ENGN 8170 Group project
Pipeline Gas Leakage Detection Robot
Final Design Report

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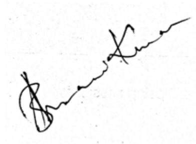
Bharani Kumar Karunyamurthi	Project Manager		18-10-2019

Executive Summary

The Oil and Gas industries of the world are facing challenges in detecting leaks and invest a lot in maintaining the pipelines. Any leaks / corrosion in a major pipeline can cause huge loss to the industry. Robots are used for remote applications where the robot will navigate the terrain and address the corresponding problem. In pipe-line scenario, various sensor-based probes, optical, acoustic and electromagnetic sensing based methods are incorporated to detect leakages caused. Additionally, to mitigate human intervention into these scenarios, to avoid various hazards, mobile robots are introduced to solve the issue. Robots are sent into/outside the pipe by housing single/multiple sensory modules (sensors, camera, communication and power) in it, to assess the situation (detect holes in the pipe) and send sensed data to the operator for visually comprehending the scenario. The project focuses

- On building 'Pipe leakage inspection prototype robot' meeting the basic requirements (leak detection) of the client.
- On developing a sustainable, user-friendly, cost-effective solution and showcasing functional correlation between various sub-modules in the robot .

This document discusses research on various methodologies used previously/currently in the pipeline industries for detecting holes, to prevent any damage to the plant or processes. Further, individual sub-component module is explicitly defined and its architecture is showed, to understand its affect on the entire robot. The robot integrates all the sub-modules to detect a hole, in a prototype environment, by checking the pressure gradients inside the pipe by using PMOD-NAV sensor and communicating it via bluetooth module, and also continuous pose (with orientation) update of the position of the robot.Additionally, Ultrasonic sensor is used to localize the holes and Arduino is used as a micro-controller interfacing the operations of all the other components.The document also analyses customer's needs from an engineering perspective on developing the prototype within the given budget and considering all the constrains in-hand, thereby limiting our robot's scope in terms of sensors incorporated, materials used for building the robot and considering flow inside the pipe. Our scope is limited to the constrains specified in the document and can be scaled up in operations, with careful consideration on the impact on the specifics listed in an operational scenario.

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1 Introduction

Robots are conceived to perform human-extensive tasks and in providing automated solutions to various problems. Problems arising due to leakage and corrosion in pipelines are hugely hazardous and cause tremendous environmental, economic and manufacturing problems. These problems can be addressed by sending mobile robots in/out the pipe, to detect and predict leakages, and communicate the information to the engineering operator at the plant/factory. Hence, we devise a solution by pitching a prototype (leakage detector robot), that carries on the functionalities on a smaller scale and propose alternatives that can be considered in achieving variations in the process parameters

1.1 Background and Context

Automation and robotics exist primarily in easing human operations (manufacturing, surgery, processing plants etc.) and increasing productivity in those operations. Robots acts as a guided-machine able to perform tasks independently, with the help of electronically-coded information. Robotics aid in mobile operations of accessing remote locations and has the capability to traverse around adverse physical locations. Likewise [1], pipelines have been vastly used in major disciplines for a long time. In these pipes, leakage and rupture occurs due to corrosion, aging, physical damage in/out of the pipe. The cost to repair or even more when re-building, is very extensive and will increase the cost required for maintenance and labour charges. Inspection and monitoring of oil/gas leakage in pipes has numerous challenges (efficient measurement, localisation, accessibility) to address, to facilitate nonhazardous outcomes [2]. The idea of utilising robots to detect leakages in pipes is extensively considered in industries and factories, using their mobility as an advantage. Further, pipe exploration robot can be classified into in-pipe and out-pip inspection robots, out of which, out-pipe inspection robots provide obvious disadvantages in detection of leakages in pipelines. The scope of our project is to build/fabricate and utilise an in-pipe robot (wall-pressing, wheel type) with help of various sensory modules (pressure sensor, IMU sensor, ultrasonic sensor) to help us in detection and localisation of the hole in the pipe. The robot consists of 5 primary modules (communication, locomotion, remote control, data collection, sensors subsystem, life-cycle/safety subsystem) and our task is to properly correlate each module to ensure optimal operations. We tested it in a real-time pipe scenario and detected/localised the hole.

1.2 Report Overview

The aim of the report is to propose a 'systems engineering-based', design and component level walk through on the 'Pipe inspection robot'. The project report consists of the following section:

- **Literature Review:**Related works are analysed and studied to get information on various parallel methodologies that governs, in solving the same problem (detection of leakage in pipes).
- **Requirement Analysis:**This section will consist of system, design requirements and stakeholder analysis.
- **Design Overview:**This part consists of an overview on the various sub-components needed to build the robot.
- **Individual Sub-system description:**These segments gives the reader a detailed depiction of each sub-component, its architecture, its design requirements and performance analysis and verification.

- **System Integration:**: This segment provides insight on how all the pieces come together. The output of integration would yield in an optimal well correlated system, independently aligned with its constituent modules.
- **System Verification:**: Various process parameters and testing is shown in this phase, were the prototype's working mechanism is segmented and described.
- **System Cost:**: Financial analysis is performed on the system and budget is allocated for the underlying components.

2 Literature Review

For controller subsystem, we performed analysis on two potential candidates which includes Arduino and Raspberry Pi. Numerous literature gave us insights on how to implement both micro-controller/ microprocessor. When performing feasibility of implementing any one of the technology into our project, our Electronics/ Software department, did an extensive in studying what type of sensors can be brought into the project to meet most of the customer requirements. Raspberry Pi showed extreme versatility in supported sensors which includes IR thermal camera, regular camera and many more. With slight compromises to the versatility, Arduino gave an economical package fulfilling most of the customer requirements. So, we decided to go on with Arduino to implement our design.

The literature review consists of research analysis on the various system frameworks and components considered. Further, the review gave us a clear insight on towards what components can be chosen, considering the budget, scalability, design constraints and time-scale for the concerned project.Pipelines are pivotal for various processes in many industries, carrying the corresponding constituents, acting as a transportation medium. Damage to the pipelines are primarily caused due to corrosion, change in pressure zones, stress-strain induced on the pipe, climatic conditions etc. It is extremely difficult for the service engineers to access the damaged pipes, because of the toxicity radius, localisation of the event, trigger-response mechanisms. Hence, it is primary to consider four most important things when handling the problem and they are [3]: (i) Reliability, (ii) Sensitivity, (iii) Accuracy and (iv) Robustness.

2.1 Various Leak detection systems

There are various leak situations, hence operators need to be aware on what the underlying problem is. The leak detection systems are listed as follows [4]:

- **Types of Fluids:**: : pipelines will transport different fluids such as crude oil, petroleum constituents, steam, carbon dioxide, coal, water, hydrogen, etc. and hence various materials will need to be utilised under inspection scenarios.
- **Types of operation:**: There are two working modes, single-batch operation which works continuously and multi-batch operation, which works based on time-scheduling. Hence, the live-relay of the robot will affect depending on the type of operation in the industry/factory.
- **Nature and character of the leak:**: Leakages in the pipe is caused suddenly (due to external damage which results in difference in temperature and pressure) or gradually (caused by corrosion). Sudden leakages are easy to detect by using internal based detection techniques, whereas gradual leakages are very difficult to monitor.

2.2 Mobile Robot applications in pipe inspection scenarios

Mobile robots are used to inspect leakages in pipe, as it can easily traverse and navigate inside the pipe and suitable for tele-operation. Detection methodology for the mobile robot can be classified into (i) visual, (ii) internal and (iii) external based, for pipeline-oriented problems [5]. Further [5] suggests that, leak-detection systems can be classified into visual, acoustic and electro-magnetic-based systems. A brief overview on the systems are discussed below:

2.2.1 Visual inspection systems

Robots will observe the pipe for detecting leakages using vision based autonomous operations. Navigation can be achieved by multiple ways (Aerial-unmanned Drones -AUVs, visual-based bolted joints monitoring, long distant probes etc.) [7]. Visual based methods aid in obtaining autonomous and un-laboured operation, but it is operated to visualise exterior of the pipes and hence it is limited to that operation alone.

2.2.2 Internal-based inspection systems

Robots are operated from inside the pipe and can contain various traversing mechanisms (Pig type, wheel type, caterpillar type, wall-press type, walking type, inchworm type, screw type). Where [8], 'pipe inspection gauges (PIG) type robot' does not require any driving mechanism and flows with the fluids in the pipe. Firstly, PIG type of robot is also called as passive robot, thereby limiting various movements and our scope of the project does not house a medium to provide either gases or liquids. Secondly [9], is the conventional wheeled robot, which are only suitable for horizontal pipeline application. Thirdly [10], the wheel base is increased and widened and housed with bands called 'caterpillar robot', this provides more grip to the inner wall of the pipe. Additionally [11],' wall-pressing robot' is used mostly in scenarios where flexible mechanism is preferred, it also has less slip-to-friction ratio. Further, [12] 'Inchworm robot' is similar to the movement of a worm and is preferred to be used in small diameter pipelines. Conclusively, last type of robot is 'screw-type', where it follows a helical-screw motion inside the pipe [13].

2.2.3 External-based inspection systems

Robots with technologies (sensing cables, vapor sensing, fiber optic methods, acoustic emission testing) are used to inspect pipelines by visualising/monitoring it from external-based sensing methodologies. However, various problems such as power source, communication localization, density of sensor nodes and network congestion control denies us from endeavouring into these methods [4].

2.3 Sensory modules considered

Multiple sensors were considered for mounting on the robot and detection of hole in pipelines, however, limitations such as housing space on the robot, budget constraints, scalability, time availability, imparted our scope. Initially, Ultrasonic sensors [14], measures the distance between the emitted and received ultrasonic waves, various optical methods use a separate transmitter and receiver for operations, but ultrasonic sensor minimises that by using a single module, thereby reducing the size and it is also cost-effective. Further, they prove to be resistant to dust and mist and able to locate intricate and complex shaped objects, however requires lots of fine-tuning and it is also affected by temperature and humidity of the gases. However, scaling down the project and for implementations purpose, we used ultrasonic sensors and devised approaches in suggestion to house improved sensory modules. Alternative to ultrasonic sensor on a higher budget and real-time application is Time-of-Flight (ToF) Li-DAR sensor [16], which works at a much faster rate and more resolution (30cm), with minimum hole detection radius of 20mm, it is also very small in size but it is expensive for the given budget, hence neglected. [15] Another sensor module Pmod-NAV which has a 9-axis accelerometer, gyroscope, magnetometer and a digital barometer with 10 Degrees of freedom (DOF) functionality, aids us in detection of pressure gradients (drop in pressure in certain areas of the pipe, denoting vicinity of a hole causing leakage) and in visualising (orientation, pose angles) the robot inside the pipe, by using Python GUI. Additionally, with increased budget and time of operations, [17] Thermal camera module (Pimoroni MLX90640 110o wide angle) was considered, which can detect drop or rise in temperature, and since temperature and pressure vary proportionally in correspondence to an imminent leakage, it is extremely useful in localisation of holes in pipelines.

2.4 Communication modules considered

Communication was performed by using TR/RX Bluetooth module, which signals the sensory data through serial connection and visualised through a mobile phone [18]. Additionally, WiFi module containing a self-contained SOC with integrated TCP/IP protocol was considered to enable the micro-controller (Arduino) to connect to the local Wi-FI network, enabling communication. Further [19], ZigBee communication module (XBee Pro) was also considered which is operated using wireless ad-hoc network at a low-power and low data rate.

2.5 Power modules considered

When incorporating robots to perform manoeuvring applications, a proper trade-off needs to be established between the weight the robot carries, power supply needed, sensory components used and the choice of motors. [20] Batteries can be chosen by considering few specifications such as voltage rating, discharge current, current/capacity rating. Firstly, we considered using Lead-Acid batteries which will have a large capacity and charging/discharging rates, however, the size of the battery is big and is not suitable for our scope. Further, Nickel-metal hydride (Ni-MH) batteries consists of voltage rating of 1.2V and current rating of 600-3300 mAh, but we refused to utilise them considering its cost. Further, we narrowed it down to Lithium-ion and lithium-polymer which consists of decent discharge rates and a voltage rating of 3.7V, it is also light in weight, however, because of its cost, and current output's bulk supply causing fire-hazards to the components, we neglected its usage. We considered using Alkaline batteries which comes with a voltage rating 1.5V and 9V and with varying capacities (1000,2000,2500 mAh). They are also cheap and operable under high temperature gradient.

3 Business Analysis

As a team, we performed SWOT Analysis to realise the Strengths, Weaknesses, Threats and the Opportunities of our Team and our project. With the help of this analysis we could determine the actual underlying problems and how to resolve them by using our strengths. It helped us in all the phases of the project till present, and it will definitely be beneficial for the future aspects as well.

Figure 1: SWOT Analysis

4 Requirements

4.1 Customer Requirements

Requirements from the customers are important in a project in order to build an effective, efficient and the final product for the customers what they actually expect for. It is the major challenge in the industry in order satisfy and fulfill the customer requirements [22]. The table shown below are the requirements from the customers and we have already discussed about this in the System Requirement Specification (SRS) document [23]. Each customer requirement has been given an ID and which is used in the upcoming section in order to derive and map with the system requirements.

Requirement I.D.	Customer Requirements
CR-1	The robot shall monitor real-time operating condition of the pipe.
CR-2	Inspection of the pipe's leakage shall be done by sensors.
CR-3	The system shall communicate wireless to operators
CR-4	Locomotion of the robot shall be inside the pipe.
CR-5	The robot shall withstand stress/strain while moving
CR-6	The robot shall use Arduino or AVR micro controller for control of actuation and for interfacing.
CR-7	The robot shall be operated wireless for locomotion
CR-8	The system shall operate under appropriate pressure/temperature conditions inside the pipe.
CR-9	The material of the robot shall be determined in accordance to the test pipe conditions.

Table 1: Customer Requirements

4.2 System Requirements

Table 2 and Table 3 shows the system requirements after the careful consideration of the customer requirements. This is also as same as in the System Requirement Specification Document [23].

System Requirement ID	System Requirement	Justification	Customer Requirement Mapping
SR-01	The system shall be able to detect the gas leakage in the gas transmission pipelines.	The aim of the project is to detect the leakage in the gas pipelines using the robot.	CR-1
SR-02	The robot shall move backward and forward inside the pipe.	Forward and backward motion enable the access of the robot in different location of the pipelines.	CR-4
SR-03	The robot shall sense pressure inside the pipeline.	This allows the robot to detect the crack where the pressure will be comparatively low when compared to other positions.	CR-2
SR-04	The system shall be easily controlled using remote controller.	This allows the user to control the robot wirelessly through mobile or computer.	CR-7
SR-05	The system shall transmit the data such as pressure readings and the location of the robot inside the pipeline.	This enables the engineers to record the readings from IMU sensor for the pressure, accelerometer readings.	CR-3
SR-06	The system shall identify its location (distance) from the start of the pipeline.	This is to ensure the location of the leak or crack on the pipeline.	CR-3
SR-07	The system shall record the pressure, temperature, and accelerometer readings.	This enables the engineer to get the details of the readings of various sensors for the observation of abnormality inside the pipeline.	CR-2
SR-08	The system on full battery charge, shall operate for 2 hours continuously.	As it is used for long transmission pipelines, the robot should work continuously for 2 hours to complete a distance.	CR-6
SR-09	The system shall be able to traverse through the pipe of different sizes.	As the gas pipelines diameter varies, it should be capable of traversing through the diameter range of 200-400 mm.	CR-9
SR-10	The components of the systems shall not react with the gas and cause harm to the pipeline and the environment.	Since most of the components are electronics, it should not cause any chemical reaction which causes any damage or explosion of the pipeline.	CR-5
SR-11	The system materials shall have an operation life of 5 years.	Since the system is a crucial equipment for detecting leaks in gas pipelines, the system should work effectively for a span of 5 years before any major repair or replacement.	CR-5
SR-12	The system shall detect the hole of size greater than 10-20mm.	This is to localise the hole on the pipeline.	CR-2
SR-13	The system shall return to the start/end point once it traverses through the pipeline for distance/time.	Since there is limited power supply from the battery, the robot should return or stop to the start or the end point respectively before the battery dies.	CR-4
SR-14	The system may be completely autonomous.	The robot can move and operate autonomously in the pipeline without any external control.	CR-5
SR-15	The system shall be able to work under a line pressure of 1 to 5 bars of line pressure.	The robot should work at a pressure of 1 to 5 bars inside the pipeline in order to work effectively and to avoid any damage to the robot due to higher pressure.	CR-8
SR-16	The system shall be able to withstand a gas flow speed of approximately 15 lit/ sec	The robot should withstand the flow rate of the gas of 15lit/sec inside the pipeline to avoid the rise in speed of movement which may damage the motors and other components of the robot.	CR-5
SR-17	The system prototype shall have a pipe of 1m length and 50mm diameter.	The robot should move within the test pipeline of length 1m and 50mm diameter to effectively validate the test parameters.	CR-1

Table 2: System Requirements

System Requirement ID	System Requirement	Justification	Customer Requirement Mapping
SR-19	The system shall not be free floating in the pipe.	The robot design should be such that there are no free ends in the structure and the robot fits to the inner circumference of the pipe.	CR-5
SR-20	The system shall have a structure that will not be a hindrance to the flow of gas.	The robot should be small and compact as possible such that the structure does not hinder the flow of the gas in the pipe.	CR-5
SR-21	The system may be able to stabilize itself.	The robot can be able to stabilize itself in the pipe to avoid any turbulence and faulty readings.	CR-4
SR-22	The system shall have quick and easy installation.	The project should be easy to install for extended usage.	CR-6
SR-23	The system production cost should be within $300	The budget for the project provided is $300, which should not be exceeded.	CR-1

Table 3: System Requirements (contd)

4.3 Design Requirements

Design requirements are those requirements that the system should satisfy in order to achieve the final expected working model. These are based on the system requirements which has been derived from the customer requirements. Table 4 shows the design requirements mapped with the corresponding customer requirement ID. This is also as same as the SRS document that we have submitted [23].

Customer Requirement ID	Design Requirement ID	Design Requirement	Eng Characteristic	Aim	TPM
CR-1	DR-01	The system shall be able to detect the gas leakage in the gas transmission pipelines.	Pressure, LIDAR	-	Pa, nm
	DR-02	The system prototype shall have a pipe of 1m length and 50mm diameter.	Distance, Diameter	+	M, mm
	DR-03	The system production cost should be within $300	Budget	Y	$
CR-2	DR-04	The robot shall sense pressure inside the pipeline.	Pressure	+	Pa
	DR-05	The system shall record the pressure, temperature, and accelerometer readings.	Pressure, degree celcius,	-	Pa, Celsius, m/s^2
	DR-06	The system shall detect the hole of size greater than 10-20mm.	Diameter	Y	mm
CR-3	DR-07	The system shall transmit the data such as pressure readings and the location of the robot inside the pipeline.	Software	-	Binary
	DR-08	The system shall identify its location (distance) from the start of the pipeline.	Hardware	+	cm
CR-4	DR-09	The robot shall move backward and forward inside the pipe.	Move forward and backward	Y	binary
	DR-10	The system will be able to move in complicated parts of the pipe like pipe bends.	Motion	+	
	DR-11	The system shall return to the start/end point once it traverses through the pipeline for distance/time.	Software	Y	binary
	DR-12	The system may be able to stabilize itself.	Control Systems	+	months
CR-5	DR-13	The components of the systems shall not react with the gas and cause harm to the pipeline and the environment.	Longevity	Y	years
	DR-14	The system materials shall have an operation life of 5 years.	Longevity	Y	years
	DR-15	The system shall be able to withstand a gas flow speed of approximately 15 litres per second	Flow rate	+	lt/sec
	DR-16	The system shall not be free floating in the pipe.	Spring compression	-	N/m
	DR-17	The system shall have a structure that will not be a hindrance to the flow of gas.	Dimensions (length, height, width)	-	mm
	DR-18	The system may be completely autonomous.	Software/hardware	-	
CR-6	DR-19	The system shall have quick and easy installation.		+	
	DR-20	The system on full battery charge, shall operate for 2 hours continuously.	Electrical charge	Y	Ah
CR-7	DR-21	The system shall be easily controlled using remote controller.	Software	+	Binary
CR-8	DR-22	The system shall be able to work under a line pressure of 1 to 5 bars of line pressure.	Pressure	Y	Pa
CR-9	DR-23	The system shall be able to traverse through the pipe of different sizes.	Diameter	Y	mm

Table 4: Design Requirements

4.4 Requirements Breakdown Structure

The requirements can be broken down based on the components and mapped with the design requirements. A mandatory section in requirement analysis is understanding the requirements of the systems, sub-systems in order to fulfill the customer requirements. The requirement breakdown structure is shown as in the Figure 2 [23]. This is as same as in our the SRS document [23].

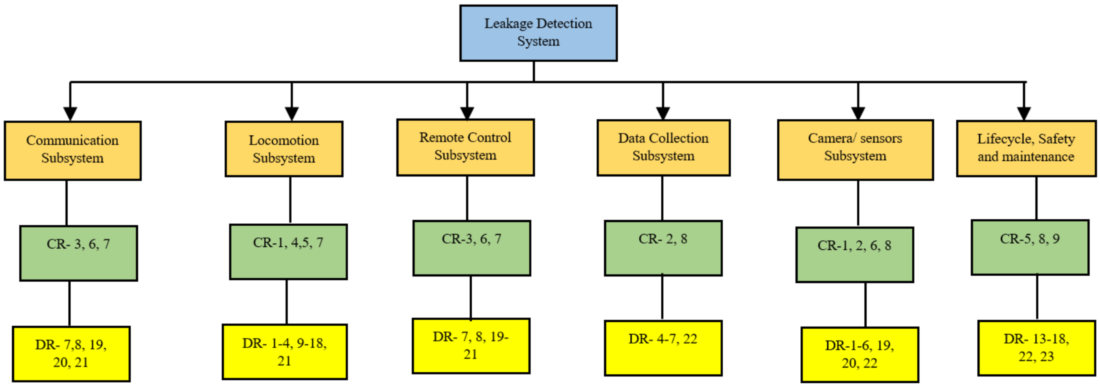

Figure 2: Requirements Breakdown Structure

5 Design Overview

There were numerous designs structures out in the real world where, we had multiple potential choices for our design structure. We narrowed down to our design based on the customer requirements, implementation complexity and time constraint. In the following subsection, we briefly introduce on how we went about our design and introduce our subsystems.

5.1 Chassis/ Body design

Our Mechanical team poured in their efforts to design and 3D printed all our necessary structure of the robot. The Mechanical department was in consistent communication with the Electronics/Software department while designing the compartment to house the controller, sensors and power sources.

5.2 Controller subsystem

We choose Arduino as our controller, as the it is one of simplest controller which is readily available. The primary reason for choosing this controller is their cost and versatility provided (5 Analog inputs, 12 Digital I/O and power pins(5/3.3V)). Additionally, we also design a motor driver circuit to drive motors in either direction and for the safety of the model.

5.3 Communication subsystem

Our choice of communication is Bluetooth, as it had official support from Arduino and one of our team members had working experience in setting up communication between arduino and mobile phone during one of the earlier academic projects.

5.4 Power supply

We powered our circuits with basic 9V alkaline batteries and as design had sensors that weren't power hungry and limiting our drives to two motors, we were able to achieve proper prototype level performance of our model.

6 Chassis/ Body

As mentioned in the literature review, we have implemented a combination of a Wall-Pressing and Wheel- type robot. The list of sub-parts can be seen in Figure 3. Most of the parts have been 3D-printed or Laser-cut using the facilities at ANU MakerSpace lab.

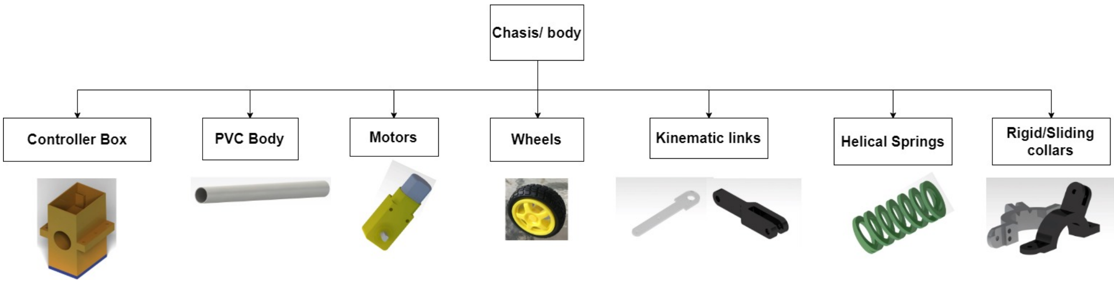

Figure 3: Chassis/Body Structure breakbown

A detailed analysis of each sub-part can be see henceforth.

6.1 Controller-box

The design includes 2 controller boxes (top and bottom), as seen in the figure. As per the spatial requirement of the Controller subsystem, the controller box has to be capable of housing an Arduino-UNO controller, a L293D motor driver, an HC-05 bluetooth module and 9V alkaline batteries. To meet this requirement, both the controller boxes have a total cavity of 96mm x 66mm x 45mm. In addition, the top box has a small compartment for holding the bluetooth module and the bottom box has 3 compartments for holding the batteries, to keep these components intact when the robot is moving. Lastly, both the boxes have slots for taking out wires. Through these slots, the wires can be transferred between the boxes, as well as to other electrical components through the inside of the pipe. The boxes are designed in a way that when they are placed on the PVC pipe, they create a rigid bond with respect to the body which is strong enough to stand the force of a fully-compressed spring. Both the boxes and their covers are 3D-printed using 2.85mm PLA filament.

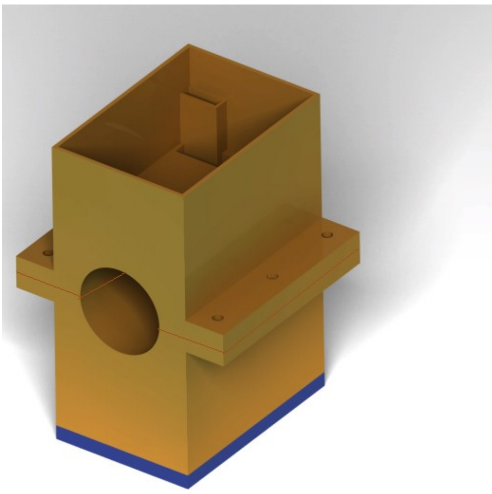

Figure 4: Controller Box

6.2 PVC Pipe

We have used a PVC pipe as the spine of the body, as it is easily available and has suitable strength to carry the weight of the robot. For our design, we got a pipe with 42mm diameter and 505mm length.

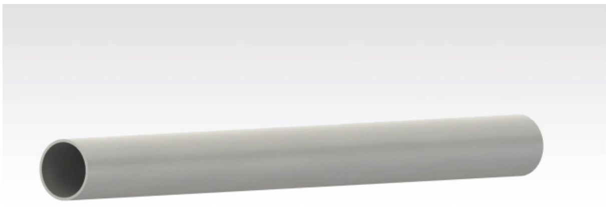

Figure 5: PVC pipe

6.3 Wheels and Motors

We have used 2 motors to drive the robot. In total, the design has 6 wheels, out of which four are connected to the kinematic links using plastic bearings. The design for the plastic bearings is shown in Figure 6 (all dimensions are in mm). The bearings ensure that the wheels can rotate freely and at the same time, stay fixed to the links. These bearings have been 3D-printed at the ANU MakerSpace lab using 2.85mm PLA filament.

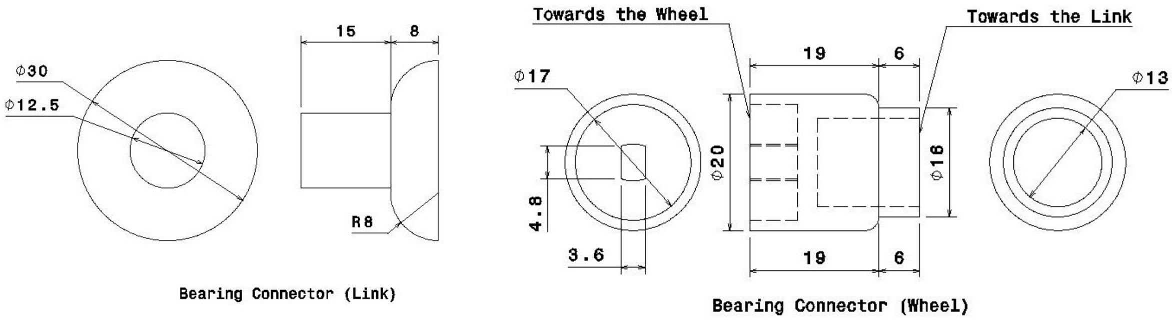

Figure 6: Bearing connector of link and wheel

The remaining 2 wheels are connected to standard DC geared motors, which are compatible with arduino. These motors and wheel have been bought from Jaycar. Figure 7 shows the wheel and motor used in our prototype.

Figure 7: Wheel and Motor

6.4 Kinematic Links

The design of the robot constitutes of 6 legs, each of which is built from a pair of a locomotion link and a connecting link. The 2 kinematic links are connected by a Scissor/Pin joint, in such a way that the 2 links have a hinge type motion. This connection is implemented to vary the overall height (and thereby, the diameter of the robots) by bending the legs. The design and dimensions for the locomotion link and connecting link can be seen in Figure 8 and Figure 9 respectively. The connecting link has been 3D-printed and the locomotion link has been laser-cut from a 5mm cast-acrylic sheet.

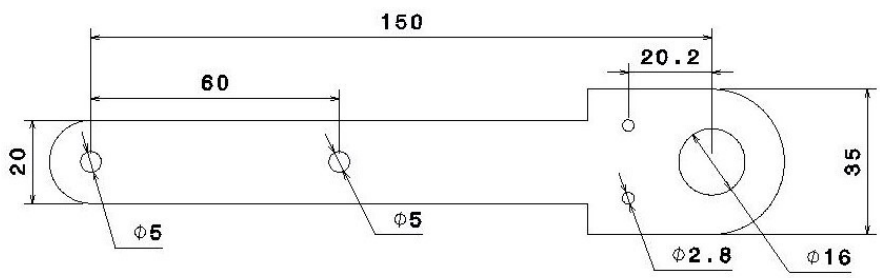

Figure 8: Design of Locomotion link

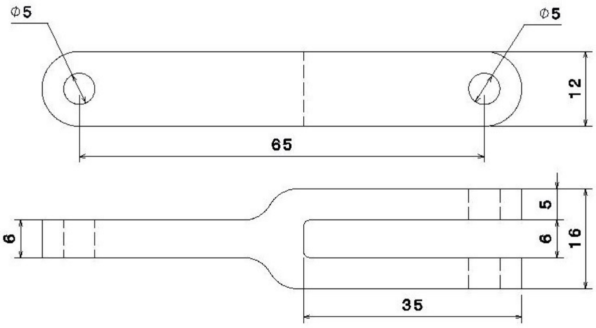

Figure 9: Design of Connecting link

6.5 Helical Springs

The design uses 2 helical rectangular springs, one for the front legs and the other for the rear legs. The spring is one of the most crucial design components for the robot, as it is the part which enables the flexible bending of the legs. We have designed springs with closed, squared and ground type ends [25] so that the spring has an even contact with the support surfaces and the force of compression exerted by the 3 legs on a spring is uniformly distributed. To get sufficient stiffness, the rectangular cross-section of the spring is set as 10mm by 6mm. Additionally, to get enough compression while retaining structural strength in the spring, we have kept the helical pitch as 22mm with 7 coils. The complete design of the spring is shown in Figure 10. The springs have been 3D-printed using 2.85mm PLA filament.

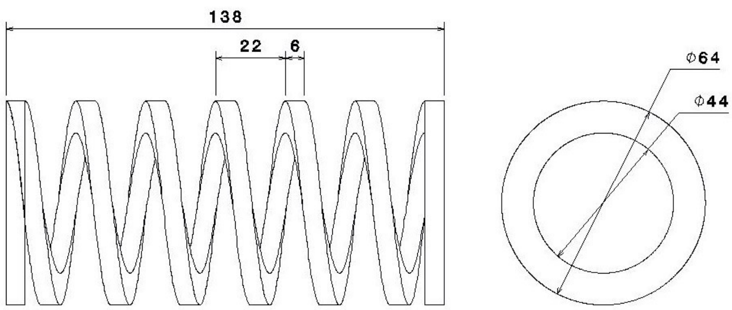

Figure 10: Design of Spring

6.6 Collars

We have designed 2 different types of collars, namely a rigid collar and sliding collar. The only difference between the two types is their inner radius. The rigid collar forms a firm bond with the PVC pipe, whereas the sliding can move freely long the axis of the pipe. The detailed designed of half of both collars is shown in Figure 11. 2 such pieces are joined to form a complete collar. These collars have been 3D-printed using 2.85mm PLA filament.

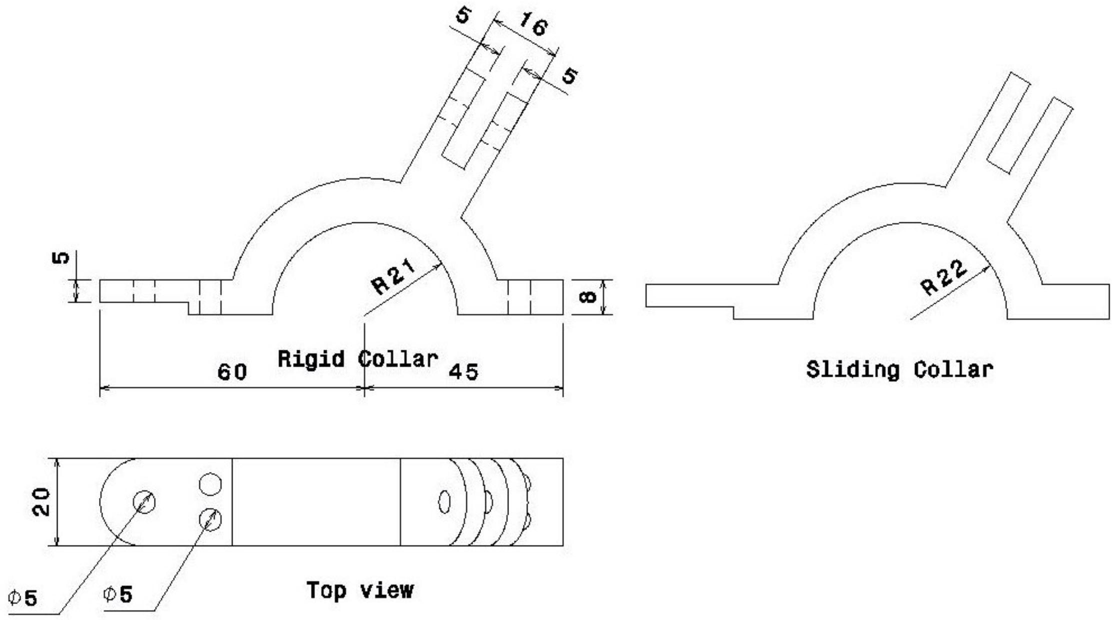

Figure 11: Design of Collars

The rigid and sliding collars are connected to the locomotion and connecting links respectively. This sub-assembly forms a slider-crank mechanism, because the angular bending of the locomotion link is converted to a linear sliding motion of the sliding-collar. In total there are 2 rigid and 2 sliding collars used in the design, one set for the front sub-assembly and the other set for the back.

6.7 Other Parts and Assembly

In addition to the parts listed till now, the prototype has 2 more components. Firstly, we had to design an end-stopper which acts as a support for the spring on the back. This part has been 3D-printed. It can be seen in Figure , which shows the final assembly. Secondly, we designed special mountings to hold the ultrasonic sensor HC-SR04 and servo motor sg90 (radar sub-assembly). The parts for this mounting, shown in Figure 12, have been laser-cut from a 5mm cast-acrylic sheet.

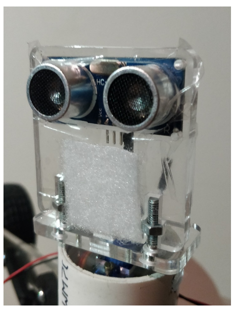

Figure 12: Sensor Mounting

All of the parts listed till now have been assembled to create the final models shown in Figure . The figure shows the fully-extended prototype, as well as the fully-bent prototype, to visualize the range of pipe sizes it can travel in. These are rendered images of the 3D model created in CATIA and the robot is designed to have its diameter ranging from 200mm to 400mm. However, the fabricated prototype has additional rigidity and the plastic printed-spring cannot be compressed to its full extent without breaking. Hence, the fabricated prototype model can travel in pipes ranging from 320mm to 400mm.

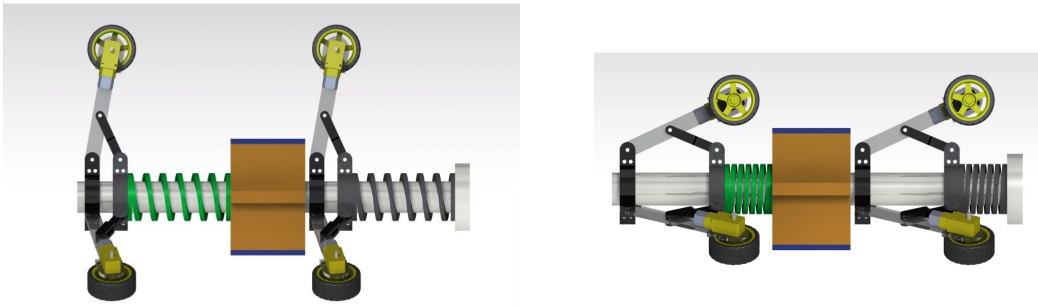

Figure 13: Assembly Full-extended and Full-compressed

This limitation can be overcome replacing the plastic springs by mass-produced metallic ones. The material for all other parts can also be changed so that further reducing the component sizes does not affect the overall structural integrity and strength. Such miniaturization of the robot can be undertaken as a future scope of this project.

7 Controller Subsystem

The Arduino is our choice of controller(CR-6). The controller provides numerous I/O pin (5 Analog In, 13 Digital I/O, PWM, Serial communication). The pressure sensor and IMU inputs were received through two of the analog inputs. Other sensors(Ultrasound) and motor signal actuators are connected to the digital pins of the Arduino. The motor driver circuit was fabricated in PCB and L293D is used as our motor driver controller. The L293D ensures the proper functionality of the actuators (regulated voltage supply) in our prototype. The power source supply the Arduino with 9V which in turn supplies the L293D, sensors and actuators. The following picture 14 give the motor driver circuit board design. The primary functions of the controller subsystem include,

- Performing calculations by receiving data from connected sensors.
- Communicating the sensor values with the user through Bluetooth terminal.
- Controlling the motors through the driver circuit 14.

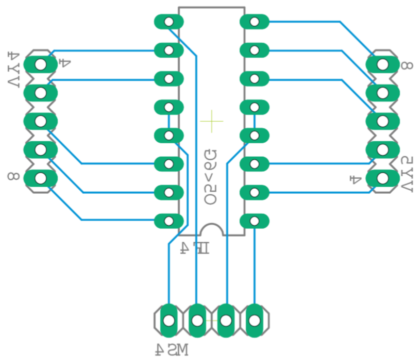

Figure 14: L293D PCB circuit

8 Communication Subsystem

This sub-system is a Bluetooth Module (HM-10) which is crucial to communicate the state of the robot and the internal conditions of the pipe to the monitor outside the pipeline. This communication of the internal conditions and the condition of the robot in the medium is the goal of the project since we are detecting leaks from inside the pipeline.

8.1 Design requirements

The major design requirements of the Bluetooth module are as follows:

- Shall be controllable from a smart phone or a computer.
- Shall be compact enough to fit into the robot.
- This system shall be a low power module.
- The system shall have a wider range of communication distance.

8.2 Design

The HM10 Bluetooth module is the communication sub-system that we have installed in our robot. The major advantage of this module is that it is a serial Bluetooth module which means that this model has a serial UART layer which makes interfacing the module with the Arduino simple.

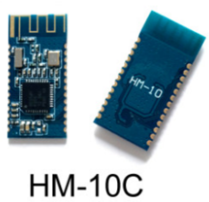

Figure 15: HM10 Bluetooth Module

The interfacing is simple where we need to connect the supply and ground pins to the Bluetooth module and the module requires 2.5v to 3.3v from Arduino to function. We use a dedicated Android application for Arduino-based Bluetooth control to receive the data from the module to an android smartphone. Another advantage here is that this Bluetooth module has a transmission range of about 100 metres which is better than the other Bluetooth modules that can be used with Arduino

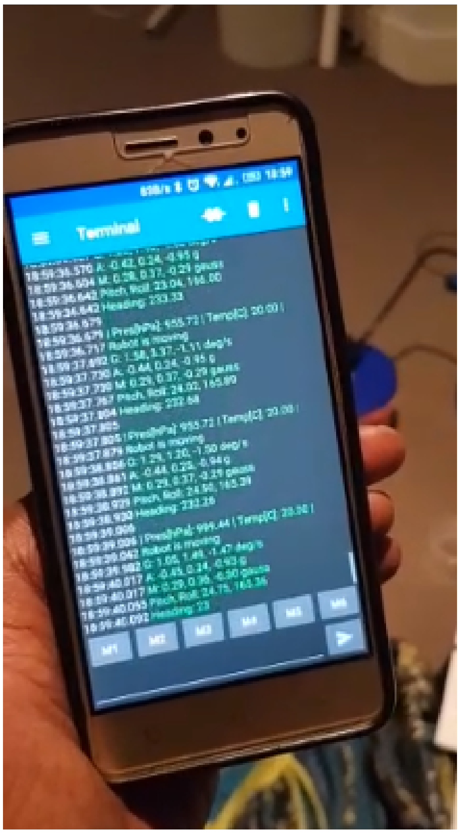

Figure 16: Data reception on android device

The communication module sends the data regarding the robot state such as whether the robot is in motion or static, the pitch and roll of the robot and it send the internal conditions of the pipeline such as pressure and temperature and pressure at every instant. Thus, the data from the IMU and the ultrasonic sensors is sent to the android device through the Bluetooth module interfaced with Arduino.

9 Battery Subsystem

This sub-system is an essential part of the robot system since it provides power to all the other sub-systems. It is a crucial sub-system because it is the only available supply of power in the system for the other sub-systems to function.

9.1 Design requirements

Requirements of Battery Sub-system:

- Reliable performance and life are expected out of this system since the robot must travelling a certain distance in a pipeline.
- The system shall provide the necessary power to the sensors of the system and other such sub-systems that control the motion of the robot.
- The battery system shall provide 9V supply to the robot system.

9.2 Design

This sub-system is mainly connected to the Arduino system and the motor driver of the robot. The Arduino controller provides power to the other components such as sensors from the battery system. The battery sub-system is interfaced with the robot system with the help of a battery clip connector.

Figure 17: Alkaline Battery

We are currently using the above mentioned 9V alkaline non-rechargeable battery to supply power to the system. This sub-system can provide power to the entire system for a continuous operation of roughly 1.5 hours.

10 System Integration

In this section we discuss about how the above mentioned subsystems shall be integrated into a single working system. The battery system provides power to the subsystem responsible for the motion of the robot and to the sensors. The control subsystem controls the overall motion of the robot in the pipe and the communication subsystem which is responsible for sending the required data and state of the robot to the external monitor. We can observe the subsystem integration in the following functional block diagram.

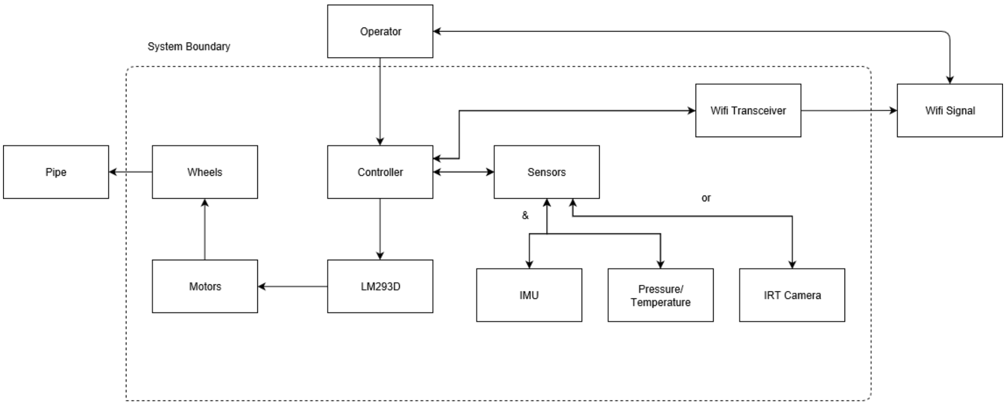

Figure 18: Functional Block Diagram

The following flow chart explains the overall flow of functionality of the robot in the pipeline including the motion of the robot and the leak detection functionality.

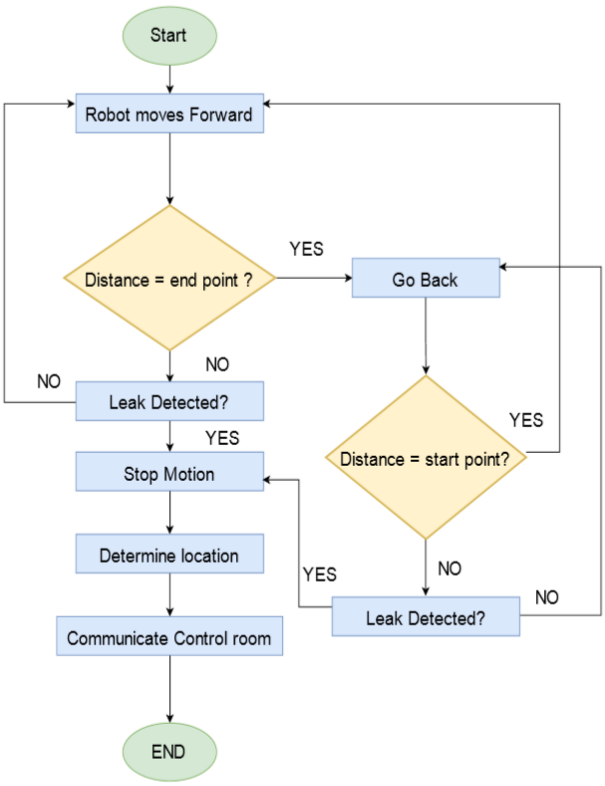

Figure 19: Function Flow Chart

We can observe the detailed explanation of the above flow diagram as follows in the Functional Flow Block Diagram. It explains briefly about the flow of functionality of the overall system along with the logic structures and control flow of each subsystem in the robot.

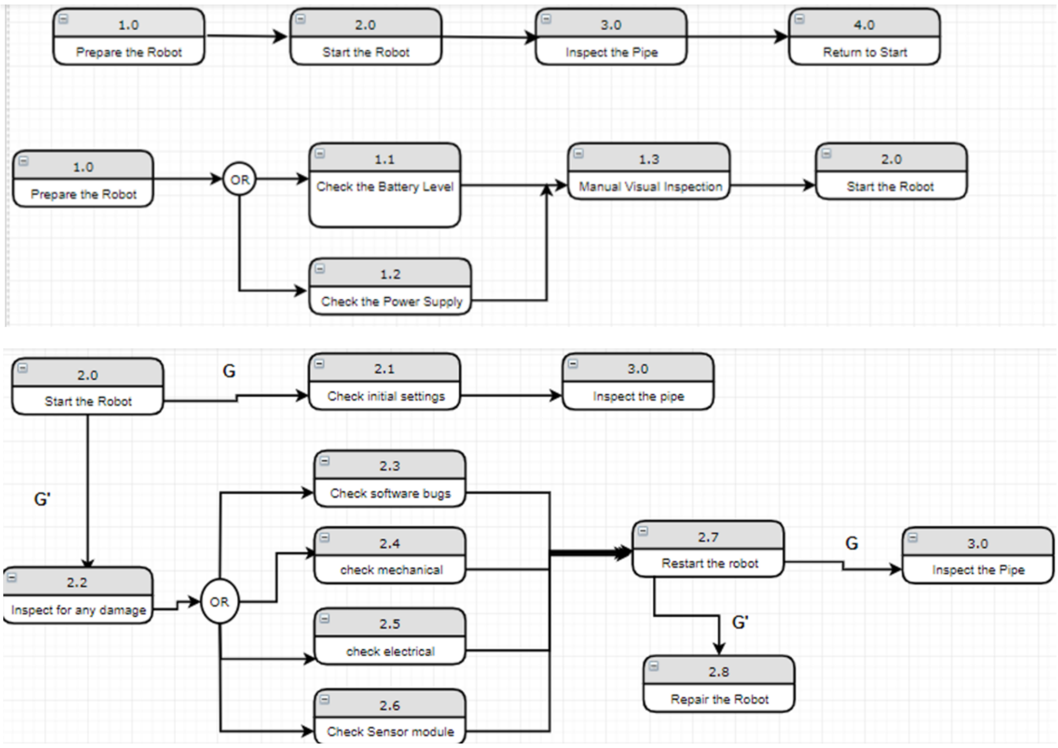

Figure 20: Functional Flow Block Diagram

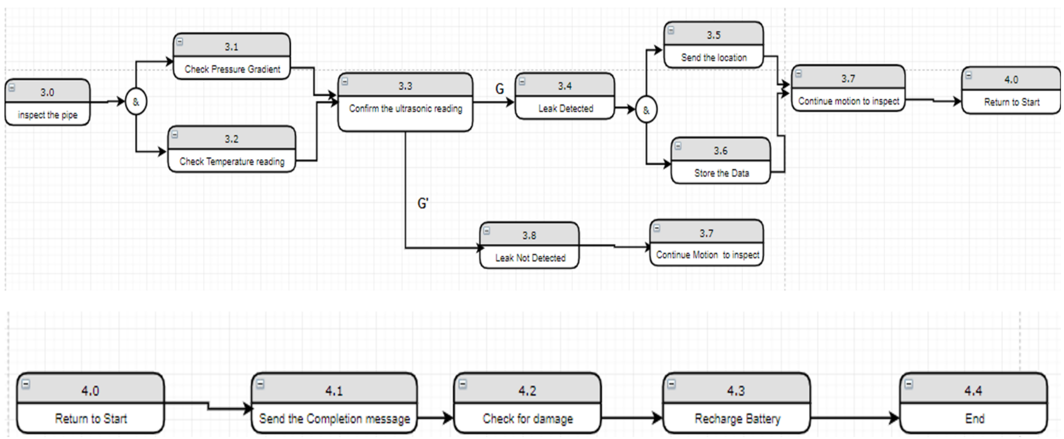

Figure 21: Functional Flow Block Diagram

11 System Verification

The following table 5 presents a short analysis on the system verification and also shows the implemented (✓), partially implemented(O), not implemented (×)

Table 5: System Verification

Design Requirement ID	Design Requirement	Eng Characteristic	Aim	TPM	Acceptable range	Verification Status	Comments
DR-01	The system shall be able to detect the gas leakage in the gas transmission pipelines.	Pressure, LIDAR	-	Pa, nm		✓	The system implements a leakage check using pressure and ultrasonic sensor.
DR-02	The system prototype shall have a pipe of 1m length and 50mm diameter.	Distance, Diameter	+	M, mm	distance>1 diameter>20	O	The final model uses a pipe of 0.5m length and 42mm diameter.
DR-03	The system production cost should be within $300	Budget	Y	$	<300	✓	The final prototype cost is less than $150.
DR-04	The robot shall sense pressure inside the pipeline.	Pressure	+	Pa	<1	✓	The robot has a mounted pressure sensor which is sensitive to pressure changes.
DR-05	The system shall record the pressure, temperature, and accelerometer readings.	Pressure, degree Celsius	-	Pa, Celsius, m/s^2	-	O	The system utilizes a mounted IMU + pressure sensor, but it does not record temperature.
DR-06	The system shall detect the hole of size greater than 10-20mm.	Diameter	Y	mm	>10 <20	✓	The ultrasonic sensor can detect a 10-20mm sized object located less than 0.5m away.
DR-07	The system shall transmit the data such as pressure readings and the location of the robot inside the pipeline.	Software	-	Binary	-	✓	This task is achieved with the help of the HC05 bluetooth sensor.
DR-08	The system shall identify its location (distance) from the start of the pipeline.	Hardware	+	cm	-	✓	The current location can be computed using the IMU data.
DR-09	The robot shall move backward and forward inside the pipe.	Move forward and backward	Y	binary	Y	✓	The robot has 2 DC motors which can promote linear motion in forward or reverse directions.
DR-10	The system will be able to move in compli- -cated parts of the pipe like pipe bends.	Motion	+	degree	<120	×	The current prototype is not capable of taking a precise turn.
DR-11	The system shall return to the start/end point once it traverses through the pipeline for distance/time.	Software	Y	binary	<3m of pipe	O	The robot will pass through to the end if no leak is detected, but it does not return to the start point.
DR-12	The system may be able to stabilize itself.	Control Systems	+	months	-	×	The current system does not have a self-stabilizing functionality.
DR-13	The components of the systems shall not react with the gas and cause harm to the pipeline and the environment.	Longevity	Y	years	-	✓	All the electrical components are placed in an airtight non-corrosive box to avoid interactions with the gas.
DR-14	The system materials shall have an operation life of 5 years.	Longevity	Y	years	5	O	The prototype is built mainly from PLA filament which has a limited operational life.
DR-15	The system shall be able to withstand a gas flow speed of approximately 15 litres per second	Flow rate	+	lt/sec	~12-17 litre/sec	✓	The stiff springs ensure a non-sliding contact between the wheels and pipe surface.
DR-16	The system shall not be free floating in the pipe.	Spring compression	-	N/m	-	✓	The system will stay concentric in 200mm-400mm pipe because of the wall-pressing design.
DR-17	The system shall have a structure that will not be a hindrance to the flow of gas.	Dimensions (length, height, width)	-	mm	-	✓	The robot structure constitutes of a physical spine and 5mm thick legs which would hardly constrict the flow of gas.
DR-18	The system may be completely autonomous.	Software/hardware	-	N/A	-	✓	The system will traverse the pipe, detect leakages and return the leakage locations without any manual input.
DR-19	The system shall have quick and easy installation.		+	days	1 - 3 days	✓	The system is re-programmed and only requires a Bluetooth connection with the serial monitor.
DR-20	The system on full battery charge, shall operate for 2 hours continuously.	Electrical charge	Y	Ah	0-2 hours	✓	The system uses 3 x 9V batteries, which are sufficient for operating the robot for more than 2 hours.
DR-21	The system shall be easily controlled using remote controller.	Software	+	Binary	-	✓	The system has an additional manual override where the user can control the motors through a remote controller.
DR-22	The system shall be able to work under a line pressure of 1 to 5 bars of line pressure.	Pressure	Y	Pa	$10^5 - 5x10^5$ Pa	×	The robot is not tested under high pressure working conditions.
DR-23	The system shall be able to traverse through the pipe of different sizes.	Diameter	Y	mm	Diameter < 200 mm	✓	The system has flexible legs which can be adjusted for pipe sizes ranging from 200mm to 400mm diameter.

12 Cost

The financial analysis was performed on the project and we have presented three major cost components for our Robot. The major expenses for our project were analysed and is presented in the chart given below.

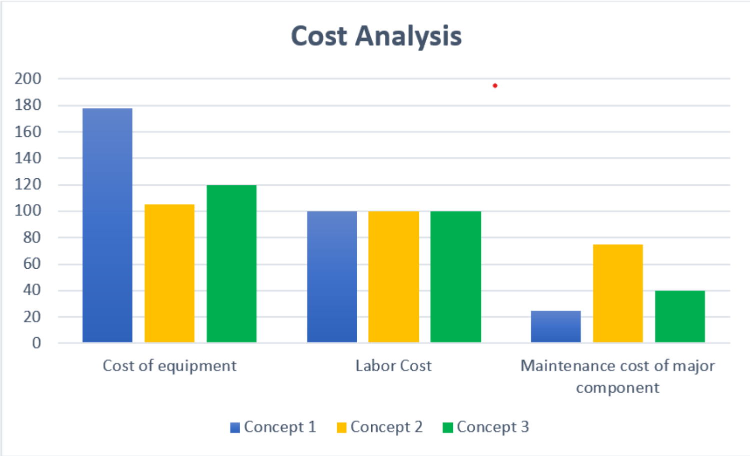

Figure 22: Cost Analysis

We have considered three concepts at once, namely:

- Concept 1-IR camera, pressure sensor and ultrasound sensor
- Concept 2- Camera, Pressure sensor and Ultrasound sensor
- Concept 3- Pressure and ultrasound sensor.

The cost of equipment, Labour and Maintenance were taken into consideration while analysing the cost of our entire project. The cost of equipment depended upon the different components and materials used in building the robot. The labor cost is similar, because there is no difference in installing the robot among the concepts. According to the Australian wage rate, we are charging AUD 100 for installing our system and inspecting the pipeline. The maintenance costs are low because we are expecting the robot with Concept 1 to have a minimum lifespan of 30 years, Concept 2 with 3 years and Concept 3 with 15-20 years(as described in their component manuals). Therefore, Concept 2 has the highest maintenance cost in the coming 5 years. The cost analysis helps us in efficiently distributing the total budget to get the best possible result.

13 Performance and Limitations

All the three concepts were considered again to check the difference in performances to get to the best solution. Our project can be implemented in different ways, according to the requirement of the customer and their budget. In the graph below, we can see the comparisons of different concepts in relation to Cost, Accuracy and Complexity.

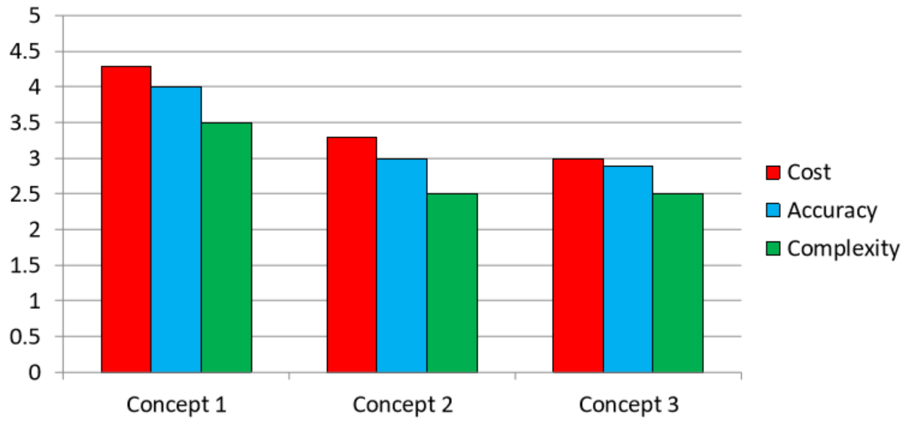

Figure 23: Concept performance comparison

The limitations in our project were mainly due to the budget constraint and also lesser amount of time to implement more sophisticated technologies.

14 Results

The robot is sent into the pipeline and it traverses in the pipe. If it finds a leakage, it stops and checks the pressure gradient using the pressure sensor. Then, the exact location of the leakage is determined by the ultrasonic sensor, present in the robot. The readings are then sent to the mobile phone of the inspecting engineer through Bluetooth. This can also be implemented via WiFi as well. The figure below shows the scenario that was anticipated.

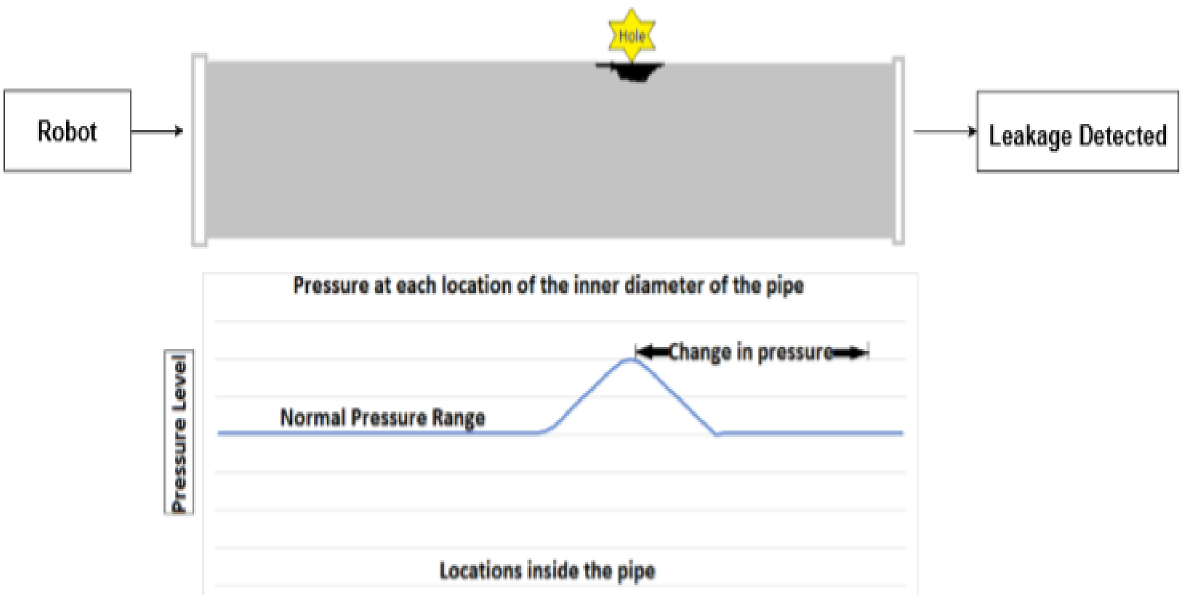

Figure 24: Anticipated Scenario

The real time image of the Bluetooth terminal was recorded and to check the accuracy and performance of the inspection Robot. The figure below describes the real world Bluetooth terminal of our implementation.

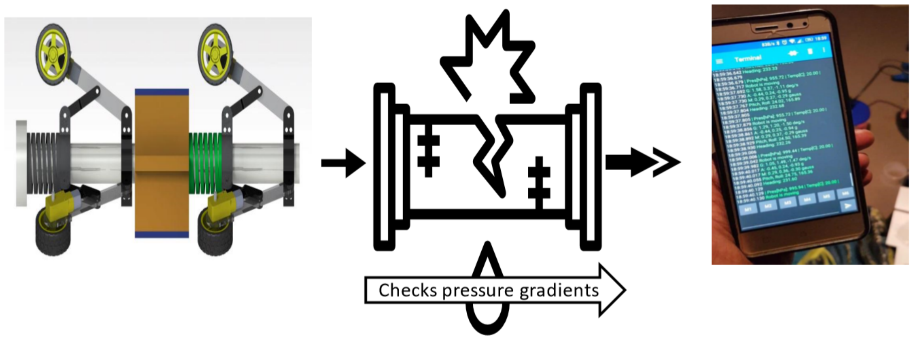

Figure 25: Real Time results

15 Conclusion and Future Work

We chose Concept 3, after a careful analysis of all the performances and Limitations to implement our prototype. It works on the Pressure and Ultrasonic Sensors. This prototype is completely scalable according to the customer requirements and the implementation environments where the project is being deployed or used. We can expand our project to use more sophisticated technologies like IR cameras, which can certainly improve the accuracy and performance scope of our project. Accounting to the number of accidents across the globe, due to pipeline leakages, our project will definitely help in prevention of such accidents. In the near future, we have also planned to use Internet Of Things for continuous real time gas pipeline monitoring for both the small and large sized leaks. Also, we are aiming at making a fully insulated common robotic structure for all applications, to eradicate the issues of any type of reactions with the gases in pipelines. The robot needs to be sturdier and it should be able to also move smoothly along the pipe bends. We are also planning to include the GPS module in the robot to find its real time exact location at all times in the pipelines. Our prototype is one of the best solutions for any pipe size with good accuracy and lesser cost and complexity.

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