Conceptual Design for a Large-Diameter Natural Gas Pipeline Inspection Platform
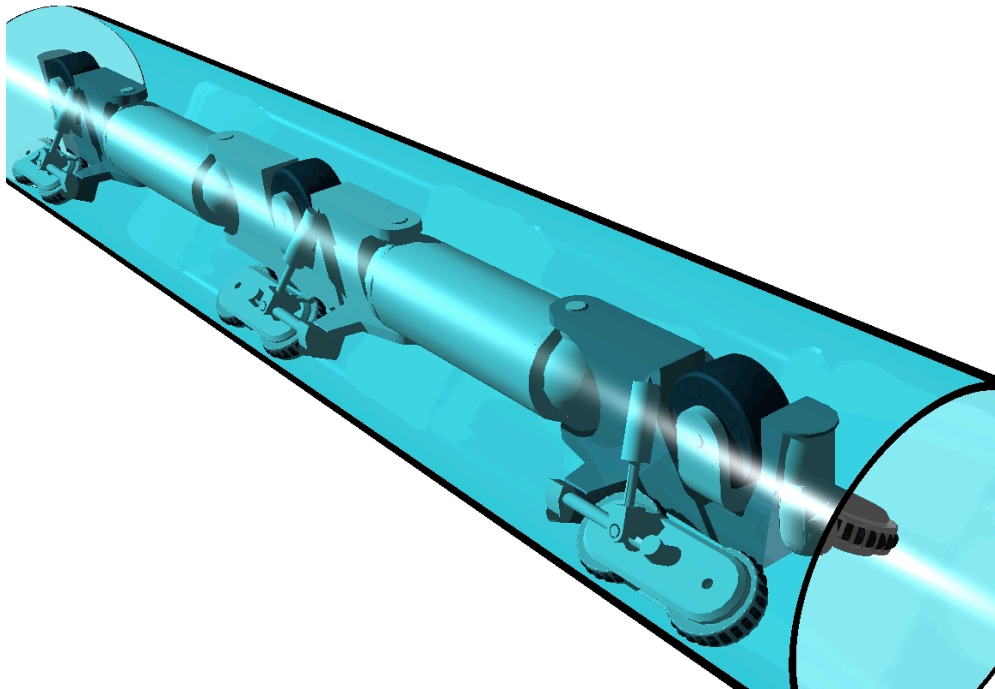
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List of Tables

List of Figures

1 SCOPE

This document covers the conceptual design of an intelligent Platform for Internal Pipeline Examination (*i*PIPE) as requested by the National Energy Technology Laboratory (NETL). The following requirements, outlined by NETL, will be used as the basis of the conceptual design:

1. The vehicle shall be equipped with wireless data transmission (no tether will be attached to the vehicle) for video and data and will provide sufficient resolution to allow for tele-operated control.
2. The vehicle design shall accommodate retrieval in the event of a system failure.
3. The vehicle shall carry all power onboard.
4. The vehicle shall operate in a high-pressure natural gas environment (up to 1000 psi).
5. The vehicle shall navigate 20" to 24" diameter pipe consisting of cast iron, metal or steel.
6. The vehicle shall be capable of traveling 2 miles round trip with an average incline of 10%.
7. Travel speeds shall be a minimum of 1 inch per second, with 1 foot per second desirable.
8. The vehicle shall have the ability to travel vertically (extended vertical distances are not likely), negotiate multiple elbows, tees, and potential obstacles protruding into the pipe up to 1/3 of the pipe diameter.
9. The vehicle shall be able to stop and position itself at a specific location within the pipe.
10. The vehicle shall be inherently safe.
11. The vehicle shall be deployed into the pipe through existing or modified fittings within 30 minutes of set up time.
12. The vehicle shall be capable of completing inspection without removing the pipeline from service.
13. The vehicle shall be capable of a variety of levels of autonomy ranging from manual control to operator-assisted guarded motion.
14. The vehicle shall be able to identify its position within the pipe to within 2 feet over a 1-mile distance.

The approach selected by the Idaho National Laboratory (INL) to meet these requirements includes applying years of experience in robotics, intelligent and behaviour-based control, and wireless communications utilizing commercially available technologies where available. National laboratory resources will be used to develop critical technologies that are not available and integrate these technologies into a complete solution.

This document discusses the conceptual designs of the vehicle, intelligent controller, and wireless communication systems.

2 VEHICLE DESIGN

2.1 VEHICLE CONCEPT

An efficient driving mechanism is essential in minimizing the size of the on-board battery pack required to travel the distance specified. Initially, a concept vehicle based on the Inuktun Minitrac

technology used in many of our robotic crawler systems was considered. However, the battery pack needed to power the vehicle over the distance required was too large due to inefficiencies in the track design. Consequently, a vehicle design powered by wheels is suggested to be the best approach as the amount of power lost due to friction is greatly reduced.

The *i*PIPE will consist of a single battery/electronics canister with wheel assemblies at each end. The main canister will be approximately eight inches in diameter and twenty-four inches long. Each transport assembly will be comprised of a single eight-inch diameter drive wheel with two guide wheel assemblies fanned outward at 120 degrees. The tri-wheel configuration is required for traveling vertically in the pipe. The complete vehicle will consist of two drive wheels and eight guide wheels. To create an angular displacement necessary for negotiating tees and obstacles, a powered pivot will rotate the drive wheel. The vehicle is able to negotiate vertical tees by using the vertical assist arm coupled with the powered pivots connecting the main canister to the wheel sections. Vehicle operating and positioning status will be monitored by on board sensors.

Video and lighting will be handled by two Spectrum 90 cameras; one camera will be mounted at each end of the vehicle. Each Spectrum 90 camera has pan, tilt and zoom capabilities essential for inspection and navigation purposes. If required, additional navigational cameras can be accommodated in the design.

Figures 1 through 3 show the conceptual *i*PIPE with one canister:
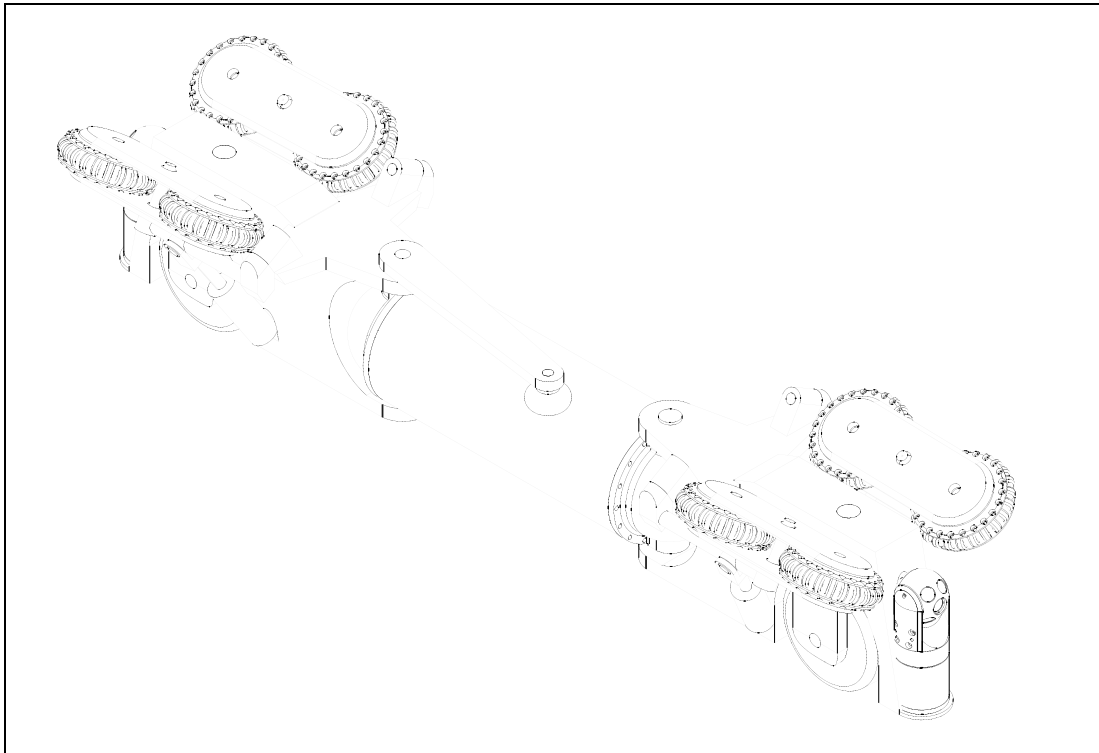
Figure 1 – *i*PIPE Inspection Vehicle
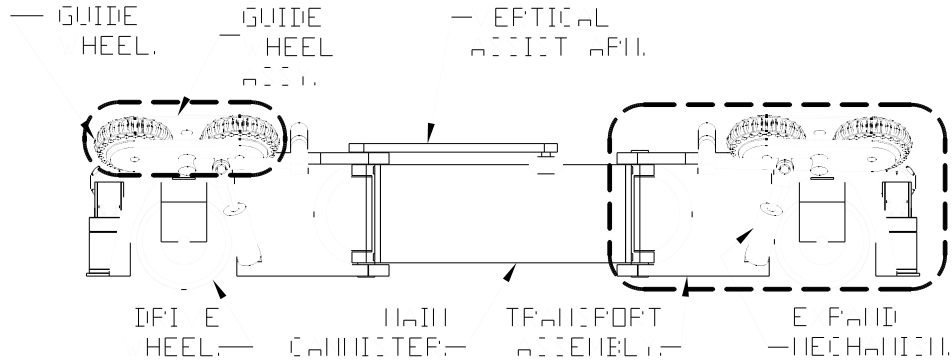
Figure 2 – Side View of *i***PIPE** Inspection Vehicle
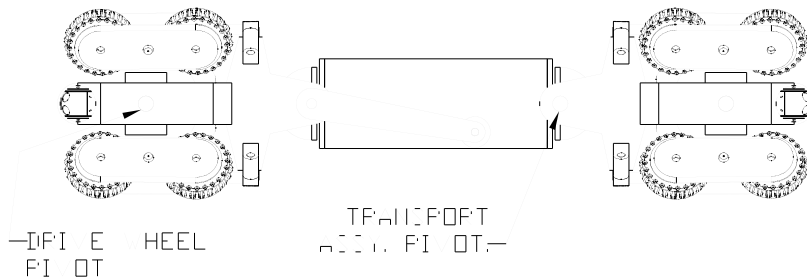
Figure 3 – Top View *i***PIPE** Inspection Vehicle

The mechanical design of the vehicle lends itself to the addition of an auxiliary canister and drive assembly. The second canister may be added to accommodate additional electronic or sensor packages. The two-canister configuration is sensor-specific and, therefore, is beyond the scope of this conceptual design. Appendix B, however, illustrates a possible approach to implementing additional canisters as applicable.

2.2 WHEEL ASSEMBLY

2.2.3 Drive Wheel

There will be one drive wheel located at each end of the vehicle. The two drive wheels will be approximately eight inches in diameter with aluminium hubs and rubber tires. The tires will have treads to provide additional traction. Also, each drive wheel assembly will be nitrogen purged to enable operation in the required environments.
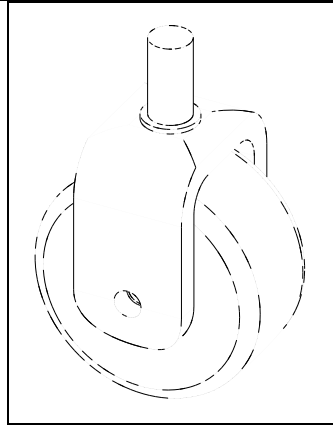
Figure 4 – Drive Wheel

Each drive wheel will further be driven by a DC motor with gear box and drive gear mechanism. Originally, a Direct Drive DC Torque motor was incorporated into the drive wheel design as the one-to-one gear ratio and physical shape were believed to be beneficial to the design. However, at the slow speeds required for inspection, the direct drive motors were extremely inefficient. As a result, the required battery size would have been tripled compared to using two conventional DC gear motors to drive the vehicle.

Each drive wheel assembly will contain electronics to drive and monitor the motor. Only power and communication will be sent to each wheel. The on-board electronics will be responsible for producing a current source, filtering and controlling power delivered to the motor while preventing current levels from exceeding safe operating limits. Temperature sensors mounted inside the hub of the wheel will provide operational feedback. The following block diagram further illustrates the high level concept of the drive wheel electronics:
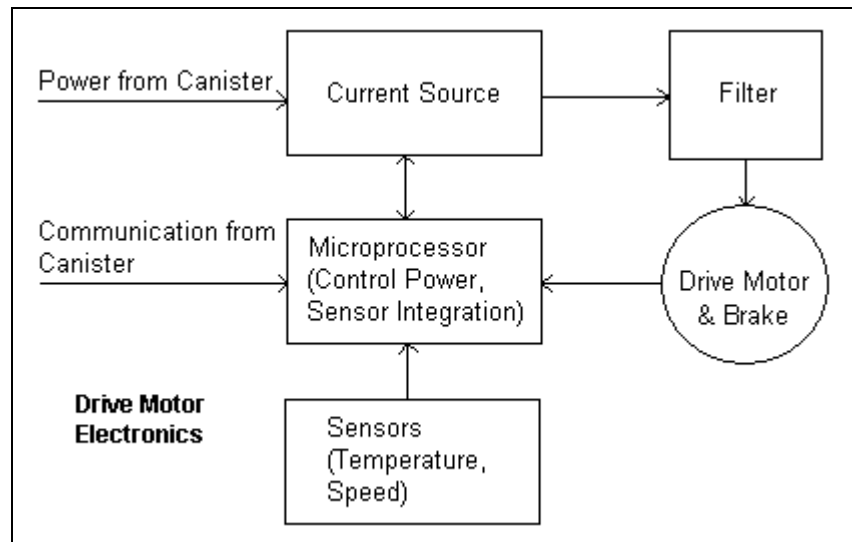
Figure 5 – Drive Motor Electronics

Each drive wheel will have a mechanical brake. Flow of natural gas in the pipe equates to a significant force applied to the vehicle at all times. As a result, the vehicle will be fighting a force while it is stopped during inspection. A mechanical brake located on the drive motor shaft will greatly reduce the amount of battery power required to prevent wheel movement. In addition, the

mechanical brake will allow the vehicle to stop in a vertical section of pipe without powering the drive wheel to overcome the force of gravity.

2.2.4 Guide Wheels

There are several purposes of the guide wheel assemblies. First is to provide balance while traveling along straight level pipe as the drive wheel will be oriented towards the bottom of the pipe. The second purpose is to apply a reflective force onto the drive wheel while rotating or traveling vertically in the pipe. Finally, the guide wheels will help the vehicle negotiate bends and corners. As previously indicated, the guide wheel assemblies and drive wheel will be fanned out at 120 degrees. The following drawing shows a front view of the transport assembly in a 20-inch diameter pipe:
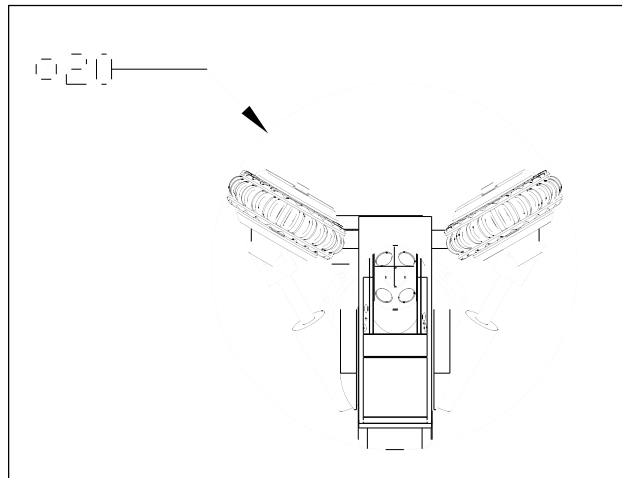
Figure 6 – Front View of Transport Assembly

The guide wheel assemblies will consist of two passive Delrin® wheels with aluminum hubs. Each free-wheeling idler wheel will incorporate multiple small wheels that enable the assembly to travel forwards, backwards, sideways and any combination thereof. This omni-directional design is required when the vehicle rotates its position down the pipe; the guide wheel assemblies will simply follow the direction of the drive wheel and not restrict the angular movement. The following diagram illustrates one guide wheel:
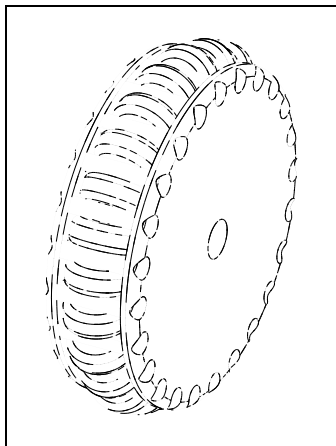
Figure 7 – Guide Wheel

The guide wheels are coupled in pairs to keep the wheel assembly aligned with the cross section of the pipe. The operator, therefore, will not be required to steer the vehicle around bends, as the vehicle will pull itself around. The complete guide wheel assembly is shown in Figure 8.
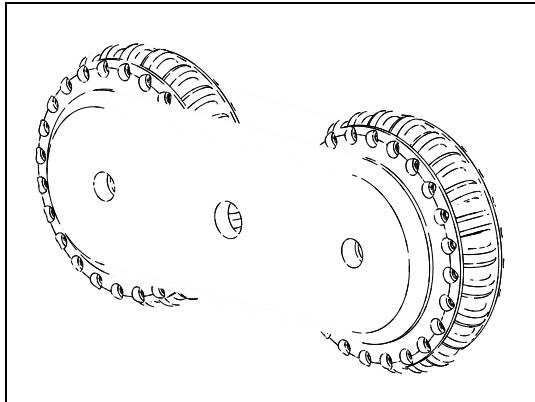
Figure 8 – Guide Wheel Assembly

2.2.5 Maneuvering

In order to maneuver around various obstacles in the pipe the vehicle will rotate its position relative to the pipe, similar to a spiral rotation. A powered pivot linking the drive wheel to the rest of the wheel assembly (the transport assembly pivot) will provide the angular displacement required to rotate the vehicle. The drive wheel will turn independently of the rest of the vehicle and the guide wheels. The operator will control the steering of each drive wheel individually to facilitate navigation around various obstacles such as tees and obstructions entering from any point in the cross section of the pipe.

2.2.6 Expand Mechanism

The guide wheel assemblies will be forced out against the pipe wall by expand mechanisms consisting of electric, linear actuators. While traveling along straight, level pipe - with the drive wheel at the bottom - only a small amount of force is required to keep the vehicle upright. The guide wheels will act as balancing arms for the vehicle. However, when the vehicle is required to spiral or travel vertically, the expand mechanism will push the guide wheels out with enough force to maintain traction of the drive wheels. It will be necessary to spiral the vehicle 90 degrees for vertical transitions as the pivot linking the wheel assembly to the main canister provides lateral movement only.

Each of the four expand mechanisms will be independently controlled and will provide force and position feedback to the operator. The four expand mechanisms will also be individually spring loaded to accommodate minor changes in pipe diameter. The following figure shows the side view of the wheel assembly including the expand mechanism:
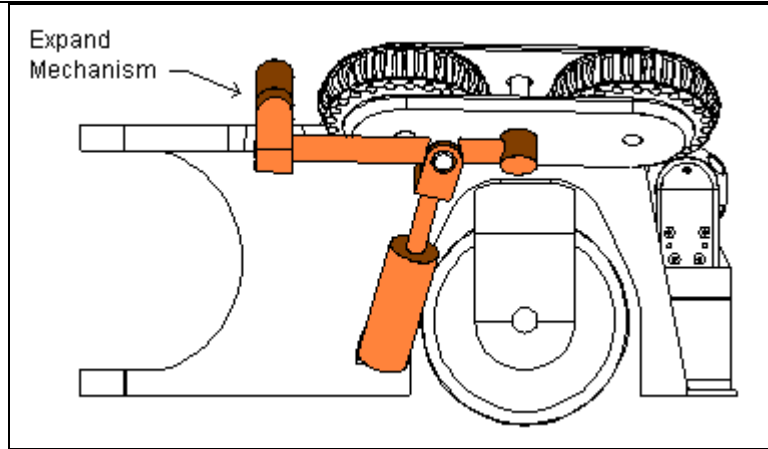
Figure 9 – Expand Mechanism

2.3 MAIN CANISTER

2.3.3 Mechanical Configuration

The main vehicle canister will house both the battery pack and the electronics responsible for power conversion, communication to the wireless transceiver, sensor integration, and various motor controls. The aluminium canister will be approximately eight inches in diameter, twenty-four inches long, and spherical at each end. The canister will be nitrogen purged in order to operate in the environment specified. The powered transport assembly pivots, linking each wheel assembly to the canister, will provide lateral movement only. A vertical assist arm, in concert with the wheel assemblies, will lift the front end of the vehicle up to negotiate a vertical tee in the pipe.
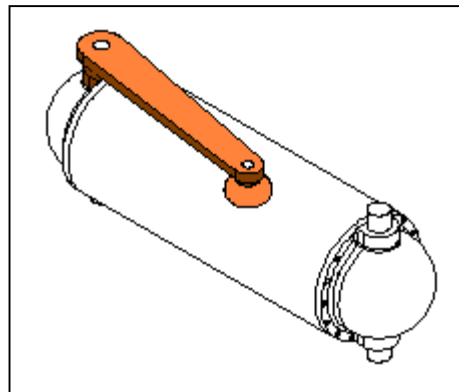
Figure 10 – Main Canister with Vertical Assist Arm

2.3.4 Batteries

The space available in the main canister will limit the volume of the battery pack, thereby limiting the amount of energy available to the vehicle. Lithium-ion-polymer batteries have been selected as their energy per weight (J/kg) is approximately four times greater and their energy per volume (J/l) is

nearly three times greater than standard lead acid batteries. Custom rechargeable battery packs will be built to take advantage of as much volume as possible inside the cylindrical main canister.

Power budget calculations were performed to determine the amount of total energy required by the vehicle to operate the two drive wheel motors, expand mechanism, steering pivots, vertical assist arm, cameras, lights and supporting electronics and sensors. Several assumptions were made to complete the calculations such as the amount of force on the vehicle from the flow of gas and the average slope of the pipe. The following table summarizes the results of the power budget calculations.

| System Parameters		
Force of gas flow on vehicle (lb Force)	22.48	Estimated by Inuktun
Average Slope of Pipe	10%	As per NETL
Number of Drive Wheels	2	System Configuration
Number of Expand Motors	4	System Configuration
Number of Steering Motors	2	System Configuration
Distance (mile)	2	As per NETL
Summary of Calculations		
Average vehicle speed (inch/s)	3.00	Minimum speed due to size of battery pack
Maximum vehicle speed (inch/s)	12.27	Maximum speed due to max motor rpm, gear ratio and drive wheel diameter
Total Energy Required (Wh)	1464.84	Energy required for motors, camera, sensors and lighting + 20%
Time for inspection (h)	11.73	Based on average vehicle speed
Weight of Li-Polymer Battery (lb)	18.92	Minimum battery required for inspection
Volume of battery (cubic inches)	241.04	Minimum battery required for inspection
Total Vehicle Weight (lb)	87.65	Weight of chassis, battery pack, motors and cameras

Table 1 – Summary of Power Budget

As average vehicle speed increases, the time required for the inspection decreases and as a result, the battery weight and volume required for powering the vehicle decreases. This is due to the constant power requirements of the cameras, lights, and on-board sensors. As shown in the Figure 11, slowing the average vehicle speed below 3 inch/s (approximately 11.7 hours of run time) will result in a significant increase in battery weight.

Battery Weight Vs Average Vehicle Speed
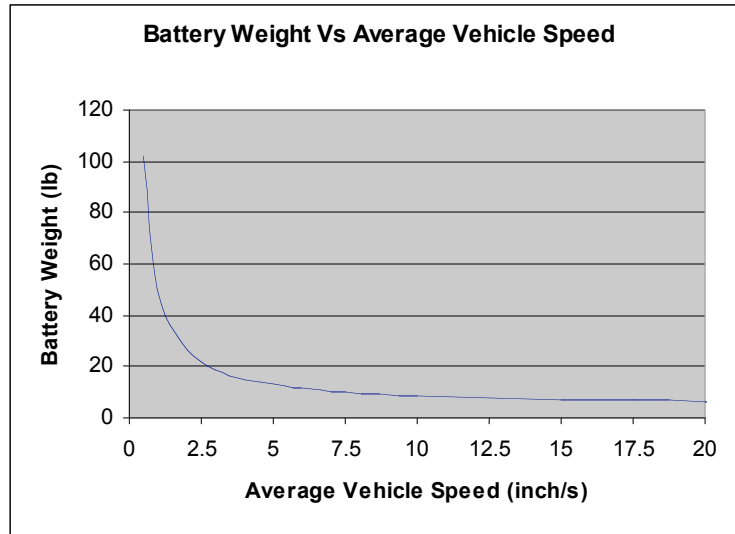
Note:
Battery weight is calculated from energy required to power all vehicle electronics and motors over 2 miles.

Figure 11 – Battery Weight Vs Average Vehicle Speed

As sensors and additional payload are added to the vehicle, the expected inspection range of the vehicle will decrease. Figure 12 illustrates the effect of additional power and weight requirements on the vehicle without increasing the amount of batteries.   Battery voltage and temperature levels will be monitored to ensure the batteries are kept within safe operating limits.

Inspection Range Vs Additional Payload
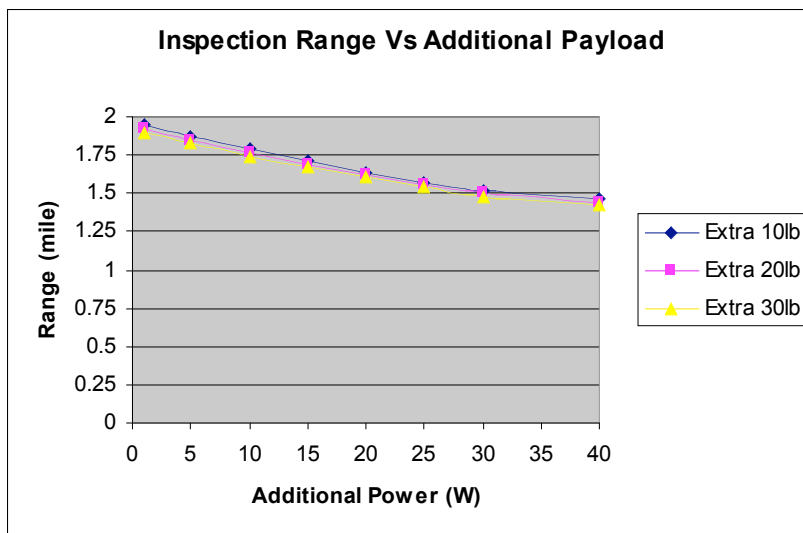
Note:
Inspection range of the vehicle was based on an 18.9lb battery pack, approximate 100W payload, 87.7 lb vehicle and average vehicle speed of 3 inch/s.

Figure 12 – Inspection Range Vs Additional Payload

2.3.5 Vehicle Electronics

The vehicle electronics housed in the main canister are responsible for interfacing video and communication with the transceiver, interfacing with cameras and drive wheels, performing power conversion, and controlling motors. There will be an on-board embedded PC for data storage, motor control, and sensor integration. The drive electronics for the motors will actively prevent input power from exceeding safe operating limits. The Spectrum 90 cameras, drive wheels, and main canister will all be controlled from the same communication bus.

Figure 13 illustrates a high-level conceptual diagram of the vehicle electronics located in the main canister.
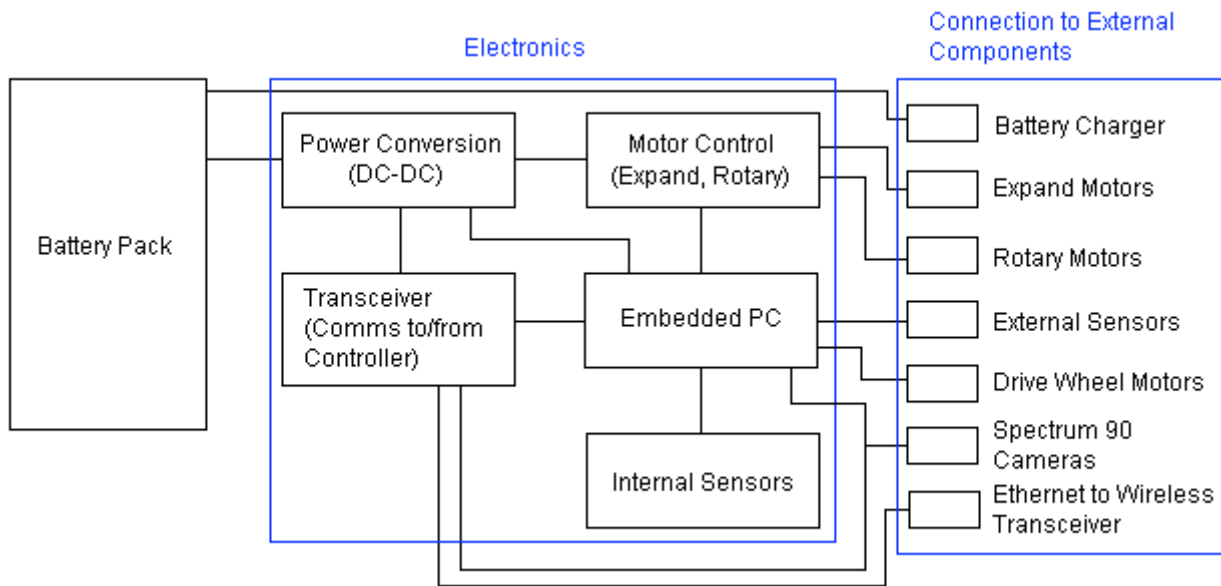
Figure 13 – Main Canister Battery Pack and Electronics

2.4 MODIFIED SPECTRUM 90 CAMERAS

One Pan, Tilt, Zoom (PTZ) camera will be mounted at each end of the vehicle. The PTZ camera will be based on the current Inuktun Spectrum 90 camera. There will be several modifications to the current product to allow operation in the specified environment. For example, further mechanical design is required to allow its operation in 1000 psi of pressure and to support nitrogen purging in all the camera housings. Also, design changes to the electronics are necessary to support power conversion, pan and tilt motor control, communication to the camera, and low voltage LEDs.

The operator can switch video feedback between cameras for different views of the vehicle and its surroundings. However, only one camera will be powered at a time in order to reduce battery consumption. Table 2 lists the specifications of a standard Spectrum 90.

Camera	
Material	Aluminum
Type	Color ¼" ExView CCD
Sensitivity	1.5 lux
Resolution	NTSC 470 TV Lines
Focus	Auto or Manual
Iris	Auto
Lights	48Watts (Flood and Spot)
Controls	
Active Controls	Pan, Tilt, Zoom, Focus, and Light
Pan	340° (360° visible)
Pan Speed	Variable $0-24^o$ / sec
Tilt	280°
Tilt Speed	Variable $0-7^o$ / sec
Horizontal FOV	46° in air
Zoom	40:1 (10x optical, 4x digital)
Clutch	Pan & Tilt Slip Clutch
Lights	Variable intensity

Table 2 – Inuktun Standard Spectrum 90 Camera Specifications

2.5 NEGOTIATING OBSTACLES

As stated in the Scope section of this conceptual design document, the vehicle shall have the ability to negotiate various elbows, tees and potential plug valves, gate valves, open taps, and obstacles protruding into the pipe up to 1/3 of the pipe diameter. The physical shape of the vehicle has been determined by examining the worst case scenario of having to navigate through a tee in the pipe. The combination of the drive wheel and the transport assembly pivots connecting the canister to the wheel assemblies enables the vehicle to negotiate a tighter turn such as a right-angle tee in the pipe. The maximum length of the main canister has been determined to allow the vehicle to handle a tee in the pipe yet provide as much space as possible for the battery pack and electronics. The combination of the vertical assist arm and the powered transport assembly pivots enable the vehicle to negotiate a transition from a horizontal pipe to a vertical tee.

By rotating the drive wheels the vehicle is able to spiral its position in the pipe to avoid various protruding obstacles. To create as much spare room in the pipe to navigate around obstacles as possible, the canister is positioned lower than the centre of the pipe (and directly behind the drive wheel). The maximum envelope of the canister and the drive wheel must be less than the diameter of the pipe minus one third to allow for enough clearance to negotiate obstacles. Therefore, the total distance from the bottom of the drive wheel to the top of the canister will be approximately thirteen inches.

2.6 ENVIRONMENT

All vehicle housings that contain electrical components, including all motors, will be nitrogen purged to handle volatile environments. Sensors will measure pressure changes to monitor the

integrity of the nitrogen purged system. All mechanical housings will be designed for the environment outlined in the scope.

2.7   SENSOR FEEDBACK AND POSITIONING

Relaying the vehicle's orientation back to the operator is crucial for maneuvering past obstacles and determining orientation within the pipe. The vehicle's position will be constantly monitored by the following on-board sensors:

- Pitch and roll sensors to monitor the degree of slope in the pipe and the vehicle's rotational position in the pipe.
- Rotation sensors to measure steering angle of both drive wheels.
- Rotation sensors to monitor angular position of the transport assembly pivots between the canister and both drive wheels.
- Sensors to measure speed of drive wheels.
- Sensors to measure amount of force each guide wheel assembly is applying on the vehicle.
- Sensors to monitor displacement of the individual guide wheel assemblies.
- Rotational sensors to measure angle of the vertical assist arm.

The following positioning sensors (to be discussed in greater detail in Section 4.0, Intelligent Controller Design) will provide the data required for determining the linear position of the vehicle in the pipe:

- Stereo vision camera system to map and localize vehicle's position.
- IR sensors to detect and map obstructions.

Operational sensors located on the vehicle will ensure that the vehicle is operating within its design parameters. For example:

- Temperature sensors mounted in the main canister will prevent the electronics or battery pack from overheating.
- Battery voltage and current level will be monitored to ensure the operator is aware of the amount of time left for the inspection.
- Current sensors will be used to monitor the amount of power being delivered to the motors and limit them to maximum power ratings.
- Pressures sensors to monitor the integrity of the nitrogen purged systems.

2.8   *i*PIPE LAUNCH MECHANISM

A launch and recovery mechanism is required for the vehicle to enter and exit the pipe line. This launch mechanism is beyond the scope of this conceptual design. However, the mechanism will interface directly with existing openings into the pipeline.

The *i*PIPE will enter the main pipeline through a series of valves and sections of pipe configured in a Y formation. The minimum diameter of the launch pipe must be eighteen inches to allow the proposed vehicle to pass through. The inspection vehicle will be able to start traveling with or against the flow of gas.

2.9 FAILURE RECOVERY

In the event of a complete power loss in the vehicle, a second rescue vehicle will be sent to remove the *i*PIPE from the pipe. In order to be towed out of the pipe the vehicle must not prevent movement in a power down state. The drive wheels will fail to a neutral position with the brake disengaged. The transport assembly pivot will act as a passive joint. The multi-wheel design of the guide wheel assembly allows for movement in any direction, therefore aiding the recovery of the vehicle. Also, the expand mechanism will retract in the event of a power failure. The design of an appropriate rescue vehicle is outside the scope of this project.

If a less catastrophic situation occurs such as failure of a drive motor, the on-board electronics and software will disengage the damaged drive wheel. The second drive wheel is able to provide enough torque to either push or pull the vehicle out of the pipe.

3 INTELLIGENT CONTROLLER DESIGN

The vehicle will be controlled by software installed on a control station. This control station will interface with the wireless transceiver to send control signals to the *i*PIPE. The control station will provide a graphical user interface (GUI) for control of the *i*PIPE in an intuitive and comprehensive manner. Various operational and positioning parameters will be visible to the operator through the GUI including vehicle temperature, light level, and system battery voltages. Also, the GUI will allow the operator to control which camera to monitor at any given moment. The control station will also provide an interface into the intelligent controller allowing the operator to adjust autonomy on demand.

3.1 ADJUSTABLE AUTONOMY IMPLEMENTATION

A mixed-initiative system that is capable of supporting aspects of the pipeline inspection tasks will be implemented. The system will be a sliding scale autonomous system (adjustable autonomy) where each level introduces increased autonomous capabilities built on top of the prior level. Therefore, as the operator increases levels of robot initiative, not only do the vehicle's capabilities increase but the operator's ability to quickly ascertain the environment is enhanced. This scheme of autonomy has been successfully implemented on a variety of Unmanned Ground Vehicles (UGVs).

3.1.1 Deviations from Ideal Perception and Control

Traditional UGVs implement a combination of laser range sensors, acoustic range sensors, and infrared range sensors to characterize the vehicle's local environment. Given these perception capabilities it is possible to piece together local perception "snapshots" and probabilistically reason these snapshots into a global map that is created on-the-fly. This mapping process is conventionally referred to as SLAM (simultaneous localization and mapping).

The environmental conditions and the operating envelope of the pipe crawler system in the natural gas pipeline preclude the use of both laser and acoustic range sensors. Consequently, a stereo-vision range sensing and terrain mapping system will be implemented. The stereo-vision system will meet the environmental and physical system constraints while providing the necessary range sensing and

terrain mapping capabilities. Additionally, the vehicle will employ an array of infrared range sensors to supply the close-in perception capabilities when navigating tight spaces.

3.1.2 Intelligent System Concept

The *i*PIPE will continuously evaluate the operability of the stereo-vision sensor and infrared range sensor and provide feedback on the state of these sensors to the user. The *i*PIPE control station will display information about the environment using various visual cues ranging from terse textual descriptions to complex graphical representations of the vehicle's local surroundings and the choices (depending on the level of autonomy) that face the human user. For each level of autonomy, perceptual data will be fused onto the *i*PIPE control station GUI.

The intelligent system architecture controlling the *i*PIPE supports the following four levels of autonomy:

Teleoperation: The user has full, continuous control of the *i*PIPE at the lowest level. The vehicle takes no initiative except to stop once it recognizes that communications have failed. It does indicate the detection of obstacles in its path to the user, but will not prevent collision.

Safe Mode: User directs movements of the robot, but the robot takes initiative and has the authority to protect itself based on its localization in the pipe line and self-status evaluation. For example, it will stop before it collides with an obstacle, which it detects via multiple sensors. The robot will refuse to undertake a task if it cannot safely accomplish it.

Shared Control: The *i*PIPE takes the initiative to choose its own path in response to general direction input from the operator. Although the vehicle handles the low level navigation and obstacle avoidance, the user supplies intermittent input, often at the system's request, to guide the *i*PIPE in general directions.

Full Autonomy: *i*PIPE will perform global path planning to select its own routes, requiring no operator input except high-level tasking such as: "return to start" or "go to point" (specified by clicking a point within the map interface module).

3.2 POSITIONING

In an effort to support positional requirements of the pipeline inspection vehicle, a 3-D dead reckoned position system will provide the basic odometry with corrections provided via the stereo-vision based SLAM system. The global positions of the *i*PIPE can be referenced in x-y-z coordinate space with respect to the starting point of the vehicle's mission.

3.2.1 Localization Concept

The development of the 3-D dead reckoned system will require the fusion of data from a wheel-based encoder and a six-axis fibre optic gyro in a kalman filtered or fuzzy logic control strategy. The optimized dead reckoned position will then provide an intermediary position as well as reduce the error in the rough order magnitude position fed to the stereo-vision based SLAM algorithm.

The stereo-vision based SLAM algorithm will probabilistically reason the position of the *i*PIPE by having the 3-D dead reckoned system solve the rough order of magnitude global localization. This

will reduce the computational complexity associated with determining a position based solely upon just the current stereo visual frame.

3.2.2 Deviations from Ideal Localization Strategies

Kalman filtered algorithms are quite mature and it is even likely that such an approach may meet the overall system requirement for positioning. However, the problem with all odometeric solutions based upon encoders and gyros is that the system's positional error is unbound due to slippage and drift. With the probabilistically reasoned approach discussed above, utilizing the stereo vision SLAM capabilities will effectively "bound" inaccuracies such that errors introduced to the system won't grow with distance traveled, but rather will have the capability to self-correct themselves through the observation of previously identified features from prior frames or by returning to a known location. Even with the probabilistic approach, the environment of the pipe crawling system offers an interesting challenge as compared to above ground systems. In order to probabilistically reason the vehicle's position, it will be necessary to identify features in the environment. The human environment is full of features, i.e. windows, doors, walls, etc., which robots can use to localize. In comparison, the inside of a pipe has sufficiently distinguishable features albeit far fewer (i.e. weld beads, pipe penetrations, elbows, tees, etc.). Thus, the 3-D stereo-vision corrected system should meet the overall positional requirements and the error will not be a function of distance traveled.

4 COMMUNICATIONS

In an effort to support the pipeline inspection requirement for wireless/non-tethered operations, a wireless communication system between the operator and the *i***PIPE** will be developed. This wireless system's design will be based on classic theory of electromagnetic (EM) propagation at radio frequencies (RF) within a circular waveguide. The system will communicate control and sensor data to/from the operator to/from the vehicle over distances up to one mile.

4.1 COMMUNICATIONS CONCEPT

With the diameter of the pipe ranging between 20 in. and 24 in., the cut-off frequency (the lowest frequency that will propagate) is found from:

$$f_c = \frac{X_{np}}{2\pi r \sqrt{\mu\varepsilon}} \qquad (1)$$

Where X_{np} is the first derivative of the mathematical cylindrical Bessel function, r is the radius of the pipe in meters, and μ^1, ε^2 are the approximate relative electrical properties of the compressed natural gas.

The cut-off frequency supported by the dimensions of the pipe would be approximately 281 MHz; however, at this frequency the signal attenuation is high. To successfully propagate over the 1 mile distance of pipe, an optimum frequency will be selected as the frequency of operation. In the

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[1] The exact magnetic permeability, μ, of methane gas could not be found. It was assumed that methane gas would have the same magnetic properties of air.
[2] Exact electrical properties for methane gas at 1000 psi at various temperatures could not be found. Table I within "Reference Values of the Dielectric Gas Components Determined with a Cross Capacitor" by M.R. Moldover and T.J. Buckley, 2000, was used to deduce a reasonable value for the permittivity, ε.

frequency selection process, consideration will be given to minimizing attenuation and assuring single mode propagation.

4.2 COMMUNICATION POWER REQUIREMENTS

Based upon preliminary calculations, the optimal F_{op} is approximately 401.6 MHz. The attenuation due to the pipe wall, assuming the composition to be pure iron, is 1.942 dB per mile and the attenuation due to the methane gas is estimated to be 84 dB per mile. The total attenuation, assuming a straight 1 mile section, is therefore slightly over 86 dB. For example, if the system were excited by an RF transceiver at a low power level, i.e. 10 dBm (10mW), the received signal at an RF transceiver located one mile away would be -76 dBm (25nW), which is well within the sensitivity of commercially available RF transceivers. These figures are only an estimate and will require empirical data to be applied to the design of the communication system.

4.3 DEVIATIONS FROM IDEAL CLASSICAL WAVEGUIDE THEORY

Classical straight-line waveguide propagation does not take into account the following physical constraints that are expected in the inspection of a 1 mile section of a high-pressure natural gas pipeline:

- Obstructions in the pipeline causing signal attenuation and reflection,

- Deviations from straight-line configurations such as tees, elbows, horizontal to vertical rises, etc.,

- Degraded surface conditions such as corrosion or contamination,

- Variation of the methane gas electrical permittivity associated with the specific gas under varying pressures up to 1000 psi, and

- Specific pipe material.

In order to determine the effects due to the above factors, the following tasks must be completed:

1. The electrical properties and performance characteristics due to gas composition and pressure will be measured in a controlled laboratory environment and analysis of the experimentally obtained data will govern the communication system design.

2. Signal propagation and degradation due to obstructions, variation in the pipe radius, pressure fluctuations, surface conditions, and different topologies (i.e. pipe curvature, tee junctions, and angled inclines) will be measured on a characteristic section of piping.

3. A computer-aided simulation package, which accounts for signal degradation and loss as measured in steps 1 and 2, will be utilized to accurately map the RF environment of the pipe and identify appropriate compensatory measures.

4. After obtaining an accurate model of the RF environment, the signal bandwidth can be determined to estimate an acceptable throughput level to support the various data types. A trade-off study will then be performed to evaluate analog vs. digital communications including effects of signal degradation and signal multi-path.

5. A scaled laboratory experiment will be developed to implement and validate the resulting signal excitation and power levels necessary to establish reliable, bidirectional communication.
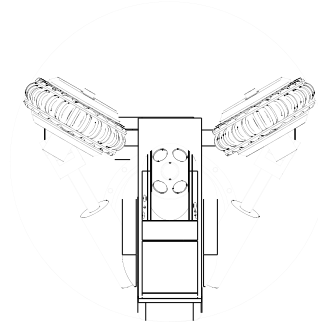
5 OPERATION

Figure 14– Operation in Level Pipe

Operation in Level Pipe
1. Insert *i*PIPE into section of launch pipe.
2. Expand guide wheel arms to meet pipe wall.
3. Drive forward through pipe.
4. When there are no obstructions to avoid, steer drive wheels straight ahead (zero position). Expand guide wheels with just enough force to provide balance. The spring loaded expand mechanisms will handle minor changes in pipe diameter. As the vehicle progresses it will naturally orient the drive wheels towards the bottom of the pipe.
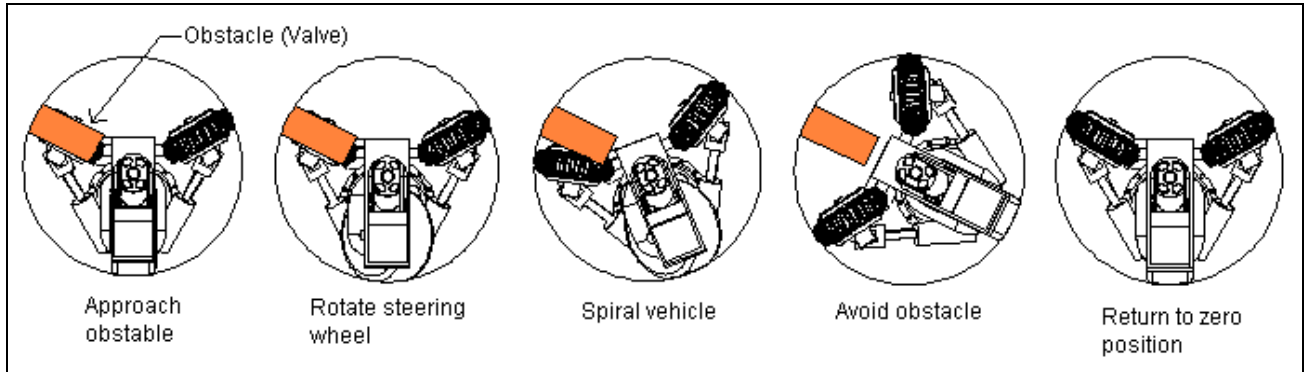
Figure 15 – Operation around Obstacle

Operation around Obstacle
1. To avoid an obstacle in the pipe, began by increasing the expand force against the pipe wall.
2. Rotate driving wheels to spiral in the pipe.
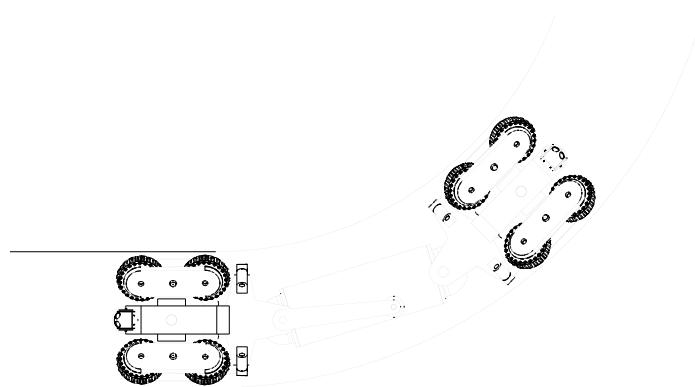3. After the obstacle, spiral the vehicle until it returns to the zero position.

Figure 16 – Operation through Horizontal Bend

Operation through Horizontal Bend
1. Drive the vehicle straight through horizontal bends in the pipe. Do not turn the drive wheel as dual guide wheel assemblies are designed to guide the vehicle around the bend.
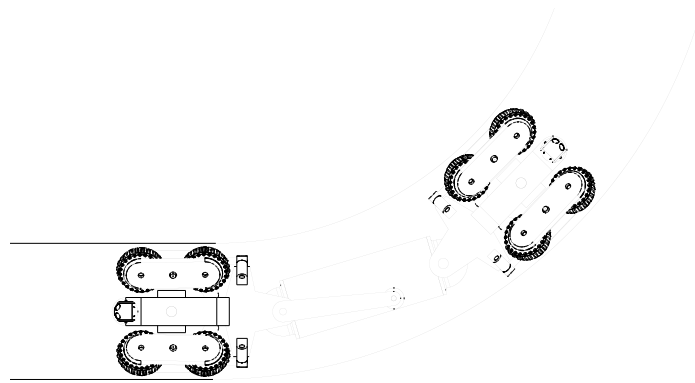
Figure 17 – Operation through Vertical Elbow

Operation through Vertical Elbow
1. To negotiate a vertical elbow, begin by expanding guide wheel assemblies and spiral the vehicle 90º.
2. As the vehicle is traveling vertically, expand the guide wheel arms to apply enough force on the drive wheel to keep the vehicle moving.
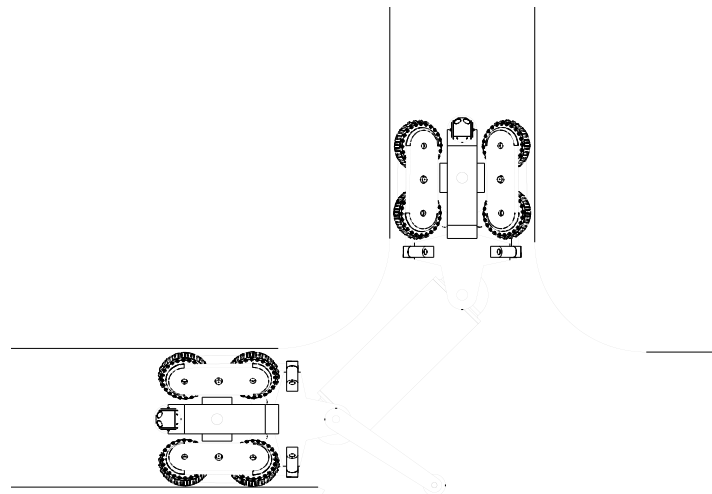

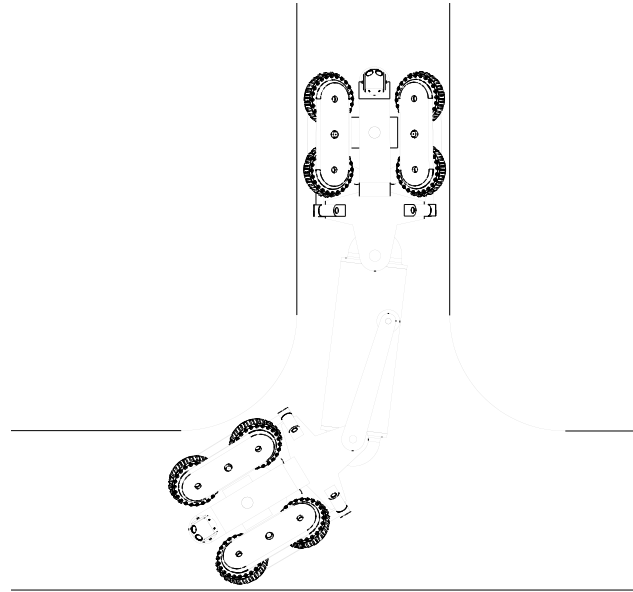Figure 18 – Operation at Beginning of Vertical Tee

Figure 19 – Operation at end of Vertical Tee

Operation at Vertical Tee

1. To negotiate a transition from horizontal pipe to a vertical branch, begin by expanding the guide wheel assemblies and spiral the vehicle 90° so that the vertical assist arm is in the correct position.
2. Lower the vertical assist arm.
3. Retract the front expand mechanism.
4. Pivot front transport assembly up.
5. Continue to lower the vertical assist arm while raising the main canister with the rear transport assembly up.
6. Continue to move the vehicle forward throughout these steps.
7. As the front transport assembly enters the vertical branch, expand the front expand mechanism to grip the pipe.
8. When the front wheel has enough traction to lift the vehicle, retract the vertical assist arm and rear expand mechanism.
9. When the entire vehicle is in the vertical branch, extend the rear expand mechanism to assist with traction.

6 DESIGN CONFORMITY TO REQUIREMENTS

The following Compliance Matrix outlines the conceptual design's compliance with the requirements outlined by NETL.

Requirement	Compliance	Note
The inspection device shall be equipped with wireless data transmission for both video and control. No tether shall be attached to the device.	√	Wireless communication will be accomplished using classical straight-line waveguide propagation as applied to 1 mile of pipe line with compressed natural gas.
The inspection device shall provide on board power.	√	On board Lithium Polymer battery pack will provide power.
The design needs to consider some type of backup mechanism that will allow the robot to bring itself out of the pipe in the event of a system failure.	√	Vehicle will self-configure to a neutral position to allowing a rescue vehicle to remove it from the pipe.
The inspection device shall operate in a high-pressure environment (up to 1000 psi).	√	All housings will be sealed to meet requirement.
The inspection device shall navigate in a cast iron (metal/steel) pipe 20" to 24" in diameter.	√	Vehicle can operate in pipe 20" to 24" in diameter. Can be reduced to 18" clearance.
The inspection device shall be capable of traveling up to 2 miles round trip.	√	On-board battery pack will supply power required to travel 2 miles depending on conditions and operations (see Table 1).
Vertical travel is a necessary capability (up to 20 ft).	√	Expand mechanism supports vertical travel.
The inspection device shall navigate angled inclines.	√	Expand mechanism supports inclined travel.
Travel speed will be a minimum 1 inch/s and recommended 12 inch/s.	√	Vehicle can travel up to 15 inch/s with recommended minimum average speed of 3 inch/s.
The inspection device must be able to stop and position itself at a specific location within the pipe.	√	Using the SLAM 3-D controller will provide this capability.
The inspection device shall be capable of negotiating multiple elbows and tees and potential plug valves, open taps, and obstacles protruding into the pipe up to 1/3 the pipe diameter.	√	Mechanical design enables vehicle to negotiate elbows, tees and protruding obstacles.
The inspection device shall be inherently safe.	√	All mechanical housings will be nitrogen purged and include pressure sensors to monitor integrity.
The inspection device shall be deployed through existing or modified fittings.	√	The development of the launch and recovery system is outside the scope of this document. Design does allow for deployment in existing pipe line accesses with at least an 18" opening.
Inspection data shall include live video feed with sufficient resolution to allow platform control	√	Two on-board Spectrum 90 (Pan, Tilt, Zoom) with high resolution color cameras will provide video feedback.
Inspections shall take place without removing the pipeline from service.	√	The inspection vehicle has been designed to handle environment specified.

The inspection device shall be capable of a variety of levels of autonomy ranging from manual control to operator-assisted guarded motion and full autonomy as applicable.	√	Intelligent Adjustable Autonomy controller with mixed-initiative will provide this capability.
The inspection device shall be capable of identifying its position within the pipe to within 2 feet over 1 mile distance.	√	Intelligent controller with applicable sensors will provide 2' accuracy per mile.
The inspection device shall be able to negotiate a transition to a vertical tee.	√	Vertical assist arm and powered pivots enable vehicle to negotiate a vertical tee.
The inspection device shall be able to negotiate a 1 inch lip (valve).	√	Mechanical design enables vehicle to negotiate protruding obstacles including valves with a 1 inch lip.
Launch set up time shall not exceed 30 minutes.	?	The development of the launch and recovery system is outside the scope of this document. Setup and launch time will be determined; however, it is expected that th 30 minute launch time will be met.

Table 3 – Compliance Matrix

Despite efforts to design a vehicle that can negotiate a large number of obstacles, vertical travel and transitions in the pipe, there are situations in which the vehicle is limited. For example, since the transport assembly pivot provides lateral movement only, the vehicle may not be able to negotiate a vertical transition immediately following a horizontal bend or turn in the pipe. Similarly, the vehicle may not be able to handle horizontal transitions immediately following a vertical bend in the pipe.

7 CONCLUSION

The *i*PIPE design is a result of balancing power requirements, battery size, and physical restraints to develop a vehicle that can handle high-pressure environments, long distance, vertical travel and various protruding obstacles. The multi-wheel configuration allows the vehicle to navigate vertical sections, travel up inclines, and spiral its position in the pipe to avoid obstacles while minimizing power requirements and sources of friction. The main canister is maximized to house the required battery power and vehicle electronics, yet small enough to negotiate tight turns. The vehicle design allows easy configuration of an auxiliary canister for additional payload. The two Spectrum 90 cameras mounted on the vehicle will provide pan and tilt capability and produce high quality video required for both navigation and visual inspection. Additionally, intelligent adjustable autonomy will allow for more efficient inspections by relieving the operator of continuous low-level control and provide a global representation of the vehicle in the pipeline. Tetherless operation utilizing innovative wireless communications and carrying all power on-board will allow for maximum navigation capability without being encumbered with a 2 mile power and communication tether. This resulting inspection vehicle system concept meets all NETL-specified requirements and has been developed with the intention of providing the user with a reliable, efficient tool to accomplish pipeline inspection activities.

APPENDIX A.   One Canister Assembly Drawing

APPENDIX B.   Two Canister Assembly Drawing