. The patience and skill of the ConEd crew allowed us to overcome the problem, with some time delay experienced.
- The electronics enclosures of the robot were purged of air and filled with nitrogen prior to inserting it into the launcher. The launcher was then attached to the fitting and was purged with nitrogen. The stopper bag was then removed and the launcher was filled with natural gas. An antenna was installed into the pipe, next to the launcher, to provide the necessary wireless link between robot and operator.
- The robot was successfully launched into the main traveling northbound. It was driven slowly towards the tee. Once it reached the tee it was stopped and brought back towards the launching point. It was then driven past the launcher towards the south, halfway to the end point. It was then turned back, and retrieved into the launcher.
- No problems were experienced during the launching, operation, and retrieval of the robot.
- The robot was then removed from the launcher following the pre-approved procedure.
- On the second day, Thursday, June 3, the robot was again launched into the pipe traveling northbound. At the tee, the robot made a left turn and traveled a small distance westbound. It moved then eastbound for a distance of about 150 ft, before it was driven back to the tee, where it made the 90-deg left turn into the original main. It proceeded southbound, past the launcher to the end of the main section being inspected. It was then driven northbound back to the launcher, where it was retrieved.
- During the entire operation the robot performed as anticipated. No operational problems were experienced.
- The pipe inspected was very clean with some debris encountered at the points where service tees had been connected to the main. Given the cleanliness of the pipe and the lack of any substantial amount of scale on it, very little light was reflected from the mid portion of the pipe. This resulted in a mostly “black” center on the image. The images of the close field, which was illuminated with abundant light, were excellent in quality.
- The US DoE representative arrived at the site on Friday morning, June 4, to review the operation of the robot.
- The participants met at the nearby ConEd facility where they watched a video taken by CMU during the second day of the demonstration. The video contained valuable images of the robot’s launching, operation, and retrieval, enough for those present to appreciate the scope and success of the demonstration during the previous two days.

On average, over a typical 6-hr. (cautious) deployment period (incl. launching and retrieval), the system was able to travel more than 3,000 linear feet, and made several T-turns in the main. Wireless range was the limiting factor, reducing the total maximum distance travel the system is capable of on a single battery charge. Features in the pipe such as taps (mapped and unmapped ones) with associated filings and debris (incl. beer-bottle caps from the original installation-days) were clearly visible (see Figure 32).

Figure 32 : Operator Interface & visible features (tap, bottle-caps, wheel-tracks)

The summary of the achieved system performance are tabulated in Table 1:

ConEd-Yonkres CI Field-Trial Data		
# Launches	3	
# Recoveries	3	
# T-turns	2	
Deployments	4	hrs./day
Length of Trials	3	days
Total On-Time	12	hrs.
Total Travel-Time	6	hrs.
Total Distance	3,000	ft
Length of inspected pipe	850	ft.
Max. Speed	4	in/sec
Avg. Inspection Speed	1.67	in/sec

Table 1 : Explorer Cast-Iron field-trial performance results

In conclusion, the first field demonstration of Explorer was an unqualified success. The robot operated flawlessly during the two days of operation and demonstrated the versatility anticipated. The launching and retrieval procedures were tested in the field and met all safety standards imposed by the utility. Overall the performance of the system clearly met every criteria it had been designed for - this represents a milestone in both the robotics and gas-utility industry, in that this is the first successful deployment of a fully tetherless and wireless remote-control inspection tool into a live, low-pressure, underground gas distribution main.

4.3 High-Pressure Steel Main - Field-Trial - Brockport, NY - Rochester Gas & Electric

The second field-trial location was chosen to be a high-pressure steel-main to prove the system could also be deployed and operated in a similarly-sized steel-pipe. The chosen location was situated at SUNY Brockport in upstate New York near Lake Ontario. The location was chosen for its ease of demonstration (permitting, low-traffic road, etc.) and its long length of straight piping. The main was an 8”-diameter, 60 psig steel main installed in 1979 (see Figure 33).

Figure 33: Live high-pressure steel main field-trial setting - Brockport, NY

A single 6 x 10 x 10 foot (deep) hole was excavated and a Mueller fitting installed, including a gate-valve to allow the installation of the launcher, and a stop-off weldolet drilled out for the installation of the long-range antenna, again using Mueller no-blow tooling.

The test-setting required the robot to travel (westward) as much as 1 mile round-trip along a straight section of welded 8-inch piping, with just a few service T-offs, all 4-inches in diameter. In addition, there were two elbows (going eastward), both a long 90^{o} and a sharp 70^{o}, to be traversed in order to demonstrate the system's capabilities in terms of power and communications range and obstacle navigation. The corresponding setting images, including the launcher-installation, and the completed launcher- and antenna-installation, user-interface imagery and in-pipe views, are all depicted in Figure 34:

Figure 34: Live high-pressure steel main deployment images

An overview and step-by-step of this field-trial is detailed below:

- CMU deployed to RG&E's Brockport distribution main area on the SUNY campus, where CMU set up to inspect a 1979-vintage 8-in 60 psig main. The run was a half-mile straight in one direction and two elbows (90 and 70 deg) in the other direction.
- Explorer spent a total of 4 days performing runs, totalling 5,500+ feet, and performing 8 successful elbow turns and travelling at least 1/2 mile in one direction from a single hole in one run, leaving ample battery-power and communications range.
- CMU did verify several mapped and unmapped features (Ts and even a main connection), but the deployment was mainly to demonstrate and test the safety and efficacy of the launcher and higher-pressure operations of Explorer.
- All targeted aspects were successfully demonstrated and the safety-procedure and operation proven to work. Launching and recovery was shown to take 30 minutes each, incl. all the safety steps - installation of the launcher and antenna was proven to take 30 and 15 minutes respectively.
- Setup and breakdown with a 3-person crew for Explorer and launcher took one hour each, leaving in essence about 4 hours of inspection time in an 8-hour day - at a speed of 4 in/sec, that translates to a total round-trip inspection distance of 4,800 feet or 2,400 ft in terms of range - this accounts for and leaves enough power for launching and retrieval off the existing battery-packs.
- The user interface was shown to be very usable and a remote display for monitoring and evaluation was also determined to be a viable option.
- Visitors from DoE, NY-PUC, NYSEG, RG&E, and NGA were in attendance and witnessed the demonstration.

The data that was collected as part of the performance evaluation at this location, is summarized below in Table 2:

RG&E - Brockport Field-Trial Data		
# Launches	4	
# Recoveries	4	
# Elbow-turns	8	
Deployments	3.5	hrs./day
Length of Trials	4	days
Total On-Time	14	hrs.
Total Travel-Time	6	hrs.
Total Distance	5,200	ft
Length of inspected pipe	2,590	ft.
Max. Speed	4	in/sec
Avg. Inspection Speed	2.89	in/sec

Table 2 : Explorer high-pressure steel field-trial performance results

Overall the performance of the system clearly met every criteria it had been designed for in terms of high-pressure steel deployment and power and communications range - this also represents a milestone in both the robotics and gas-utility industry, in that this is the first successful deployment of a fully tetherless and wireless remote-control inspection tool into a live high-pressure underground gas distribution main with inspection distances an order of a magnitude greater than those achievable by competing systems requiring an order of magnitude more excavations (and thus becoming a costlier aternative).

5.0 Summary

The Explorer robot system specifications led to a segmented actively articulated and wheel-leg powered robot design, with fisheye imaging capability and self-powered battery storage and wireless real-time communication link. The prototype went through a lengthy testing and evaluation period both in the laboratory and an above ground pipe-network, in order to debug all mechanical, electrical and software subsystems, and develop the necessary deployment and retrieval, as well as obstacle-handling scripts. In addition, the test-period included the honing of the safety design and safety procedure for launching and retrieval.

An early in-air pressurization test indicated that the system was capable, as designed, to withstand pressures up to 120 psig, and was tested during launching and operation at those pressures in the laboratory. The next step of operation in a pressurized natural gas main, and the associated procedures related to safe launching/retrieval and operation in such a medium, were valid and acceptable. As part of the final field-demonstrations, the Explorer robot was shown to be capable of operating in low- and high-pressure natural gas mains. In addition, the capability of performing scripted and manual launches, both vertical and angled, elbow (short and long) turns of varying degrees, as well as Ys and Ts, clearly demonstrated the systems' design-capabilities.

At the end of the field-trials, the system had logged at least 10 miles of operation in the laboratory and the test pipe-network, performed at least 50 elbow/Y/T-turns, and around 50 launches and recoveries in angled and vertical launchers. Real-world footage included around 1.5 miles of travel and 12 obstacles with 15 launches and recoveries under live conditions.

6.0 Conclusions

The Explorer robot design, with its compact and active articulations (steering, centration and driving), was clearly shown to be a viable and successful implementation of an inspection system for launching, operation and retrieval in 6- and 8-inch diameter natural gas distribution mains. The use of the wheeled leg-design, with passive centration- and support legs (including odometry), was shown to be capable of providing the needed drive and articulation to optimize fisheye pipe-inspection. The battery-power source was shown to be more than reliable for full-shift operation. The wireless communications link and associated GUI was clearly demonstrated to be the backbone of the system and not limit its operation, especially in steel mains. The simplified angled launching system for cast iron and the vertical launcher proved to be very successful in the field. The developed safety design and operational safety procedures for launching and retrieval were well motivated, executed and proved themselves to provide a safe operating system.

The test-results were collected over a lengthy evaluation period and included a large number of tests. Laboratory testing for launching/retrieval and obstacle handling successfully uncovered electro-mechanical issues that were resolved as part of the integration phase of the program. In addition, long-term driving in the outside (above ground) test network allowed for the run-in and endurance testing and long-term failure-mode evaluation. Compressed air testing validated the operation of the specialized purging and ventilated enclosure design and certified operation to 125 psig. In-gas pressure testing provided proof to the utilities of the safety procedures, safety design and endurance of the materials and systems to natural gas exposure (including mercaptan).

The conclusions that can be drawn from the two low- and high-pressure cast-iron and steel main field trials are fairly general and powerful. It is clear that deployment and retrieval into live gas distribution mains is very feasible and can be performed safely given the Explorer design and procedures. The ability to make turns in elbows and Ts was clearly shown in repeated settings as was the ability to find, view and visually analyze features (joints, debris, taps, feeds, etc.) using the operator GUI and the digital fisheye camera video. Endurance and wireless control range were shown to be well beyond that possible with current tethered pushrod camera systems.

In combination with all the previous features, Explorer was shown to best existing camera inspection systems by at least an order of magnitude in range from a single excavation and be capable of navigating straight- and obstacle pipe sections. This capability will drastically reduce the inspection costs of underground pipe-sections by limiting the number of excavations by at least an order of magnitude over its closest competing technical alternative (tethered pushrod inspection-camera).

It would seem that Explorer has not only a future in live-main video-inspection, but also in corrosion-inspection of higher-pressure steel mains should it be desirable to add an NDE sensor capability to the platform.

7.0 Recommendations

During this multi-phase prototype development and field-demonstration program, many firsts and milestones were created and met. But as in any development program, there always remain improvements that are worth considering for a follow-on phase or commercialization. The following groupings of bullets represent our view of the areas that could stand improvements into the future. The groupings and their respective bulleted improvements are as follows:

- **Robot Prototype**
  - **Clutched Joints**: Making all actively-steerable joints free-wheeling might help in speeding up turning and retrieval - space-permitting of course!
  - **Dirt & Water Sealing**: Keeping all oxides and any water out of electronics and exposed mechanics is critical.
  - **Alternate Camera & Lighting**: A simpler (smaller) wide-angle camera with brighter lights might be cheaper and easier to drive with
  - **Improved Feedthrus**: Reducing wire-count and sealing would improve feethrough integrity and assembly simplicity
  - **Increased battery density**: Denser chemistry batteries would reduce weight and increase drive-time and thus range and inspection-time
  - **Standardized OEM CPU**: Use of (now available) low-power small-sized 32-bit CPUs should be considered
  - **Overdriveable Motor Electronics**: Allowing for current-control and/or overdriveable or well heat-sunk drive electronics is also important in this highly integrated system
  - **Generic Scripting**: Allowing for faster and easier obstacle-handling script generation would be helpful!
  - **On-board sonde**: A miniature (if available) on-board sonde would allow tracking and locating a failed system should it need to be recovered.

- **Launcher**
  - **Unpowered Launcher - ST & CI**: Using an unpowered launcher with simple fittings would reduce size, weight and cost of the launching system, especially if launching into steel.
  - **Reduced-weight**: Reducing launcher weight is critical to reduce crew-size and on-site equipment requirements. This can be accomplished by developing the robot to be capable of launching/retrieving from/into standard pipe-sections and through standard fittings.
  - **Standardized launcher-fitting interface**: Using a standard interface suitable to more than one manufacturer's fitting would ease use across the nation.
  - **Built-in antenna**: It might be worth exploring using the permanent antenna in the launcher for operations to avoid having to drill another antenna port in the main.
  - **Manual retrieval override/assist**: In case of power or robot failure there should be a way to manually extract the robot from the main.

- **Operations & Safety**
  - **Built-in odometry correction**: The odometry from the robot needs to be accurate enough to measure individual pipe-sections and accumulate to allow accurate plate updates.
  - **Digital Plate/GPS overlay**: It would be the ultimate in mapping of plates were digitized, GPS-referenced and allowed for the overlay of the Explorer position in real time.

8.0 Acknowledgements

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