LIDAR AND PATTERN RECOGNITION BASED FEATURE DETECTION IN CLOSED GAS PIPE STRUCTURES

S. (Saumya) Vijaykumar

MSC ASSIGNMENT

Committee:
dr. ir. J.F. Broenink
N. Botteghi, MSc
dr. ir. E. Dertien
dr. M. Poel

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Robotics and Mechatronics
EEMathCS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Summary

A process/system/product has to undergo routine maintenance checks in order to avoid sudden breakdowns and disruption of the process. Currently, maintenance of gas pipelines is a manual, time consuming and expensive process. Robots capable of autonomous navigation has been developed in the past. To use a robot for the application of pipe maintenance it has to autonomously navigate throughout the entire network and successfully identify damages. The PIRATE is being developed into one such robot to conduct autonomous maintenance of gas pipelines. Feature detection is a process which is a necessary step towards achieving this goal.
Research has been done into all the feature detection concepts available and two sensory system concepts were formulated and tested in this thesis. Here, we consider the combination of a pattern and a camera to detect features which make up sensory system 1 and we use an array of LIDARs (sensory system 2), using the concept of changes in distance measurements to detect features.
The concept of using patterns and LIDARs was tested before but in this thesis we make use of multiple LIDARs and a non-continuous circular pattern (point sources arranged in a circle)in the simulation experiments conducted in order to analyze if these methods are able to overcome some of the constraints faced in earlier conducted experiments.
Simulation based experiments were conducted for sensory system 1 and 2. A few parameters were kept constant in both the simulation experiments and the results from both the experiments has been compared, the method which is more adaptable for this project is concluded to be the better sensory system. From the tests conducted in a virtual simulation environment the sensory system using LIDARs provided more accurate results in accordance with the requirements set in Chapter 3. This is further justified when the number of point sources used for setting up the circular pattern are reduced and the number of LIDARs used are also reduced. Both the experiments were tested in the same simulation setup (pipe network) and from the results obtained it is seen that the concept using LIDARs provided the best results.
Recommendations for improving feature detection and using these detected features a map of the environment can be built by incorporating an IMU and an Odometer. Another option is the use of LEDs to increase the visibility of the environment which then further helps in using a broader variety of cameras and possibly eliminating the use of patterns. The addition of ultrasonic sensors can be used to determine the thickness of the wall of the pipes which helps in calculating pipe degradation, which is another factor to be checked during pipe maintenance. Further converting the simulated experiments into real-time experiments gives a better idea of the functionality of the sensory system which is another recommendation to be considered.

Contents

1 Introduction

This thesis is part of a project, which focuses on helping large scale industries conduct maintenance more efficiently for their network of pipelines. This Chapter gives an introduction to the entire project.

1.1 Context and Problem Statement

Industrial plants use pipeline networks as distribution systems of their products to various locations. The main focus of this thesis is on the pipe networks used by petrochemical and gas industries. These distribution systems consist of pipes which have to undergo periodic maintenance checks as damages can occur both internally and externally due to excessive loads, oxidation or corrosion under isolation on the surface of the pipe (Kumar, 2019).
Although in the recent past, the use of autonomous pipe inspection robots have increased for pipes of larger diameters such as sewer pipelines, maintenance of gas and petrochemical pipeline networks are still largely carried out manually. The process of manual maintenance proves to be quite tedious, time consuming, labour intensive and an expensive task. Two of the main disadvantages which arise with manual maintenance is the limited accessibility of these pipelines and the shutting down of an entire plant for a long duration in order to conduct maintenance. Information regarding the condition of the pipe and specific location of the leaks are not known beforehand which result in unnecessary removal of non-damaged insulation layers and pipes, which cannot later be reused and hence discarded. This creates unnecessary expenses and a wastage of time and materials.
This inspired the idea behind the PIRATE (Pipe Inspection Robot for AuTonomous Exploration) Robot project, which is currently being developed and worked on by the Robotics and Mechatronics Group at the University of Twente. The project is further developed under the European Smart Tooling project, of which the main focus is automation by developing newer robots for the process industry and making it safer, easier and more efficient. Smart tooling consists of a collaboration of partners from the industrial side and the academic side of which the UT is a part (Starmigioli and Botteghi, n.a.).
The PIRATE is designed to navigate through natural gas pipelines with varying diameters from 65 mm-125 mm.(Dertien, 2014) The current version of the PIRATE, as shown in Figure 1.1. It consists of 6 modules in which the center module rotates at an angle of 360° for better navigation of the PIRATE through bends and corners. A tethering cable is responsible for providing power and communication to and from the PIRATE but as the end goal of the PIRATE is for it to autonomously navigate throughout the entire pipe network the cable will be later replaced. For maintenance checks and autonomous navigation to be successfully completed by the PIRATE it has to recognize features present on the internal surface of the pipe. This includes cracks, obstacles, bends and intersections present within the pipe network.

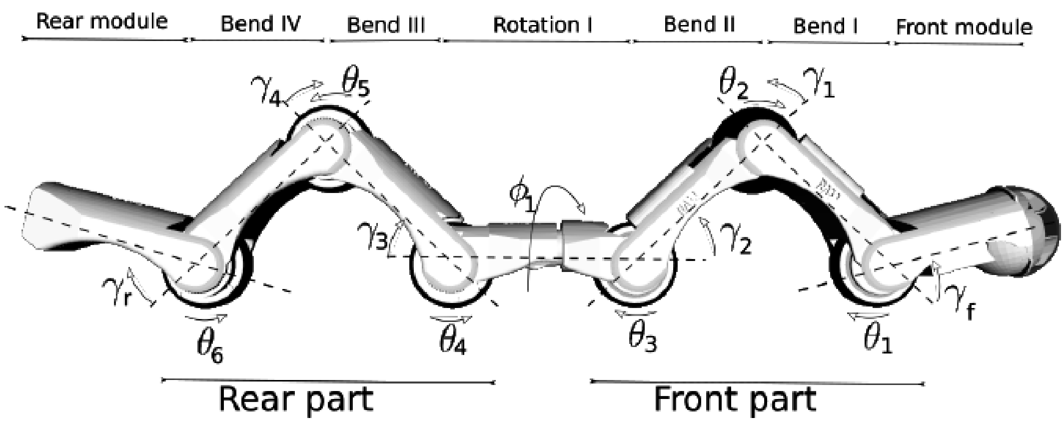


Figure 1.1: PIRATE Prototype II – Design Model (Geerlings, 2018)

As the pipe dimensions are limited between 65mm-125mm and the PIRATE has to travel through a dark and static environment, this research aims towards developing an efficient sensing system (technique) to accurately identify and recognize features present within the pipe. Feature recognition not only helps in identification of damages and bends to the internal surface of the pipe but also assists in autonomous navigation and localization of the PIRATE along with the building of an accurate map of the environment as recognition of features such as different corners and types of pipes present in the network would be possible. The on-board sensing system for feature recognition has been developed following the requirements as explained in Chapter 3.

1.2 Related Work

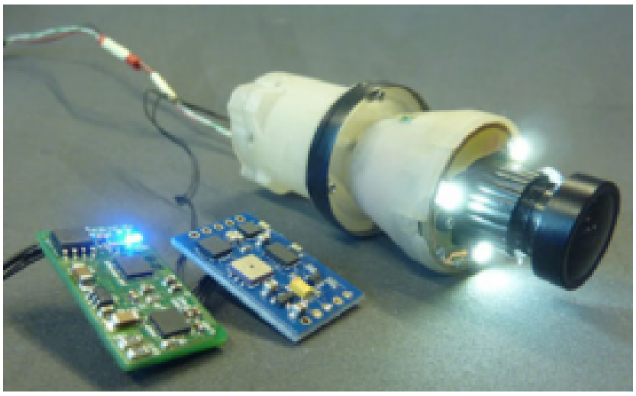
This section describes previous research done in the field of Feature Recognition in closed pipe networks. This also consists of feature detection research previously conducted using the PIRATE for gas/fuel pipelines.

The two main classes of methods which are used for the detection of features inside pipelines are vision-based systems and acoustic/sound based systems. Ultrasonic sensors are sound-based systems which incorporate sound waves for pipe exploration tasks. Francisco et al. (2003) further worked on this by using a combination of these sensors to provide both 2D and 3D outputs of the environment. This was then worked on by Ali Ahmadian Mazraeh and Sahari (2016) where the combination of Ultrasonic sensors and eddy currents (which falls under magnetic sensing) proved effective in providing an increased accuracy for crack and corrosion detection. However, in this project ultrasonic sensors cannot be taken into consideration while building the sensory system as sound waves bounce off the inner pipe and cause false readings in case of pipes with smaller diameters such as the one considered in this project (Dertien, 2014).

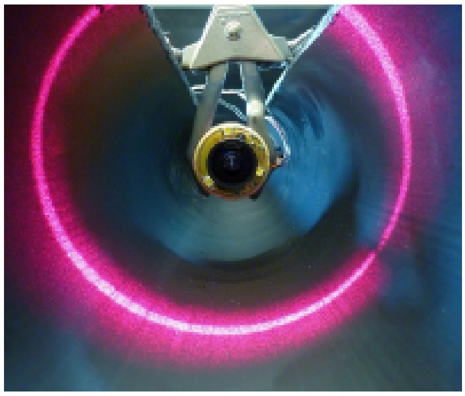
Some of the main research done using vision-based systems are concentrated on two main concepts which highlights the use of LIDARS and pattern recognition (using cameras) to provide a 3D output of the environment. Although LIDARs which are capable of providing a 3D output are readily available on the market and provide accurate output as researched by (Kleiboer, 2019) but they cannot be directly applied here due to restrictions in the project.

One of the main constraints considered while choosing a sensor is its dimensions as the pipe dimensions are limited. Due to this a single sensor which can provide a 3D output like Velodyne (3D LIDAR) cannot be used. Hence, in this project we are working towards providing a 3D output with a sensory system consisting of a combination of sensors.

Earlier research conducted on the PIRATE in the field of Feature Detection included detection based on the use of a LIDAR and detection using a structured pattern. The research done by (Reiling, 2014) used a combination of a laser and a mirror to project a circular pattern on the internal surface of the pipe as shown in Figure 1.2. Experiments were conducted by using structured light for quality inspection, obstacle and landmark detection for autonomous navigation in pipes with small diameters (57 mm up to 119 mm). Calibration was found to be a big limitation in this method although it was able to produce outputs with an accuracy of 0.35 mm.
Kleiboer (2019) worked on feature detection with the help of a 2D LIDAR, based on her findings the algorithm proved to work in the simulation but a major drawback of this method was its dependency on the minimum range and resolution of the available off-the-shelf LIDARs. She was able to achieve a 3D output by using a LS02 LIDAR placing it on a servo motor and rotating it but this entire system proved to be too large to be used practically on the PIRATE. The sensor arrangement used during hardware testing is shown in Figure 1.3
Therefore, this project is based on finding a sensory system which consists of a combination of sensors to provide a 3D output of the environment while successfully recognizing the features present in the environment i.e the internal structure of the pipe.

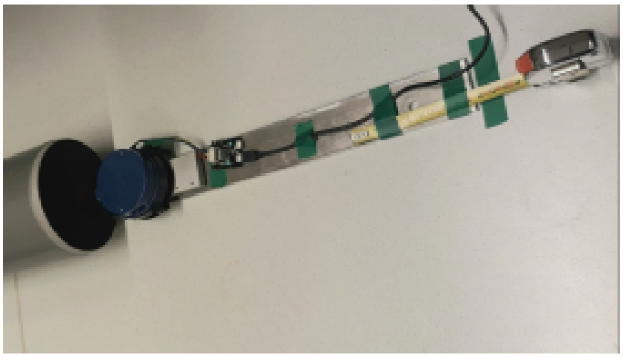


(a) Sensor and Control Board

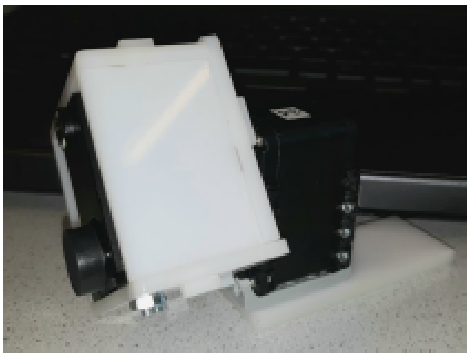


(b) Circular Projection inside the pipe

Figure 1.2: Structured Light Sensing Method (Reiling, 2014)



(a) YDLIDAR setup for testing of the 2D algorithm



(b) LS02 LIDAR on a servo motor for testing the 3D algorithm

Figure 1.3: LIDAR Sensing Method (Kleiboer, 2019)

1.3 Research Objectives

The final objective of this thesis is to design a sensory system in simulation for feature detection within gas/fuel pipelines. This is achieved with the help of the following sub-objectives.

1. Designing sensory system 1 (pattern recognition using a camera) in the V-Rep simulation platform (Builtin, n.a.a)
2. Designing sensory system 2 (array of 1D LIDARs) using the V-Rep simulation platform
3. Deduce the better sensory system based on the requirements as set in Chapter 3
4. Find the minimum number of point sources required to make the pattern such that it is recognized by the camera in order to detect features (sensory system 1b)
5. Find the minimum number of 1D LIDARs required to detect features with the pipe (sensory system 2b)
6. Obtain the better sensory system from the outputs seen based on points 4 and 5
7. Find the overall better sensory system (from points 6 and 3) in accordance with the requirements in Chapter 3

1.4 Assumptions

Testing and experimentation were conducted using the simulation software V-Rep. The following assumptions are considered mainly regarding the simulated robot and its environment.

1. Alignment: In the simulation the vision sensor (camera) is placed behind the circular pattern approximately such that it aligns with the center of the pattern. Placing the camera in the center indicates that the camera is placed at an equidistant position from all the point sources which make up the pattern such that any changes to a point in the pattern has equal opportunity of being recognized as the others. This alignment is considered to be consistent while the robot moves through the pipe.
2. Non-Transparency: The properties of the pipe are set such that the pipe is opaque. This is a necessity for proper measurements so as to prevent the light rays from passing through the pipe which results in false measurements.

1.5 Thesis Methodology

The entire workflow of this thesis is as indicated in the Figure 1.4. As this is focused on feature recognition the first stage falls under background research done on the previous work conducted on the PIRATE and other research published under feature recognition. After which a set of requirements to be followed for this project are set. The actual environment is a closed pipe with almost no light source which greatly reduces the visibility in the environment. We try to replicate a similar environment in the simulation as well. The features to be recognized such as a straight pipe, T-junction pipe and a corner/bend are first identified. Next, to obtain the required output we implement two methods of feature detection. Detection Algorithm for both theses methods are tested in the next step and the results are analyzed. As a final step in order to conclude the research and experimentation, a comparative analysis of the results are discussed based on the requirements as set for this thesis in Chapter 3. The two methods which are compared are as given below:

Sensory System 1
This is based on the concept of pattern recognition. Using a red coloured multi-point circle projected onto the internal surface of the pipe and reading the information via a camera system to identify the features.
Sensory System 2
Using an array of 1D LIDARs placed at an angle in a circular shape at the head of the PIRATE to identify features.
The experiments conducted in this thesis are simulation based. Hardware based experiments were not conducted due to Covid-19 induced restrictions.

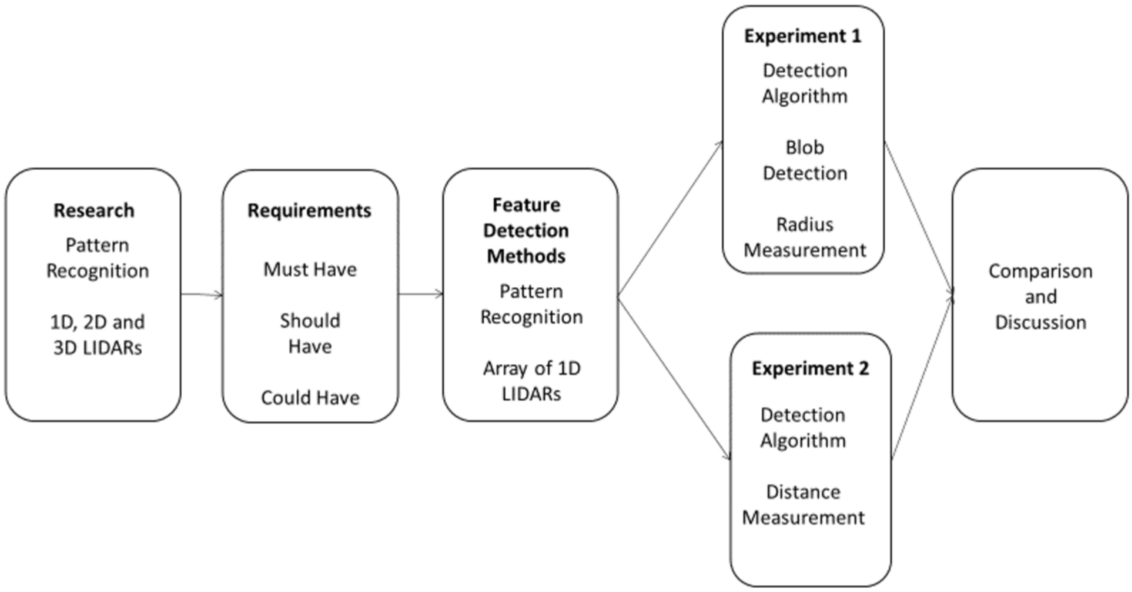


Figure 1.4: Thesis Methodology

1.6 Report Organization

The following steps highlight the organization of the remaining part of the report:

Chapter 2 explains the background information required to understand the main concept of this thesis. It describes both the sensor systems used and a general outline of the PIRATE and other pipe inspection robots.

Chapter 3 discusses the project requirements and the reason for choosing research objectives along with the sensor choices and the adopted algorithms incorporated for testing conducted in this thesis

Chapter 4 describes the experimental (simulation) procedure to be conducted in order to validate the detection algorithms

Chapter 5 explains the results obtained in the experiments and further analyses the results based on the requirements of the project

Chapter 6 focuses on providing the final answers for the research questions. Further methods which can be implemented are also discussed here.

2 Background

This chapter focuses on understanding the different types of pipe inspection robots and the sensors which make up the sensing techniques used for this thesis.

2.1 Types of Robots

There are mainly 5 types of robots which are currently popularly available. (Builtin, n.a.b)

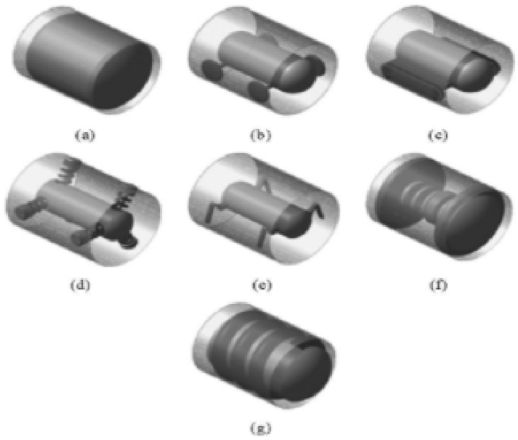
1. Pre-Programmed Robots: the robots which fall under this category consists of machines which perform a few monotonous and simple tasks, for example a pick and place robot.
2. Humanoid Robots: these robots perform human-like activities and behaviour and look very similar to humans, for example Hanson Robotics' Sophia
3. Autonomous Robots: robots which fall under this category navigate and perform activities on their own without the assistance of a human. They are made to function in both a static and dynamic environments. They make use of on-board sensors to perceive the environment they are in while also incorporating decision making algorithms which are designed based on its end goal. For example: Roomba, the vacuum cleaner robot.
4. Teleoperated Robots: these robots function based on a master-slave concept. The robots are generally located in extreme conditions which are difficult or not suitable for humans. They are controlled by operators who are present at a distance from the actual robot.For example: DaVinci Surgical System.
5. Augmenting Robots: they help humans enhance or replace human capabilities which have been lost for example a prosthetic leg.

2.1.1 Autonomous Robots

As mentioned above, robots which are capable of performing tasks while navigating on their own without explicit human control/supervision fall under this category of autonomous robots. As the final goal of the PIRATE is for it to Autonomously perform maintenance checks by navigating through the pipe network and successfully detecting the location of cracks or damages to the internal structure of the pipe the PIRATE eventually will fall under this category.

2.2 Pipe Inspection Robots

As manual pipe maintenance is a strenuous and difficult task, different types of pipe inspection robots (this includes inspection of sewage, petrochemical and gas pipelines) has been developed in the past. Pipe inspection robots which are mainly used for gas pipeline inspection mostly rely on robots which fall under one of the below categories i) Wheeled type, which move by using powerful wheels ii) Crawler type, which use caterpillar type motion for movement iii) Screw Type, which make use of a rotational motor and angled wheels to drive the motor along the pipe iv) Inchworm Type, moves by mimicking the inchworm type movement for the robot to move within the pipe. The Figure 2.1 as seen below depicts the different types of movement techniques inside a pipe which are used by pipe inspection robots while navigating through pipes (Gargade and Ohol, 2016).



(a) Pig Type (b) Wheel Type (c) Caterpillar Type (d) Wall-press Type (e) Walking Type (f) Inchworm Type (g) Screw Type

Figure 2.1: In pipe robots classification (Gargade and Ohol, 2016)

The PIRATE falls under the category of Wheeled Type as the motion of the robot is primarily due to the rotation of the wheels present which is better highlighted by the sketch seen in Figure 2.2 of the PIRATE moving through the pipe.

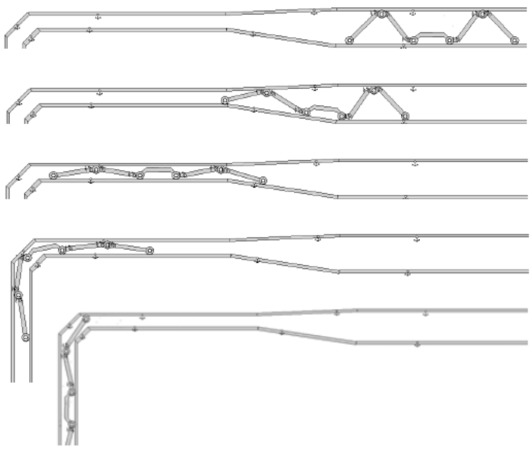


Figure 2.2: A Sketch of the motion of the PIRATE inside a pipe (Dertien, 2014)

AIRO, MAKRO, MRINSPECT and Piko also incorporates the use of wheels to aide in the motion of the robot which is similar to that of the PIRATE(more such examples are shown in the table below). They are built for the purpose of pipe inspection and maintenance checks while autonomously navigating through the pipe. As the environment inside a pipe is dark and as vision based sensing methods are the most commonly used by these robots they make use of LEDs as a source of light. In case of AIRO-2.1 they make use of a single LED light source and a single camera to identify bends in the pipe based on Anisotropic shadow based technique. The pathway of the bent pipe can be estimated by detecting the center point of the shadow based on the orientation of the robot as seen in the Figure 2.3 (Atsushi Kakogawa and Ma, 2017)

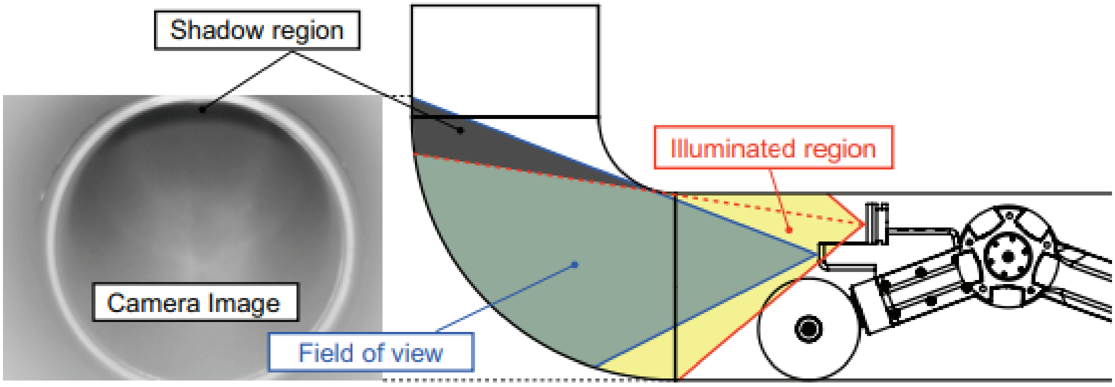
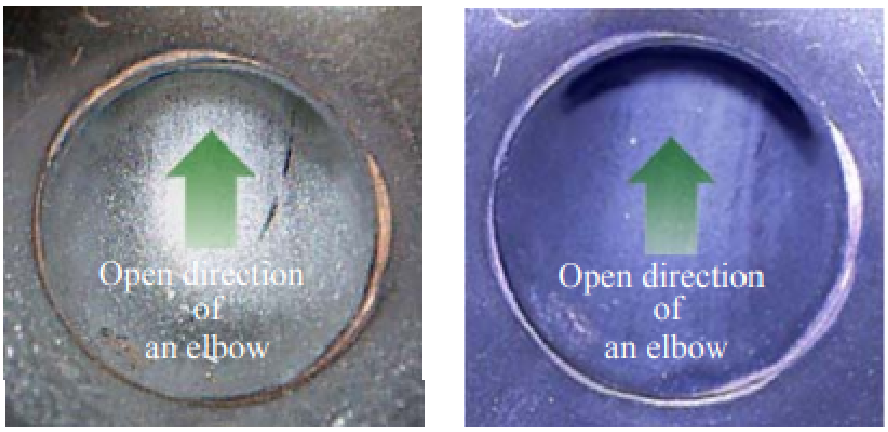


Figure 2.3: Shadow Appearance Principle (Atsushi Kakogawa and Ma, 2017)

MRINSPECT (Multifunctional Robotic Crawler for In-pipe inspection) here a vision based landmark recognition system is used. Bends and branches in the pipe network are termed as landmarks. The front of the robot has an array of LEDs in a circular configuration along with a CCD centrally placed. The shadow obtained is analyzed to detect the landmarks. As seen from Figure 2.4 the type of illumination used in this method also aids in the process of feature recognition. The sensing system researched for the PIRATE also falls under the vision-based sensing techniques as used by AIRO and MRINSPECT based on vision-based sensing (Jung-Sub Lee and Choi, 2009).



(a) (b)

Figure 2.4: (a) Inside the elbow when it is normally illuminated (b) Inside the elbow when illuminated using the method mentioned above (Jung-Sub Lee and Choi, 2009)

Currently available MultiLink Articulated Wheeled robots along with their clamping and movement method has been highlighted in the following Table 2.1 (Kakogawa and Ma, 2016).

Clamping type	Robot	Joint type	Diameter (mm)
N/A	MAKRO & KAIRO	A-O	250
Expandable arm	INSPECTOR	P-P & P-Y (Flexible)	75-750
	Explore	A-P & A-Y	150-200
	MRINSPECT VII	A-P & A-Y	150-200
Body-bending	PIRATE	A-P & A-R	75
	PIPETRON-I	A-P & A-Y (Tendon)	75
	PIPETRON-II	P-P & A-Y	75
	PiKo	A-P & A-Y	250

Table 2.1 Multi-link Articulated Wheeled robots (Kakogawa and Ma, 2016)
Joint Type: mentioned in the table above indicates the different types of joints used category. A-O: Active oblique, A-R: Active roll, P-P: Passive pitch, A-P: Active pitch, P-Y: Passive yaw, A-Y: Active yaw

Figure 2.5 illustrates a few examples of the different types of wheeled robots currently available.

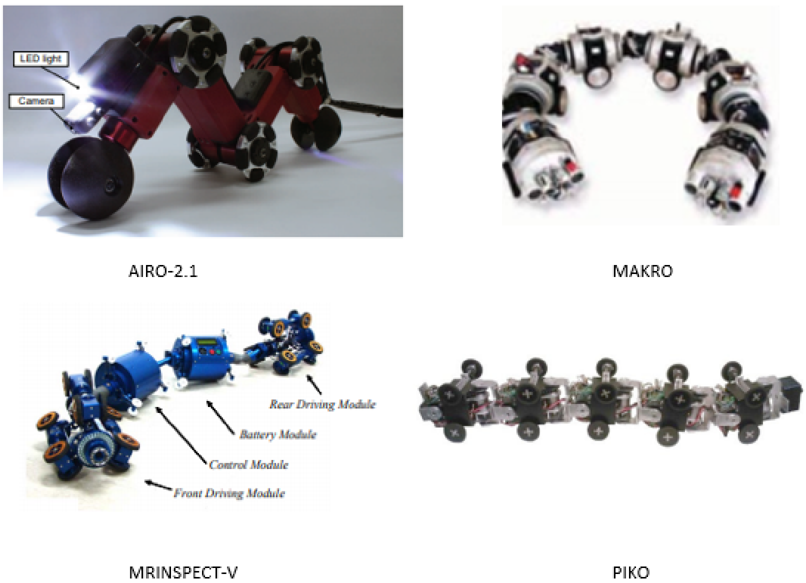


Figure 2.5: Wheeled Type Multi-Link Robots (Kakogawa and Ma, 2016)(Jung-Sub Lee and Choi, 2009)(Hagen Schempf and Crowley, 2009) (Sigurd A. Fjerdingen and Transeth, 2009)

2.3 Feature Recognition

This refers to features present within the pipe network. Features are used to help the robot in terms of navigation and localization of the robot within the pipe network. As gas pipelines run underground throughout the city and are completely closed, this project mainly focuses on recognition of such features within the pipe in a dark and static environment. Detection of these features can also aide in the decision making module of the PIRATE. Features which are considered here fall under two categories: i) Features based on different types of pipe configurations ii) Features based on changes to the original internal structure of the pipe.

2.3.1 Types of pipe Configurations

The pipe networks through which the PIRATE is meant to conduct maintenance checks are made of metal (Floris Taminiau, 2017). The entire network comprises of different types and shapes of pipe connected together. The diameter of the pipe throughout the entire network is assumed not to be constant and can therefore vary based on the requirements. Hence, we consider the diameter to be within the range of 65-125 mm (Dertien, 2014). In this project we are working with 3 types of pipes a) A straight pipe b) A T-junction c) Bend/Curved pipe. This is represented in the Figure 2.6. As the experiments were conducted in the simulation (V-Rep), Figure 4.6 highlights the different types of pipe which are tested during in the experiments.

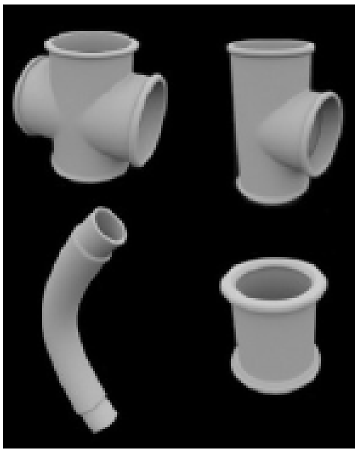


Figure 2.6: Different Pipe Configurations (Kumar, 2019)

2.3.2 Internal structure of the pipe

Any irregularities to the internal surface of the pipes are also considered as features. These include but are not limited to obstructions caused by foreign objects preset inside the pipe or the pipe itself (due to damages which results in a change in shape), corrosion of the pipe which leads to reduced thickness of the pipe and internal and external crack on the pipe all fall under this category. Under this class of features any changes to the pipe from how it appeared when it was first installed are taken into consideration and are defined as features.

2.4 Sensor Selection Process

The above section talks about the detailed description of the functionality and dimensional requirements of the sensors to be chosen for implementation in choosing the sensory systems used in this project. As a first step towards sensor selection, we focus on the method used for sensing. There exist mainly two categories, Contact and Contactless Sensing. Contact based sensing requires physical contact between the sensor and the target object. An example for this is seen in (Liam Brown, 2018) where mechanical feelers are used at the front of the robot.

These are capable of detecting features of the pipe such as elbow junctions but are not very useful in detecting cracks within the pipe. In case of Contactless based sensing, here sensors do not physically come in direct contact with the target object but instead send out signals which reflect off the target area and are received back by the sensor and the measurement is done based on the received signal. These two methods are further illustrated in the following flow chart.

Based on the research conducted, it was observed that the methods mentioned in the below Figure 2.7 were the most widely used in pipe inspection robots.

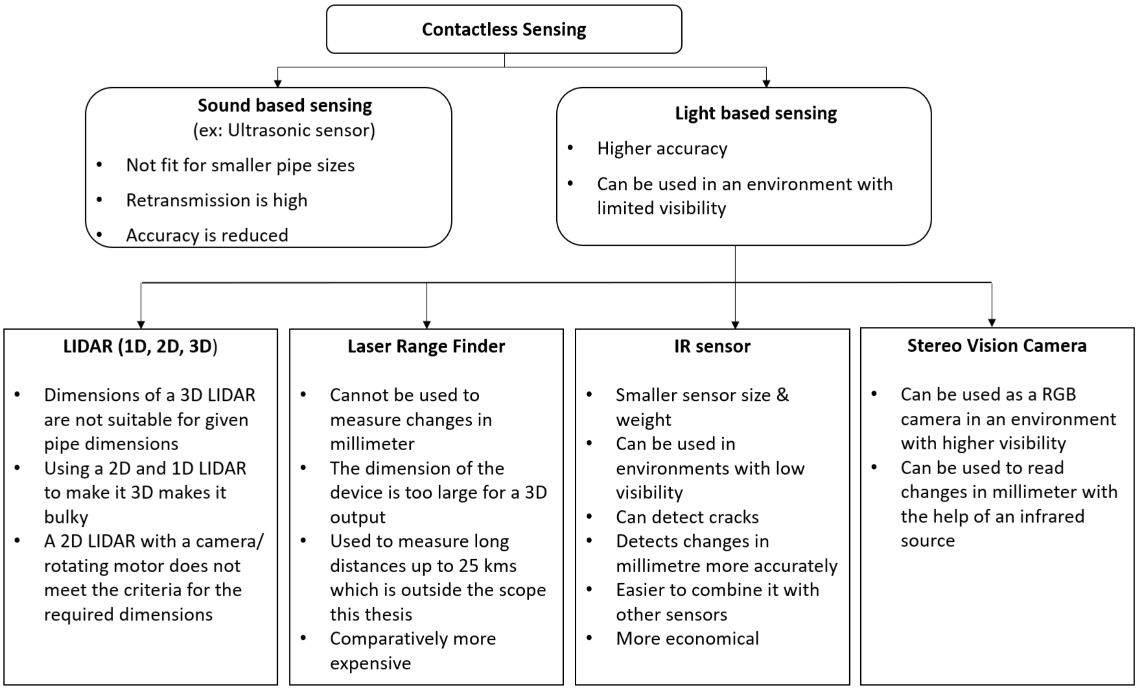


Figure 2.7: Flow Chart for Sensor Selection

2.5 Sensory System

As highlighted earlier, the sensors which make up the sensory system are responsible for identifying the surrounding environment of the PIRATE and location of the PIRATE on a continuous real time basis as it moves through the network. It can consist of either a single sensor or a combination of sensors (Sensor Fusion) in order to obtain the desired output. In this thesis, as later described in Chapter 4 experiments are conducted with two types of sensory systems and their outputs are compared to determine which produces a satisfactory output for the PIRATE according to the necessary conditions/requirements as given in Chapter 3. The two Methods are as described in Chapter 1 Section 1.5

2.5.1 LIDAR (Light Detection and Ranging)

A LIDAR is an active sensor which illuminates its surrounding environment by emitting laser beams. The distance of an object is measured by processing the received signal which has been reflected off of the object. The basic concept of a LIDAR works on the basis of scanning the Field of View (FoV) with one or more laser beams. An amplitude modulated laser diode which can emit a near-infrared (NIR) wavelength of light is responsible for the generation of this laser beam. (Li and Ibanez-Guzman, 2020) LIDARs can be divided into two categories mainly a Scanning LIDAR and a Non-Scanning LIDAR

Scanning LIDAR
It comprises of a laser diode, scanning motor, microprocessor and a receiving sensor. It can further be divided into a single line and a multi-line scanning LIDAR. The laser is continuously pulsed while the scan occurs and the laser's scan rate and its angular width help in determining the angular resolution of the system. A single point detector can be seen in the returning beam which is collected by an imaging optic in case of a a 2D scan and an array of detect ions are observed in case of a line scan. To obtain a 2D output a single line scanning LIDAR can be used as it scans the environment in the x-y direction (or plane). In case of a multi-line scanning LIDAR this combines the scanning conducted on many scanning planes and produces the output by means of a point cloud data.

Non-Scanning LIDAR
As compared to the scanning LIDAR the non-scanning LIDAR has no moving units. This works on the basis of a flash system in which the field of view of 2D detector array is completely illuminated by the laser. An overview of the detection techniques are give in the Table 2.2 (Warren, 2019).

Technique	Type	Strength	Weakness
Direct Detection (PD, linear APD)	Scan & flash	Maturity	Amplifier noise
Photon Counting (SPAD)	Flash & scan	High gain low noise	Background sensitive
Integrating Direct (CMOS)	Flash only	High resolution	Short range
Coherent Detection	Scan only	No background & cross talk	Cost & complexity

Table 2.2 Detection Techniques – LIDAR (Warren, 2019)

2.5.2 Working Principle - Time of Flight

One of the main methods of implementation of a scanning LIDAR is by implementing the time-of-flight principle (ToF) for the required measurements. Various processes whose motion is based on autonomous navigation work on this principle. The distance is calculated by first emitting a single (or a continuous) pulsed laser on to the target. This instantly triggers an internal timing circuit. The distance is calculated by measuring the time at which the pulsed laser was first emitted and the time required for it to reflect off its target and be detected by the receiver. The time difference is denoted by Δt. The distance can be measured using equation(1). The working principle is illustrated in the Figure 2.8.

$$R = 1/2c * n * T = c/2fn = ln \quad \text{—>} (1)$$

R->Distance Measured
c->speed of light
n->clock pulse number
T->pulse interval

f->clock pulse frequency

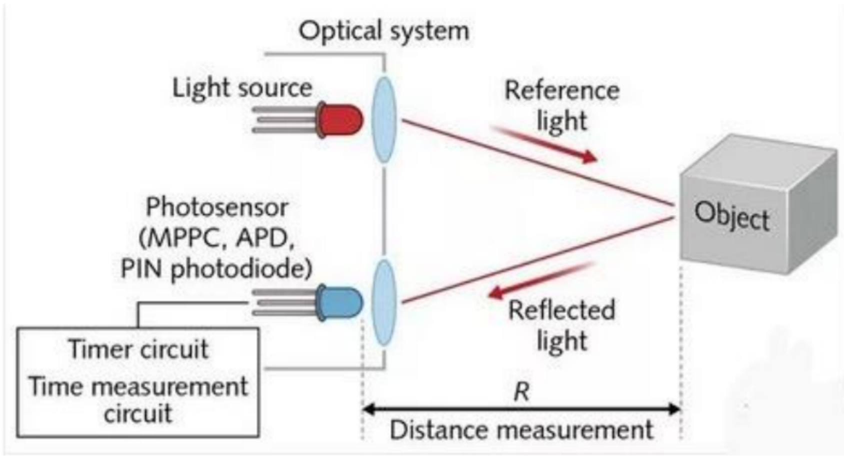


Figure 2.8: Time of Flight (ToF) Principle (J. Liu and Jia, 2018)

This is the concept used in Sensory System 2 which is followed in this thesis to detect features in the pipe network(J. Liu and Jia, 2018).

2.5.3 Pattern Recognition using a Camera

In this section, the method of projecting a pattern onto the internal surface of the pipe and using a camera to detect any changes which occur to this projection is discussed. The different changes in the pattern are analyzed to detect the features of the pipe.

Structured Light Projection

In today's modern technological world, obtaining a real time 3D output has become highly useful as it can be used by various processes especially in the field of autonomous navigation. A system where structured light is utilized, different light patterns are projected onto the scene and then captured using a camera. It then uses the information of the projected pattern on the scene and analyzes it in order to detect any distortions which may have been formed to eventually convert this and recover its 3D geometry. For the data to be acquired on a real time basis the speed of data acquisition and processing should be quite high which helps in applying this method onto various other fields including but not limited to biology, medicine, remote environment reconstruction, security, manufacturing, communication and consumer electronics. Real time basis indicates the steps of acquiring, processing and visualizing of the 3D data to be done at a speed of at least 24 Hz (Bell et al., 2016).

Applications in Pipe inspection robots

In case of pipe inspection robots, as the environment through which the robot is meant to travel is mostly circular the projected pattern is usually a circle. In the research conducted by (Reiling, 2014), (Olga Duran and Seneviratne, 2003), (Tamura et al., 2016) and (Gunatilake et al., 2019), all the papers highlight the use of a circular pattern which is created with the help of mirrors or rotating laser light to form a circular pattern which is projected on to the inner surface of the pipe. Changes caused to the default circular projection is further processed to indicate the changes in diameter, shape, bends as well as cracks and obstacles in the inner surface of the pipe. As seen in the Figure 2.9, any distortions/changes in the circle are recorded and the data is processed to detect the different features of the pipe.

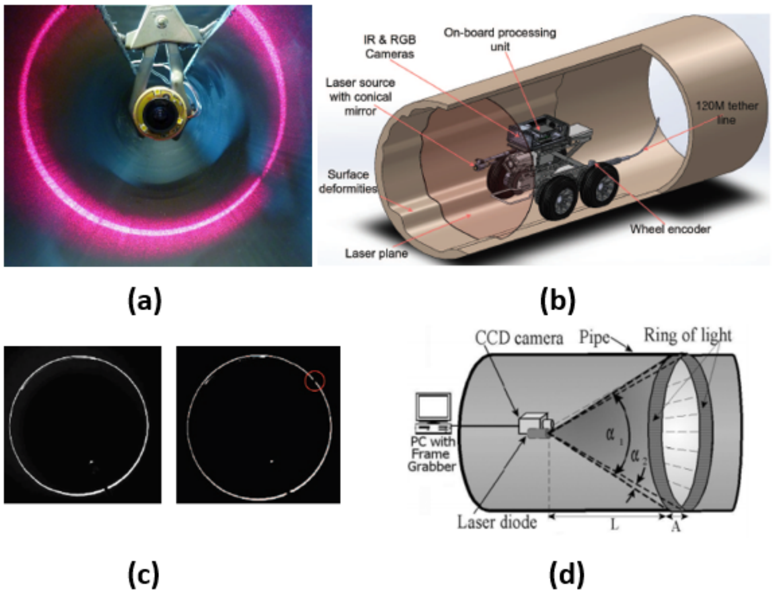


Figure 2.9: Circular Pattern Projection by (a) (Reiling, 2014) (b) (Gunatilake et al., 2019) (c) (Tamura et al., 2016) (d) (Olga Duran and Seneviratne, 2003)

Light profilers are responsible for the projection of circular rings onto the pipe wall which contain both the structural as well as the geometrical information of the pipe. This information can later be extracted with the help of a camera. The two main methods by which a circular pattern can be obtained are i) By using optics such as diffractive points, prisms or mirrors which help in transforming the laser beam into a circular/ring shape pattern ii) Another method is by projecting individual laser beams on to the wall of the pipe and then rotating it so as to obtain a circular pattern (Olga Duran and Seneviratne, 2003)

2.5.4 Camera

Cameras are optical instruments which function as a mode of preserving images seen through their lenses. The aperture (a small opening) allows light to pass through and fall on a digital sensor which aids in capturing the image. The aperture and the lenses are capable of deciding the amount of light which can enter and how the light is focused. Cameras are also incorporated as one of the sensing methods when it comes to navigation of robots and recognizing features in their surrounding environment. (Gunatilake et al., 2019) and (Reiling, 2014) in an environment where the visibility is minimal there is not enough light available for the camera to record images. In this case, it relies on external sources such as a structured pattern.
There exist different types of cameras which can be used based on the information requirement. The cameras are combined with other cameras or other sensing methods to obtain the required information. In (Gunatilake et al., 2019) which is a sewer inspection robot, two stereo vision-based cameras are implemented. A stereo vision IR camera is used to read the IR information from the projected IR patterns while the true colour RGB data is read by the other camera. The advantages of using a stereo vision camera-based system here is in measuring the depth of the laser beam while it moves through the pipe and to remove the need of field calibration. A stereo camera is designed to have similar effects as a human binocular vision which helps in 3D image visualization. MAKRO and KANTARO which are also sewer inspection robots make use of stereo vision cameras for a 3D model reconstruction of junctions and determination of the distance of the robot from various features respectively for the purpose of navigation.

In case of (Drost, 2009) an Active Stereo Vision System was used which consisted of a projector which projected structured light and was identified using a single lens wide angle camera. This is very similar to the method used by (Reiling, 2014) where a single beam in a circular pattern was emitted by a monocular structured light sensor and a wide-angle camera was used to detect this laser beam. Here, a single wide-angle camera is considered which is represented by a vision sensor in the simulation software V-Rep.

3 Analysis and Design

Finding the right sensory system for feature recognition within the pipe brings us one step closer towards automating the PIRATE. As mentioned earlier, feature recognition helps the robot in mapping the environment while also localizing the robot within the pipe (SLAM) which helps in achieving the main end goal, which is performing maintenance checks on the internal surface of the pipe. Before setting up the test environment and conducting experiments, it is important to define the specific requirements of the project. As the research questions have already been defined in Chapter 1, here the conditions/specifications under which these questions are to be answered are discussed. This chapter is divided such that the requirements for undertaking the entire project are discussed in more detail after which the procedure for sensor comparison and selection is highlighted. We further go on to talk about the details pertaining to the software setup and algorithms used for both the sensory systems of Sensory System 1 (Pattern Recognition) and Sensory System 2 (Array of LIDARs).

3.1 Sensor Requirements

As the main goal of this thesis is designing a sensory system, here we discuss the criteria required to be taken into consideration before a design for a sensory system is made. As the sensors are to be placed on the PIRATE and its working environment is inside pipes with custom specifications the sensors are required to meet a few conditions if it is to be implemented. These requirements have been divided based on their priority levels into MustHave, ShouldHave and CouldHave following the MoSCoW method. The requirements to be followed in the simulation are given in Table 3.1a. Table 3.1b sets the additional requirements to be followed while conducting experiments using the PIRATE. The requirements for Table 3.1a are defined keeping in mind the below points:

1. Sensing Method: consists of contact and contactless methods. Contact sensing requires additional structures (example: mechanical feelers) to be added to the robot. This results in a change in the overall design of the PIRATE and could interfere with motion of the robot inside the pipe.

2. Feature Detection: features to be detected within the pipe which would help with navigation and localization of the PIRATE and detection of damages within the pipe.

3. Internal Pipe Diameter: in the actual environment, the diameter of the pipe changes due to which pipe diameter measurement is required.

4. Crack Detection: as the end goal of the PIRATE is to conduct maintenance detection of cracks within the pipe falls under the checks done while conducting maintenance.

5. Working Environment: an actual environment is a closed pipe network which should also be considered here as actual constraints should also be taken into consideration while designing the sensory system.

Requirements	Must have	Should have	Could have
Sensing Method	Contactless Sensing ▪ As this does not require large additional structures to be added to the PIRATE which could result in changes to the design and can influence the motion of the PIRATE		
Feature Detection	• Straight Pipe Detection • T-Junction Detection** • Bend Detection***	Detection from a distance of 2.0m	Measurement of the angle of the bend
Internal Pipe Diameter Measurement	Continuous measurement on a real time basis	Changes in mm must be observed	Measurement of the angle and diameter of the bends
Crack Detection	Identification of cracks on the internal structure of the pipe	Measurement of the length and depth of the crack	Identification of damages to the external surface of the pipe
Working environment	• Static environment • Low visibility	Obstacle Detection	Loop detection

Table 3.1a Requirements to be considered for Sensor Selection - Simulation based Experiments (Dertien, 2014), (Reiling, 2014) and (Kleiboer, 2019)

Requirements	Must have	Should have	Could have
Accurate data	Detect Features in a low visibility environment	Changes in mm must be observed in a low visibility environment	• In the presence of dust • In the presence of moisture
Pipe thickness		Measurement of the pipe thickness	Continuous real time measurement of the thickness
Map of Pipe Network		2D map of the features detected	3D map of the features detected
Field of View (FoV)	Detection of what is ahead of the PIRATE	Obstacle Detection in front of the PIRATE	360 degrees view (detection ahead and behind the PIRATE)
Sensor performance		30-40 frames per second	
Sensor Weight	• Total of 300 grams(as the PIRATE weighs 1 Kg) [1] • Higher weight, higher power consumption (while moving through horizontal and vertical pipes)	A total weight of 200 grams	
Sensor Fusion Complexity		The algorithm should not be too complex which results in feature detection to be too slow thus not providing real time results	

Table 3.1b Requirements to be considered for Sensor Selection - Real Time Experiments (Warren, 2019), (Dertien, 2014), (Reiling, 2014) and (Kleiboer, 2019)

*Straight Pipe: If criteria a or b is met it is determined to be a straight pipe
(a) Open in the front, closed on both sides
(b) closed in the front and on both sides

**T-Junction: If criteria a, b or c is met it is determined to be a T-Junction bend
(a) front-closed and openings on the right and left side
(b) front is open and an opening on either the left side
(c) front is open and an opening on the right side

***Bend/Curve: If criteria a or b is met it is determined to be a bend
(a) closed in the front and has one opening on the left side
(b) closed in the front and has one opening on the right side

3.2 Sensor Comparison

The sensors discussed in Section 2.4 have been used to recognize its surrounding environment in applications such as indoor environment mapping, sewer pipe recognition and landscape mapping to name a few (Gunatilake et al., 2019). For this thesis, the sensor(s) selected must not only be able to detect features within the pipe but it should also follow the set of requirements as mentioned in Section 3.1. Information gathered from the research conducted have been used to better compare the sensors as given in the Table 3.2 which represents a table indicating sensor comparison.

A	B	C	D	E	F	G	H	I	J	K
Priority 1>2>3>4	Requirements	Ultrasonic Sensor	LIDAR 2D	LIDAR 3D	Laser Ranger Finder 2D	Laser Range Finder 1D/2D +motor	LIDAR 2D+ motor	Array of 1D LIDARs	IR Sensor (source+ receiver	IR Source+ pattern+ Stereo Vision Camera +IMU+ Wheel Encoder
2	Sensor size (Overall dimensions)	+ –	– +	– –	– +	– –	– –	+ +	– +	+ +
1	Type of sensing	– –	+ –	+ +	+ –	+ +	+ +	+ +	+ +	+ +
1	Detection of Features in the pipe	– –	+ –	– +	+ –	– +	– +	+ +	– +	+ +
1	Internal Pipe Diameter Measurement	+ –	+ –	+ –	+ –	+ –	+ –	+ –	+ –	+ +
2	Distance Measurement	– +	+ –	+ –	+ –	+ –	+ –	+ +	+ –	+ –
2	Crack Detection	+ –	+ –	+ –	+ –	+ –	+ –	+ –	+ –	+ +
4	Pipe thickness	+ +	– +	– +	– +	– +	– +	– +	+ –	– +
2	Accurate data	– –	+ –	+ –	+ –	+ –	+ –	+ +	– –	+ +
3	Building a map of the pipe	– –	+ –	+ –	+ –	+ –	+ –	+ +	– –	+ +
1	PIRATE visibility	– –	+ –	+ –	+ –	+ –	+ –	+ +	+ –	+ +
1	Working environment	– –	+ +	– –	+ –	– –	– –	+ +	+ +	+ +
2	Sensor performance	– –	+ –	+ –	+ –	+ –	+ –	+ +	– +	+ +
3	Sensor Weight	+ –	– +	– +	– +	– +	– +	+ +	+ –	+ +
4	Sensor Fusion Complexity	+ +	+ +	+ +	+ –	+ –	+ –	+ +	+ +	+ –

Table 3.2 Sensor Comparison

The scores assigned to each type of sensor combination mentioned under columns C to K is assigned based on the priorities of the requirements mentioned in column A and the two sensor combinations with the highest scores are considered for the simulation based experiments in this thesis. All the requirements set in column B do not have the same level of priority, due which column A is used to indicate the requirements which have a higher priority than the others present column A. A four point scoring method (++, + –, – + and – –) has been chosen to rate the different sensors as it indicates not only the best and the worst options but it also helps in determining average choices which could also be looked into if necessary.

Table 3.2 (a) assigns a score to each of the sensors under each category. The ++ = 4, +– = 3, –+ = 2 and – – = 1. The priorities set in column A are to indicate the importance of each of the requirements in a simulation and for implementing this in an actual experimental setup. Based on the details and requirements of sensors as seen in the Table 3.2a, it is seen that the

Sensor Combination	C	D	E	F	G	H	I	J	K
Sensor Score	29	41	37	38	32	36	48	36	52

Table 3.2(a) Sensor Score

methods mentioned in column I and K prove to be the most feasible options available as they satisfy most of the requirements required in this thesis currently and for the overall hardware applications on the PIRATE. Hence, we now proceed towards comparing these two sensory systems to conclude which provides the best output with respect to this project.

3.3 Sensory System Design

Detection of features within the pipe is one of the most important factors when it comes to localizing the robot and in the identification of defects within the pipe.

3.3.1 Sensory System 1: Pattern Detection

Previously, detection using a circular pattern (Reiling, 2014) was experimented on and showed promising results but then there were still a few drawbacks. As positive results were also obtained, it was decided to follow the same concept but with a variation in the process which consists of how the circular pattern is obtained. It was changed from a continuous circular pattern to an array of IR point sources arranged in a circular manner.
To better answer this, the maximum number of sensors which can be arranged in a circular pattern inside the pipe in the simulation is considered.

3.3.2 Software Design

The Python script which runs the detection algorithm helps in detecting the types of pipes present in the network. Here we consider three types of pipes. A combination of the IR point source and the camera is helpful in this case as the surrounding environment is closed with extremely low visibility. The python script uses a function which helps in communicating with the vision sensor used in the simulation. The raw data (initial image) then undergoes a few image processing techniques after which the detection algorithm is run to identify the different features.

Algorithm 1: Detection of Features using a Pattern

Result: Straight Pipe, T-Junction and Right bend detected
Camera/vision sensor detects the circular pattern projected by the multi-point IR source;
The detected image undergoes image processing before it passes through the detection algorithm;
Detection Algorithm:;
while *measured radius is within a defined range* **do**
    Straight pipe detected;
    Continue moving ahead;
    if *Change in radius is seen and blobs are detected* **then**
        Feature is detected;
        (if the radius measured is larger than the default value on the right, then a T-Junction is detected. If the measured radius is lesser on the left and larger towards the right side of the circle then a right bend is detected. If a much higher value is detected then it indicated a crack in the pipe);
    else
        No feature is detected;
        Continue running the program until an output is seen. If no output after 1 minute, the robot has stopped moving.;
    end
end

3.3.3 Sensory System 2: Array of 1D LIDARs

From the previous research done by (Kleiboer, 2019), the technique of using a LIDAR was implemented with the help of a 2D LIDAR placed on a servo motor to obtain a 3D output which made the entire sensory system too bulky to be placed on the PIRATE.

Answering these sub-questions require the LIDARs to be placed in the same position and orientation as the IR sources used in the previous method in section 3.4.1. As the processing is relatively simple and the components are also not too bulky this method was considered as one of the two methods incorporated in this project for feature detection.

3.3.4 Software Design

The simulation is set up with an array of 1D LIDARs arranged in a circular form. We run a python script which uses a function to get the distance measurement from each of the LIDARs. As the system is setup with an array of 1D LIDARs, here we do not incorporate the use of a camera system as well which makes the processing steps easier and faster as no image processing is required.
The circular pattern formed by the LIDARs in the simulation setup is considered to be divided into 4 quadrants. If the distance measured by each of the LIDARs is similar, it detects a straight pipe. If a feature is present, the light from the LIDAR will hit the target and be received back by the sensors with a different distance data as when compared to the rest of the LIDARs. If the distance measurement increases or decreases in any of the quadrants it indicates a turn

(feature) or an obstacle ahead respectively.

Algorithm 2: Detection of Features using an array of 1D LIDARs

---

```
Result: Straight Pipe, T-Junction and Right bend detected
while Distance measured from the each of LIDARs is below the threshold value do
    Straight pipe detected;
    Continue moving ahead;
    if distance measured by a few LIDARs are higher than the threshold value then
        Feature detected;
        (If LIDARs on the right measure a higher distance then the feature detected is a
          T-Junction. If another set of LIDARs on the right measure a higher value, the feature
          detected is a right bend).;
        Detected LIDAR(s) name is read in the detection algorithm and based which LIDAR
          outputs higher values the features are identified;
    else
        No feature identified;
        Continue running the program until an output is seen. If no output after 1
          minute,the robot has stopped moving.;
    end
end
```

For LIDARs the variation in the distance measured values determines the detection of features, obstacles or breaks in the pipe.

4 Design of Simulation Model and Setup

In the previous Chapter we discussed the algorithms and steps to be taken in order to find solutions for the research objectives. As we are comparing two sensory systems to identify which option provides better results, we further test the algorithm explained in the previous chapter in a simulation by conducting various experiments.
This chapter begins with a short description of the software used and the simulation. We later talk about the experimental set up which brings us closer towards answering the research objective. The algorithms discussed earlier for both the methods are tested in the experiments which are further explained here.

4.1 Simulation Design

The top level diagram of the simulation setup gives an overview of the rest of the experiment as seen in Figure 4.1 and Figure 4.2.

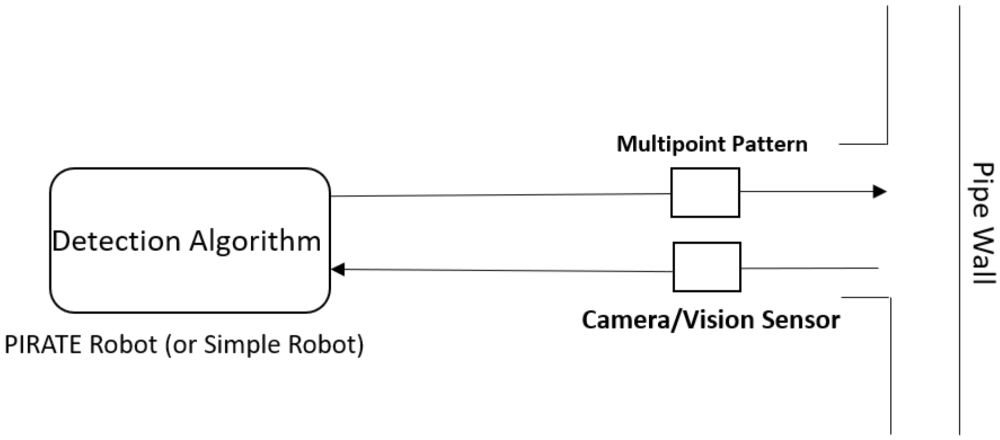


Figure 4.1: Top Level Diagram-Simulation 1

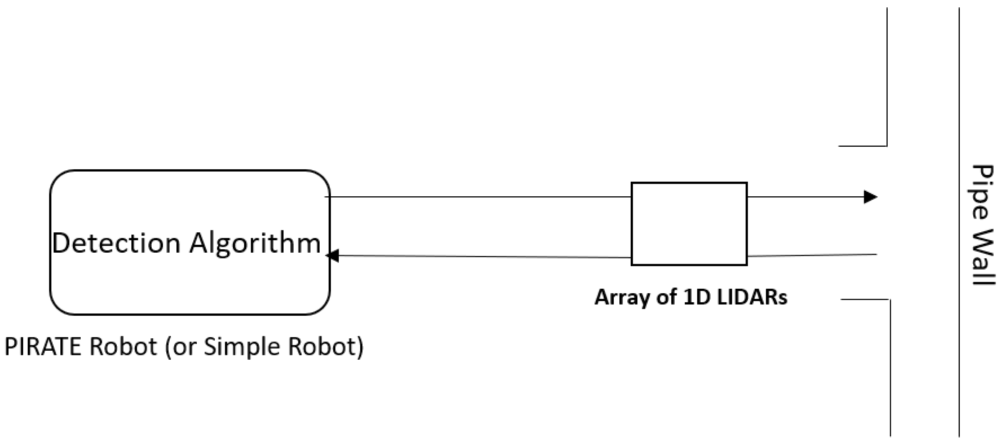


Figure 4.2: Top Level Diagram-Simulation 2

4.2 Simulation Setup

The simulation environment V-Rep is used while testing both the sensory systems. Sensory System 1: pattern recognition using a camera and Sensory System 2: using an array of 1D LIDARs.
The algorithm is tested in V-Rep which is a 3D simulation software. The software is compatible with ROS (Robot Operating System) and so the simulation is run through ROS while using python scripts to control the simulation during the experiments. The version of ROS used is ROS Kinetic along with V-rep version 16.08 and with Python 3.8 which are all supported on Ubuntu 16.04. As discussed earlier, we are testing two sensory systems to determine which provides the best results based on the project requirements. Running the main Python script starts the simulation where it first loads the file which contains the PIRATE along with the necessary sensory system setup which is to be tested.It then runs the build pipe file which builds a pipe network as seen in figure 4.6 in the simulation scene. Once the entire simulation is set up the simple robot (Figure 4.5) starts moving and the experiments are conducted as explained below. The entire Simulation Setup is shown in the Figure 4.6
Here, a simple robot is considered instead of the PIRATE as the thesis focuses on detection of features within a pipe and not navigation of the PIRATE through the pipe network. For mounting and motion of the sensors the simple robot is sufficient.

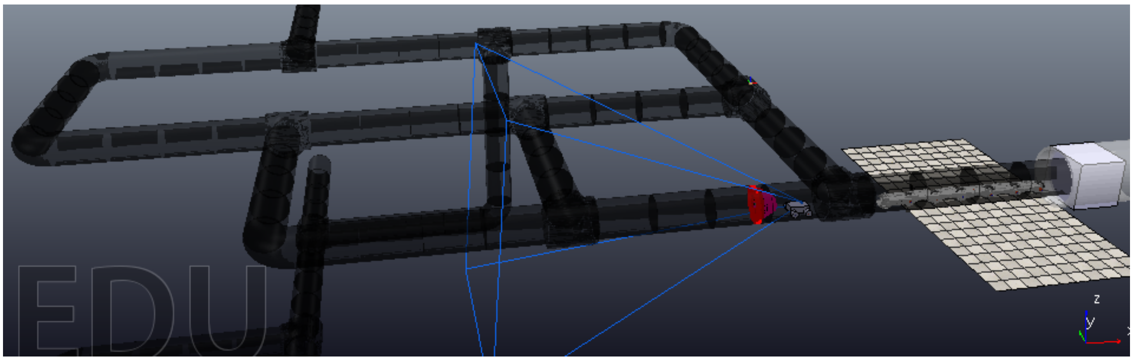


Figure 4.3: Simulation Setup

The Moving Module

Figure 4.4 represents the PIRATE model built in the simulation. Each of the wheel also represents a joint which helps the PIRATE to move throughout the pipe network.
In the experiments conducted for this thesis,as PIRATE itself is not required for detecting features and as navigation of the PIRATE is out of scope for this thesis, a simple linearly actuated robot is used. This is done to give an idea of how the sensors will be placed on the PIRATE (if experiments are done in the future using the PIRATE with sensory system 1 or 2). It is made to move in a straight line path of the network. In this path, it encounters a straight pipe, T-Junction and a right bend. The simple robot consists of a rectangular block which is supported by 4 wheels and this the sensors placed on it. The revolute joints are attached to the wheel and are responsible for the actuation of the robot. It rotates at a target velocity of 100 deg/s (this velocity is set while building the robot in the simulation). As the robot does not move too fast at this speed and the output can be read properly without missing any results as the outputs are seen on a continuous basis while the robot is moving. This is as seen in Figure 4.5.

In an ideal scenario the robot moves in a straight path inside the pipe. As the simple robot is not designed to move through the bends in the pipe (as navigation is not in the scope of this thesis), currently it is not capable of moving through the entire pipe network. The robot is in the default position i.e placed centrally in the pipe while it travels and detects features. The robot

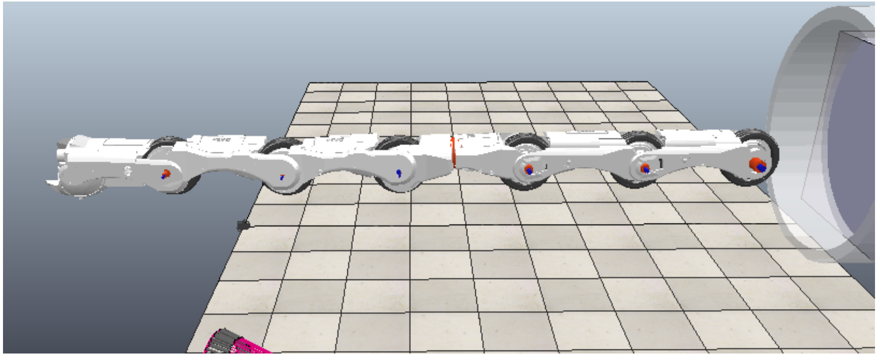


Figure 4.4: The PIRATE

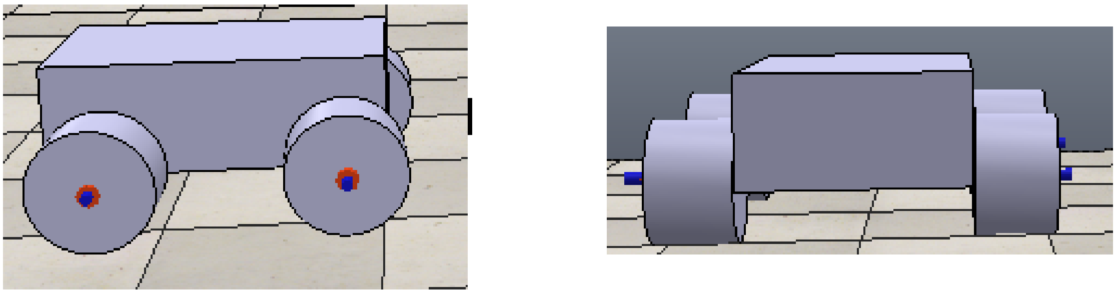


Figure 4.5: Simple Robot

moves from the default position/alignment in the pipe when it moves through a T-Junction as the joint is bigger in diameter which causes the alignment of the robot to change which results in no output being displayed in Figure 4.6.

Figure 4.6: Position of the robot in a T-Junction and in a straight pipe

4.2.1 Common Parameters

A few factors are kept constant in the experimental setup between sensory system 1 and 2. This is done to better compare the results of these two methods taken into consideration.

1. The position and angle of the point source(s) is the same in both the experiments
2. The distance of each of the point source from the basic robot in the simulation is also constant in both the experiments
3. The PIRATE is not used in order to test the sensory systems in the simulation
4. The Simulation experiment for Sensory System 1 and 2 are both initially conducted using 127 point sources/LIDARs. The number 127 is decided based on the circular arrangement of sensors

4.3 Simulation 1: Feature Detection using pattern recognition

This experiment initially focuses on identifying features within a pipe where all the IR point sources (these make up the multipoint circular pattern) are arranged such that it projects a circular pattern on the inner wall of the pipe.
This section is further divided into:

1. Goal: discusses the result which is to be achieved using simulation 1
2. Detection Principle: the simulation technique used for feature detection
3. Simulation Method Implementation: talks about the simulation set-up
4. Image Processing: steps required before applying the feature detection algorithm
5. Feature Detection: algorithm used to identify changes/features in the pipe
6. Minimum point sources: trial and error done by reducing the number of point sources used to determine the minimum number required

4.3.1 Goal

The last part of the experiment focuses on producing similar result with reduced number of IR point sources (pointers). Here, we reduce the number of point sources required to form the circular pattern and conduct tests to obtain the minimum number of pointers required to successfully identify features and provide similar results when compared to the results provided by the first part of the experiment.

4.3.2 Detection Principle: Sensory System 1

The main concept of detection followed here is for the camera to detect changes which occur to the projected circular pattern and process these changes in order to identify the different features within the pipe. In order for the camera to successfully identify these features the below steps are followed. The capture_rgb() function helps in reading the vision sensor data from the simulation using the function SimReadVisionSensor.

4.3.3 Simulation Method Implemented: Sensory System 1

To obtain the circular pattern we use an array of 127 (Laser Pointer0-Laser Pointer126 as named in the simulation) laser pointers (it is set such that IR rays are emitted from these sensors) in a circular form, with each pointer projecting a ray of red light on to the inner surface of the pipe. 127 sensors were chosen as this was the maximum number of sensors which could be arranged in a circular pattern in the simulation setup. This helps in building an overall circular projection on to the pipe wall. Behind this projection at almost the center of the circle, we place a vision sensor which is working as a camera at a distance of 1.5mm away from it. This distance was decided based on tests conducted to check at which distance features are more accurately detected. The vision sensor is placed on the mobile robot while the source pointers are place a little bit away. In a practical scenario the pointers will be attached to the robot at a distance approximate to what is used in the simulation setup. The entire simulation is setup as seen in the figure 4.6.

4.3.4 Image Processing

As the circular pattern consists of small point sources the initial image or the raw data received by the camera consists of a non-continuous circle. The light sources are to be arranged such that the pattern is projected from the source onto the inner wall of the pipe. The function cv2.cvtColor(originalimage, cv2.colorRGB2GRAY) is used in order to convert the red circular image against a black background (of the pipe) into a gray scale image. This step acts as a first step in conducting further image processing techniques. As the pattern consists of gaps/points which could cause issues when features are being detected, the image undergoes dilatation using the function cv2.dialate() which results in filling/adding a structure between the points to form a complete circle. As dilatation adds extra pixels of data around the main image it makes the circle too broad for which we then apply erosion using the function cv2.erode() which leaves us with a continuous circle while removing the non-essential background around the circle. We then set a threshold where the brightest or pixels with values greater than the threshold value are displayed which helps in making the circle more defined. Finally, the blur function is used to filter out the noise.

The Figure 4.7 is the pictorial representation of the images after each processing step. After the all the image processing steps have been completed the final image is used as the input for the next step which is the detection algorithm.

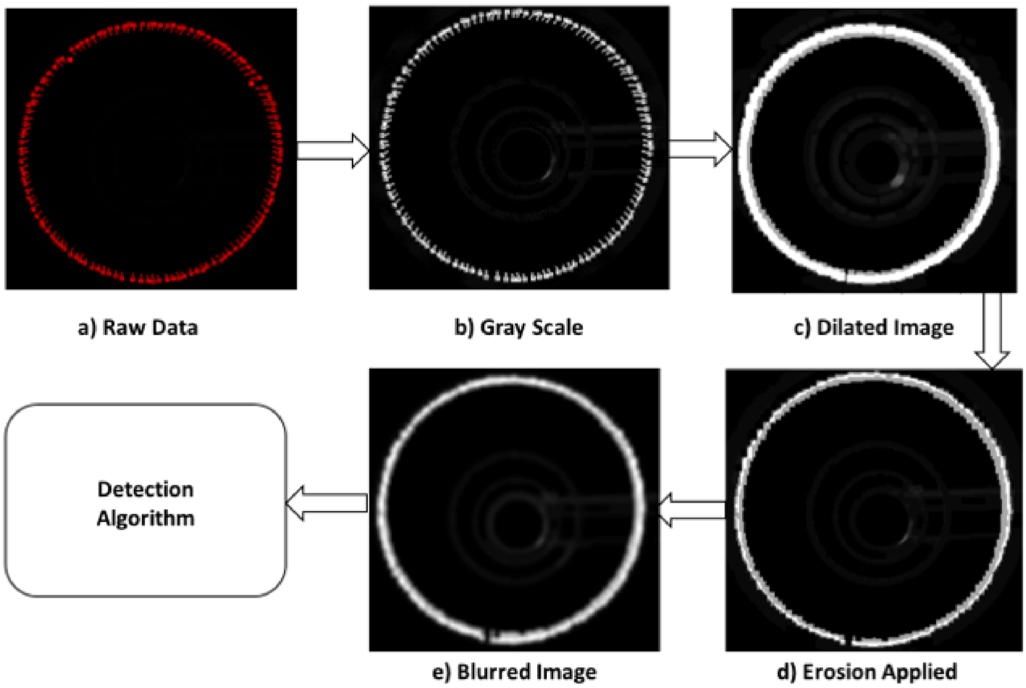


Figure 4.7: Image Processing Workflow

4.3.5 Feature Detection: Sensory System 1

Application of HoughTransform to the final blurred image using the function cv2.HoughCircle() identifies the circle while also measuring the radius and obtaining the center coordinates of the circular projection. Using this function, you can also mark the circle and its center. Let us assume the radius of the circle is said to be ‘r’. The diameter (d) of the circle i.e the internal pipe diameter is twice the radius (d = r2).

$$d = r * 2$$

where d is the diameter in pixels

When the diameter is constant, a straight pipe is detected which indicates that the robot is moving through/will move through a straight pipe ahead. Any other changes observed to the circle are read by the detection algorithm which identifies the feature these changes fall under. If the radius is measured to be higher than a certain defined value the program then runs the blob detection function. The image is first converted into a binary image after which the blobs are detected. Blobs are by default solid figures of a certain area which means any breaks in the circle which leaves unattached (independent) points are detected as blobs. The side of the circle where blobs are detected indicates a break in the circle pattern. The blob detection algorithm is also capable of indicating the location (x and y coordinates) of the detected points. Based on the location and number of blobs along with the distance of the blobs from the center of the circle, we are able to detect if there are any variations to the pipe structure. This could be regarding both object detection or types of pipes. The changes in the radius and the method used to detect the changes are explained with the help of the images below in Figure 4.8.

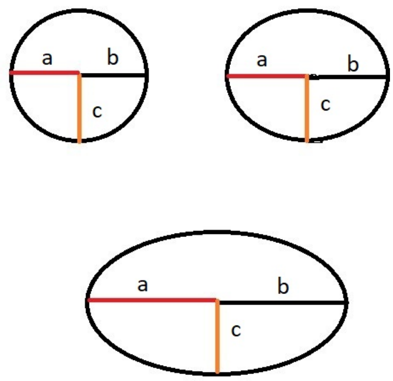


Figure 4.8: Radius Calculation

The figure represents three lines, red, black and orange. Let us consider Red Line = a, Black Line = b and Orange Line = c

As seen in the first figure, if there is a straight pipe ahead, a=b=c which means the length of the line from the center to the three points on the circle is equal. In the second figure it is seen that a>b and a>c, this represents that the pipe is turning towards the left. If b>a and b>c this indicated that there is a turn towards the right ahead. In case of a T-junction we consider both (a and b)>c.

4.3.6 Minimum Point Sources: Sensory System 1

The next step is to gradually reduce the number of pointers previously used in order to obtain the minimum pointers required to detect features within the pipe. This experiment was contin-

uously performed on a trial-and-error basis while reducing the number of points during each test until the most optimum results were obtained in comparison to the first set of tests with all the 127 pointers.
As the detection algorithm works when the circular patterns is continuous, reducing the number of point sources produced a negative output as the circular pattern was not always detected. it was seen that when using 97 pointers (this number was reached by reducing sensors on a trial and error bases and reaching the number of pointers which provided the best results), the straight pipe could still be detected after which no features were detected. The number of sensors were reduced by 30 as this removed an equal number of sensors from the different positions at which the sensors were placed in the circle.

4.4 Simulation 2: Feature Detection using an array of 1D LIDARs

This experiment is divided into two parts, Part A and Part B. The steps followed in Part A is the same as that of Part B. The only difference is the number of LIDARs used are different in both the parts. This section is further divided into;

1. Goal: discusses the result which is to be achieved using simulation 2
2. Detection Principle: the simulation setup used for feature detection
3. Feature Detection: algorithm used to identify changes/features in the pipe
4. Minimum 1D LIDARs: discusses the trial and error done by reducing the number of point sources used to determine the minimum number of LIDARs required

4.4.1 Goal

The 1D LIDARs are arranged in the same positions as that of the point sources in the previous experiment. The end goal of simulation 2 is to find the minimum number of 1D LIDARs required to adequately detect the features within the pipe.

4.4.2 Detection Principle: Sensory System 2

The detection principle followed here is based on the distance measured by each of the individual 1D LIDARs. Based on the variations in the distance measured, different features are detected.

4.4.3 Feature Detection: Sensory System 2

The array of 127 LIDARs is used to detect features within the pipe. The read() function obtains the distance measured by each of the 1D LIDAR(s). If the distance obtained from each of the 1D LIDARs is similar then it is considered to be a straight pipe. If there is larger distance measured by some of the LIDARs in comparison to the rest, then the LIDARs are compared with each other to identify the different features of the pipe. If the 1D LIDARs present in Quadrant 1 and 4 have a different value this detects a feature on the right. If changes are seen in Quadrant 2 and 3, a feature is observed on the left. As this method mainly relies on the comparison of distances measured by the 1D LIDARs this required less processing as compared to the previous method.

Minimum 1D LIDARs Required
The number of 1D LIDARs are gradually reduced and the experiment is conducted where each time the results are compared with the initial results where 127 LIDARs were incorporated until the minimum number of LIDARs required to produce accurate results as obtained from the initial test setup are found. Using this method it was found that a minimum number of 30 LIDARs are required to provide similar results to when 127 LIDARs are used. A minimum of 8

LIDARs can also be used if less accurate results are accepted i.e for each feature to be detected the changed in distance is compared with a lesser number of 1D LIDARs to detect the features.

5 Results and Discussion

In the previous chapter, we discussed the simulation setup used to run the simulation for both the sensory systems. In this chapter we explain and analyze the results obtained. These results are discussed and validated which then helps in answering the research objectives. Based on the literature research conducted it is seen that both the methods prove to be quite promising for this project. We shall now analyze the results for both these experiments and discuss which provides a better solution in regards to this thesis.

5.1 Results for Simulation 1: Feature Detection using pattern recognition

The first simulation was conducted to test the performance of the sensory system 1 (feature detection using a pattern and a camera). These pointers are set such that they are only used as a light source and not as an individual sensor. The default pattern projected is circular and as the robot moves through the pipe, the pattern attached to the robot also moves along with it. Changes to the internal surface of the pipe causes the changes in the pattern which is different from the default pattern as explained in Chapter 4 Section 4.3.2. These changes are observed by the camera and the detection algorithm to detect the features within the pipe.
The initial simulation was done keeping the camera and the pattern at a minimum distance apart (0.5m). Although the diameter and the straight pipe were detected, the features (T-Junction and right bend) were not detected until the robot was almost next to the feature. This could not give the robot enough time for the decision-making process to take place which would be necessary in the future for autonomous motion of the robot. Hence the distance 1.5 m was considered for the simulation to be an optimum distance between the camera and the point sources as the point sources is close enough to the camera for changes in the pattern to be detected and not too close as to not provide enough distance from the feature during detection for the decision-making process to be implemented.
When the simulation starts, the initial position of the robot is already at a T-junction. As mentioned earlier, the joints/pipe connectors are of a bigger dimension and not properly placed, due to which the alignment of the robot gets affected and so it does not return any measurements. When this occurs, initially the program does not return an output or produces unusable outputs.

Camera

In the current simulation experiment conducted we make use of a vision sensor. For a real time scenario we propose to use a webcam as the size and precision of the camera is compatible with the requirements of this thesis. This was also considered as when we look at experiments conducted by (Reiling, 2014) he was able to identify positive features using this camera.

Pipe Diameter

The vision sensor is placed at a distance of 1.4 m away from the the center of the circle around which the light sources are arranged. The camera is placed at the same plane/level as the center of the circle. The only function of the light sources is to provide a pattern for the vision sensor to read and comprehend. As in this case there is an overall data to be read, the diameter and hence the changes to the diameter can be captured/measured with the help of the vision sensor. Although in the simulation the build pipe (simulated pipe network) does not change in diameter apart from the connecting pipe at the T-Junction, when the diameter is measured it varies from a range of 90-110 pixels (radius). This is due to the function HoughCircle which is used to identifies and measure the radius of a circle which is not always consistent as seen in the figures below. The green circle is the output displayed by the HoughCircle function. The circle is white is the multi-point projected pattern, Figure 5.9 (a) displays how pattern should be detected while (b) and (c) display errors which occur during detection. This occurs due to the circular structure of the pipe sometimes getting detected. On an average the image as seen in 5.1b occurs three times during the entire simulation. The break in the circle (marked in red)

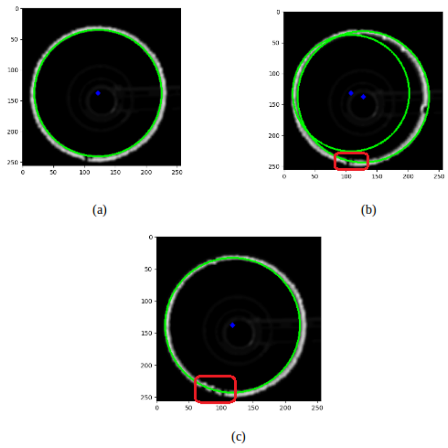


Figure 5.1: Hough3

is seen due to the output from point source component which is available in the simulation. At some points the laser does not emit any ray of light. This is not part of the experiment this occurs due to the working of the component (light source) available in simulation. This will not occur during an actual experiment as the light source will produce an output on a continuous basis.

Straight Pipe

The next step is the robot traveling in a straight pipe. Here, the pipe diameter is continuously measured with a high precision. The measurement is not always accurate as seen in Figure 5.9 as previously explained. As mentioned earlier the pipe diameter is not constant due to errors in HoughCircle detection. The robot detects a straight pipe when the radius is between the range 100-112 pixels. This range was set based on the radius measured while the robot moves through the straight pipe segment of the simulated pipe network.

T-Junction

The experiments are conducted on a T-Junction with a right bend. If the radius of the detected circle increases towards the right but remains constant on the left, it indicates a T-Junction ahead. The blue and green dots as seen in Figure 5.3 indicate the extreme points left and right point of the pattern. This is used as explained in Chapter 4 Section 4.3.5.

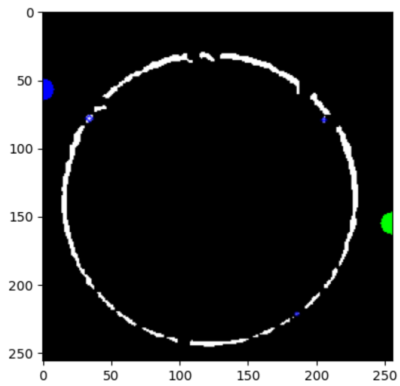


Figure 5.2: Straight Pipe

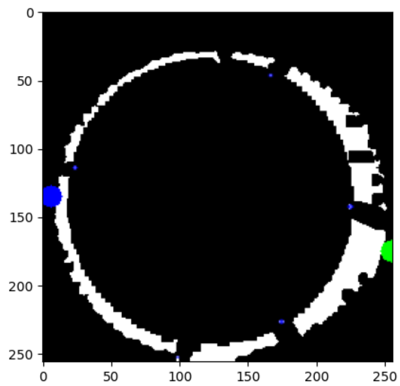


Figure 5.3: T-Junction

Bend/Curve Detection
Similar to the T-junction, the bend is detected based on the radius measured and blobs detected. This is less accurate than T-junction detection.

Figure 5.4 displays the results while detecting features using the maximum number of IR point sources. It is seen that the straight pipe and T-junction are detected but the right bend is not always detected. In case of the straight pipe, there are about 3-5 instances which produces and error and does not detect the pipe. This is because of an error in detection of the circular pattern while using the Hough Transform Function. The radius and changes in the radius (i.e diameter) are detected continuously. From the output it can be concluded that three of the 5 required features can be detected.

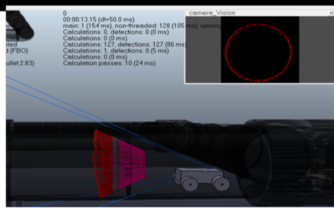
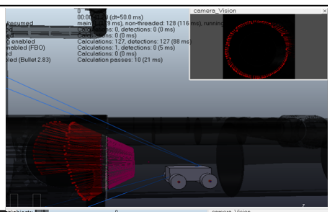
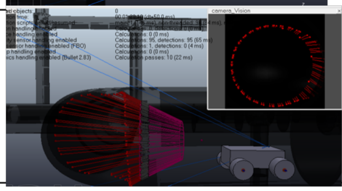
Feature Detected	Output	Camera/Vision Sensor Output
Straight Pipe	109 r Straight Pipe Identified Keep moving forward 109 r Straight Pipe Identified Keep moving forward 106 r Straight Pipe Identified Keep moving forward	
T-Junction	T-Junction Ahead T-Junction Ahead T-Junction Ahead T-Junction Ahead T-Junction Ahead T-Junction Ahead	
Bend	110 r Decision Making Required 110 r Decision Making Required 110 r Decision Making Required 110 r Decision Making Required 110 r Decision Making Required 110 r Decision Making Required	
Radius Measurement	109 r Straight Pipe Identified Keep moving forward 109 r Straight Pipe Identified Keep moving forward 106 r Straight Pipe Identified Keep moving forward	
Cracks	NA	NA

Figure 5.4: Results whiles using the maximum number of point sources

Minimum Number of point sources

We now gradually reduce the number of sensors i.e 30 at a time (the number 30 is considered as these are the number of sensors initially placed to form the circular pattern and then gradually doubled) used and compare the output and have reached a conclusion that 97 is the minimum number of sensors required to detect a straight pipe as other features are not recognized.

As lesser points are used, the HoughTransform function does not detect a complete continuous circle and hence this interferes with the feature detection algorithm used. The results for the simulation experiment using 127 multipoint pattern projection and 97 multipoint pattern projection are as given in Figure 5.4 and Figure 5.5 respectively.

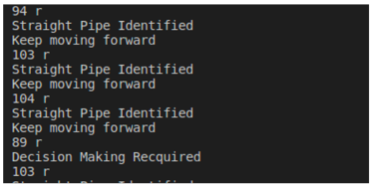
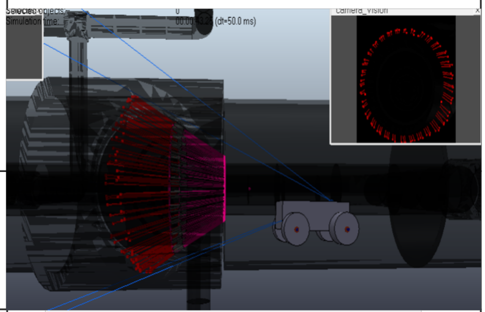
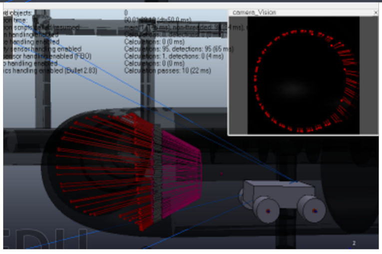
Feature Detected	Output	Camera/Vision Sensor Output
Straight Pipe	 94 r Straight Pipe Identified Keep moving forward 103 r Straight Pipe Identified Keep moving forward 104 r Straight Pipe Identified Keep moving forward 89 r Decision Making Recquired 103 r	
T-Junction	No Output	
Bend	No Output	
Radius Measurement	No Output	
Cracks	NA	NA

Figure 5.5: Results whiles using the minimum number of point sources

5.2 Results for Simulation 2: Detection using an array of 1D LIDARs

The results of the second experiment is compared with the results of Simulation Experiment I in order to determine the method which gives better output results based on the requirements set in Chapter 3. Here, the results obtained from the experiment conducted in Section 4.1.3 to further analyze the effectiveness of using an array of 1D LIDARs to detect features in a pipe. The LIDARs are placed at the same position as the point source in the previous experiment. Keeping as many factors constant in both the experiments helps in better comparison and analysis of both the methods.

Since an array of 1D LIDARs are being used and as discussed in Chapter 2 LIDARs measure the distance from the target object, in this method, detection of features inside a pipe is mainly focused on setting a standard range for the distance obtained by each 1D LIDAR and an analysis of any changes to the output.

Simple Robot

As previously mentioned, the robot follows mainly two alignments 1) default state where the robot moves through the pipe while simultaneously detecting features. 2) Misalignment from the default position i.e when it moves through a T-Junction connection point false/incorrect output is seen in the Figure 4.4.

When misalignment occurs the sensors do not record any data and hence provides 5.0 as the output as defined in the read() function which uses simReadProximitySensor to obtain the sensor output.

Precision

One round of completely running the experiment involves moving the robot from the start position, moving it through two segments of straight pipe, two segments of T-junctions and one right bend. The robot moves at a speed of 100 deg/s for a total time of 8 minutes 34 seconds when the complete experiment is run. To check the precision with which detection occurs, the complete experiment is run continuously for a total of 10 times. Out of which the output was replicated 9 times. Straight pipes were detected without any errors and the T-Junction and bends were detected at a distance of 2.5 m away. The points which provide non usable outputs were also replicated 9 times. This helps in concluding that the overall experiment is reliable 90% of the time. Note: One point to be noted is that the LIDARs are arranged in a circular manner as similar as possible. But it is not possible to arrange all the sensors at the same level due to which some sensors are placed slightly behind the others as seen in the figure below. Due to this, there is always a slight variation in the distance measured by the LIDARs. Which in turn leads to a range of distances which are taken into consideration for feature detection and not one absolute value of distance measurement.

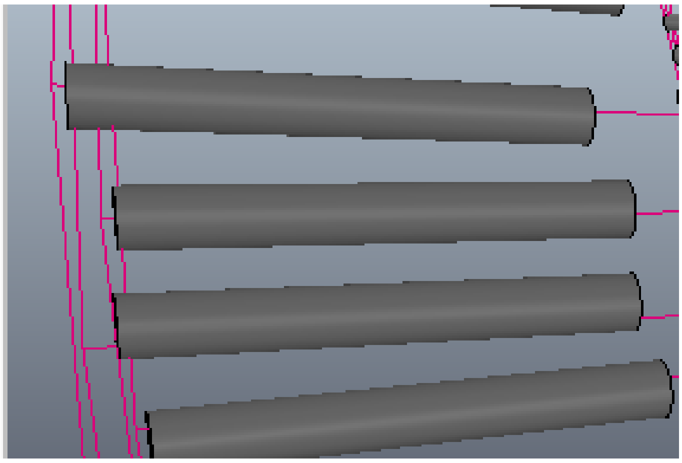


Figure 5.6: Laser

Cracks

In the simulation, cracks are not present in each segment but in between two segments as seen in the Figure 5.7. This is mainly because at junctions the connecting pipe is bigger than the normal pipe. As the cracks are openings the light passes through this there is no target objects for it to detect and hence it output similar results as when the robot is misaligned.
To differentiate the cracks from the data obtained due to misalignment an object has been added at the location of the pipe as a second check in order to confirm that the object identified is a crack and not junk data.

Pipe Diameter

Here, it is quite difficult to find the diameter of the pipe as each pointer gives individual data and the data of each pointer is compared with each other in order to recognize features. Unlike the previous experiment we do not have a vision sensor which looks at the overall data together.

Straight Pipe

The concept where the distance measured by each of the 1D LIDARs should be the same or almost the same is utilized here. Hence, in order to identify a straight pipe, the distance from

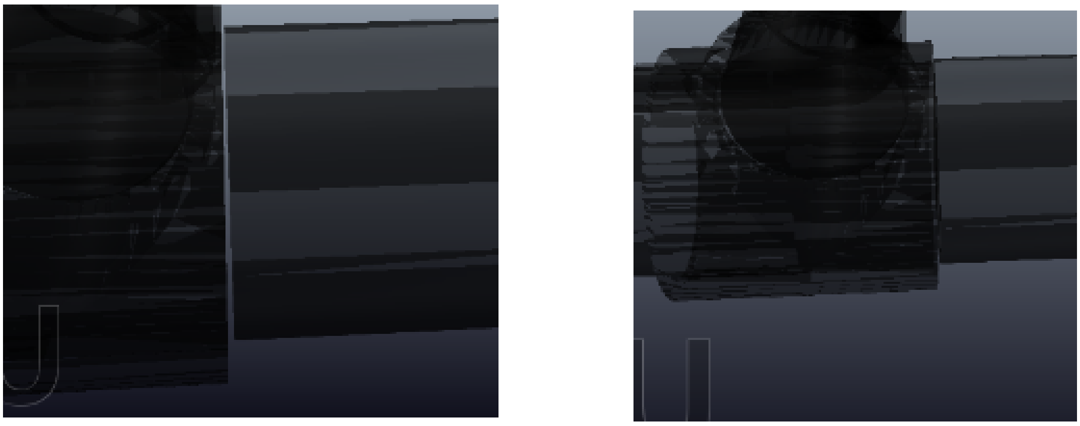


Figure 5.7: Cracks

each of the LIDARs are taken and compared against a threshold. Two straight pipe structures are used to check the efficiency of the algorithm and in both the cases the feature is accurately detected.

Figure 5.8: Laser

T-Junction

The T-junction which is tested here is one which has an opening up ahead and on the right side. Initial detection of the turn is done when the sensor (17) measure a higher distance then the rest. As the robot continues to move ahead, sensors(7,8,9,11,24,39,40,41,43,56,71,72,73,83,88,103,104,105,107,120) also start measuring larger distance values than the default range of values measured. Based on the sensors which measure higher values, the T-junction is identified. The T-junction is not continuously identified, it meanly measures the start, middle and end of the T-junction.

Right Bend

As the angle for the right bent is different than that of the right turn in the T-Junction due to which the sensors (8,40,102,104) measure a larger distance. As the basic robot is not designed to travel thorough bends and turns in the robot, it is unable to make this turn and move ahead and it gets misaligned beyond where it is capable of realigning itself. Figure 5.10 show the results obtained while using a maximum of 127 1D LIDARs.

From Figure 5.11, it is seen that the straight pipe, T-Junction and the Right Bend gets detected. The straight pipe is always detected with no errors. The T-junction and the Right bend are not always detected. Detection of these two features occur at the beginning and end of the feature

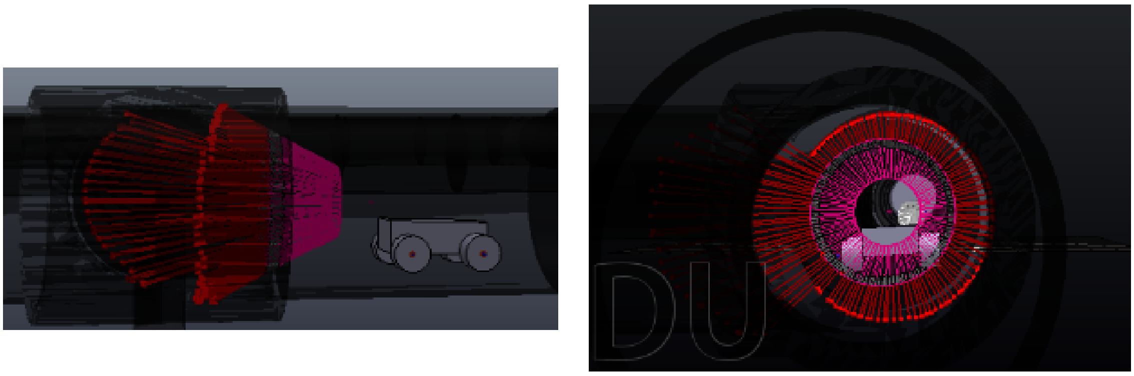


Figure 5.9: T-Junction

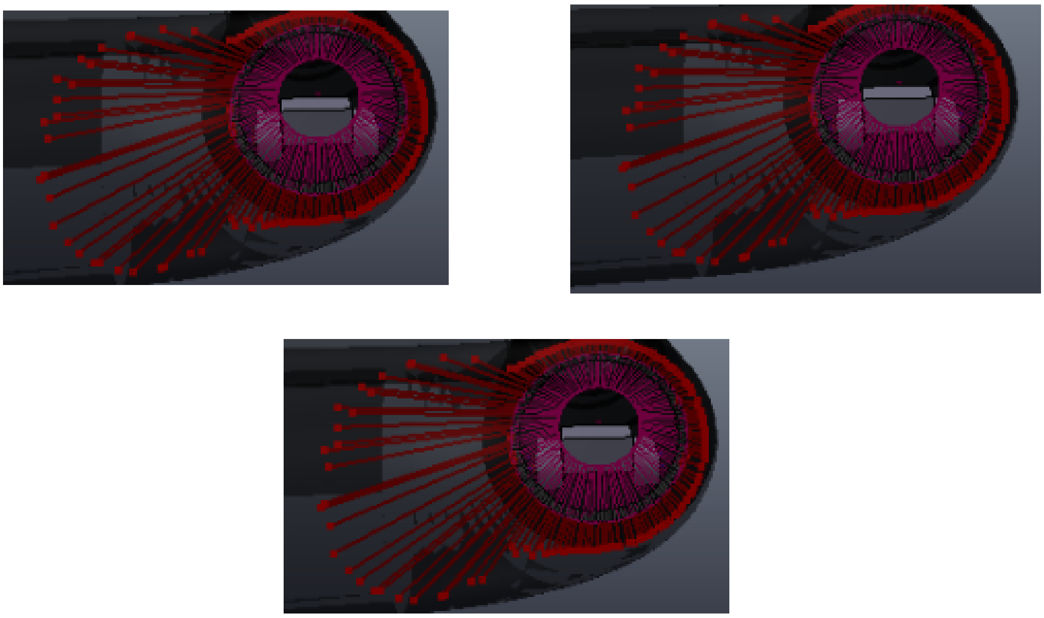


Figure 5.10: RightBend

and once in the middle. From this, we can conclude that 4 out of the 5 factors required are satisfied.

Feature Detected	LIDAR Output
Straight Pipe	{} [] b1 {} Straight Pipe detected keep moving ahead {} [] b1 {} Straight Pipe detected keep moving ahead
T-Junction	{17: 0.500971794128418} T-Junction Ahead. Decision to be made to move ahead or turn {} [] b1 {17: 0.5013346672058105} T-Junction Ahead. Decision to be made to move ahead or turn
Bend	Right Bend Ahead {} [] b1 {1: 1.0103473663330078, 5: 0.7301781177520752, 7: 1.3369928598403 19: 1.0321288108825684, 24: 1.2051631212234497, 27: 0.6809493899 10693, 40: 1.3702528476715088, 41: 1.2925093173980713, 43: 1.1054 6658668518, 65: 0.5921947360038757, 71: 1.390210509300232, 72: 1. 865650653839111, 88: 1.3599886894226074, 90: 0.7163941860198975, 104: 1.3565762042999268, 105: 1.2523088455200195, 107: 1.03453540 2620429993, 123: 0.9225851893424988} Right Bend Ahead {}
Radius Measurement	NA
Cracks	Crack in pipe detected Crack in pipe detected Crack in pipe detected Crack in pipe detected Crack in pipe detected

Figure 5.11: Results when using maximum number of 1D LIDARs

Minimum Number of 1D LIDARs

We now compare the results obtained from the experiment with all 127 LIDARs present and one in which the minimum required number of 30 LIDARs. Figure 5.12 show the results obtained while using a maximum of 127 1D LIDARs.

From Figure 5.12, it is seen that using minimum number of 1D LIDARs it outputs the same results as when the maximum number of LIDARs are used. We can conclude that for the the sensory system which uses LIDARs the option of using the least number of LIDARs is more feasible for the thesis as it produces the same output but with lesser number of sensors which also reduces the overall weight and dimensions of the sensory system.

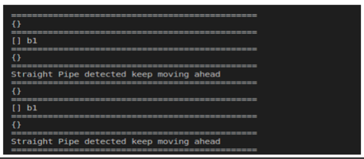
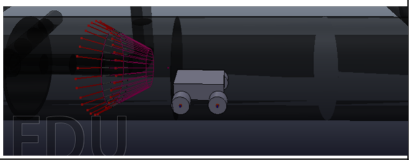
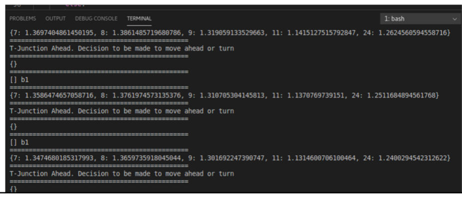
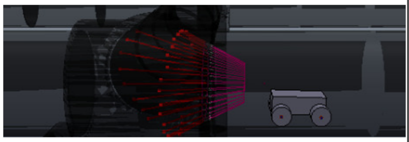
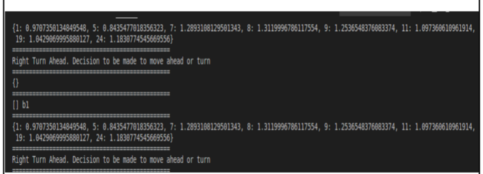
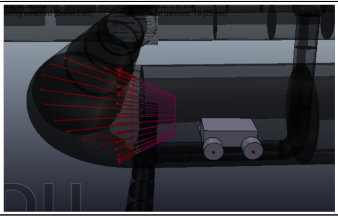
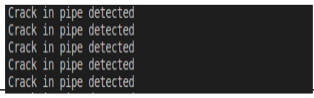
Feature detected	LIDAR Output	
Straight Pipe		
T-Junction		
Bend		
Radius Measurement	NA	
Cracks		

Figure 5.12: Results when using minimum number of 1D LIDARs

5.3 Discussion

In this thesis, the main goal is to design a sensory system to detect features within the pipe. Two detection principles have been proposed as solutions. From the results, it is seen that both the sensory systems have their own pros and cons where each system is capable of detecting a few features better and more accurately than the other.

The feature detection results from both methods can be used to identify features. The pattern recognition does provide a higher amount of inaccurate data that the LIDARs. On further comparing the results, it is seen that when both sensory systems are on their minimum number of points/sensors which can be used, the LIDARs proves to be far more effective as it can provide accurate results with a much lesser number of sensors when compared to the other sensory system. In the simulation which has been tested, features on the right were the main focus. In which case only 12 sensors are required to provide accurate results.
If it is required to test only the beginning and ending of the features, the total number of sensors used can be reduced to a total number of 8 sensors. The important part of this algorithm is that it is more adaptable and can be used on any robot based on the number of sensors it requires which varies based on the accuracy or duration for which the features need to be detected. Currently, for navigation the feature needs to be detected at a particular distance which the current algorithm is capable of doing. As this algorithm is more accurate it is able to detect a feature such that the robot can use this information to navigate through the network. On the simulation it does provide adequate results. A point to remember is that in the simulation the LIDARs were arranged a bit away from the robot and not attached to the robot. This was to have a better comparison of the results of this method with the ones of pattern

recognition. When this method is applied practically, it would have to be attached to the robot with a fixture to the head of the PIRATE such that it is capable of moving throughout the pipe network without causing any damages/obstruction to the process.
From the analysis of the results, it is seen that both the sensory systems individually satisfy different criteria as mentioned in Chapter 3. Hence, a combination of both the methods should prove to be quite helpful. In the simulation, laser pointers are used in both the experiments. In pattern recognition method, all the other features of the laser pointers are disabled such that it acts as only a pattern which can be recognized by the camera but the laser pointer do not have any other separate functionality of their own. In the other experiment the functionality of the laser pointer is enabled such that it is now able to detect the distance of a target object ahead of it by utilizing the Time of Flight (ToF) method as explained in Chapter 2. Using laser pointer where the distance can be recognized by each pointer while they project a pattern which the camera can read seems to provide a more accurate solution than using only one of the two methods discussed. The algorithm will in fact have to be changed a bit here where the data from the laser points can be read to provide a verification of the information received from the LIDARs.

6 Conclusion and Future Work

The main goal of this project was to extract features within the pipe network using the most suitable sensors selected based on the requirements of Chapter 3 Section 3.1. We further deal with this task by using two sensory systems and comparing their results to denote which provides better results for this project. This is done by dividing the main objective into further sub-objectives.

Designing sensory system 1 and 2 in the V-Rep simulation platform

To answer this sub-objective, sensory system 1 within a multi-point circular pattern with a camera and sensory system 2 using an array of 1D LIDARs were set up in the simulation.

Deduce the better sensory system based on the requirements as set in Chapter 3

Here, the sensory systems were tested in simulation using the maximum number of IR point sources for sensory system 1 and and the maximum number of 1D LIDARs in sensory system 2. Both methods were capable measuring the straight pipe and T-junction. But sensory system 2 was better in detecting bends and sensory system 1 was better in measuring the internal diameter of the pipe. Both methods had a repeatiblity rate of 90% as each experiment was conducted continuously 10 times and 9 times the same outputs were obtained.

Finding the minimum number of IR point sources and 1D LIDARs required

On a trial and error bases the number of IR point sources and 1D LIDARs were reduced in each of the sensory systems until a minimum required number to provide use-able outputs was reached. It is seen that 30 LIDARs and 97 points sources were required to detect features.

Obtain the better sensory system from the outputs seen based on points 4 and 5 (as mentioned in the research objectives)

From the simulation experiments conducted and keeping in mind the requirements set in Chapter 3, sensory system is capable of being scaled down and still able to produce desirable outputs. In sub-objective can be concluded such that sensory system 2 with a reduced number of 1D LIDARs is the better option for this thesis.

Find the overall better sensory system (from points 6 and 3 as mentioned in the research objectives) in accordance with the requirements in Chapter 3

As both the systems had almost equal pros and cons when the maximum number of sensors were used and the system using a minimum number of 1D LIDARs provided almost equally good results, for this thesis the system with minimum 1D LIDARs overall proves to be the better system.

All four options discussed provide results where features are detected. But keeping in mind the requirements of this thesis and the salable option of sensory system 2 to answer the main objective to design a sensory system, the final design would be in using sensory system 2 with minimum number of 1D LIDARs.

6.1 Recommendations

This section discusses the next steps which can be taken in order to improve the outputs obtained from the results. Suggestions focused on improving the method by adding additional features to the already existing methods or implementing completely new methods are as discussed below:

6.1.1 Real World Experiments

The experiments conducted in this thesis are only simulation based due to restrictions. Real time experiments on the Jackal which is a differential drive robot and the PIRATE would help in better understanding how the sensory system works in a real time scenario and if the results obtained in the simulation can be replicated in real time.

6.1.2 Using a combination of IMU and an Odometer

Adding an IMU and an Odometer in addition the the sensory system. The experiments conducted focuses on identifying the various features within the pipe but the distance travelled to and from these features are unknown as it is not possible to obtain this information from the current experimental setup. A Wheel Encoder is an odometer which computes the distance travelled based on the number of rotations of the wheel. Recorded data can be incorrect due to the wheel slipping especially while turning. An IMU provides acceleration and orientation data. Using a combination of these two sensors will provide a double check for the distance travelled and an extra check for the orientation of the robot. Hence, this can be implemented in providing information regarding the distance travelled by the robot between two points and also the over all distance travelled by the robot. Obtaining this information increases the accuracy with which the map of the environment is obtained.

6.1.3 Usage of LEDs

The very idea of using a pattern recognition method was due to the lack/absence of light in the environment. Placing LEDs on the robot can help with this issue. As LEDs weigh less and are not very big, this should not add too much stress on the robot and should easily be placed on the PIRATE as well. Having an environment with light brings a higher possibility of using a stand-alone vision-based recognition systems such an independent camera to identify features.

6.1.4 Ultrasonic Sensors

Although ultrasonic sensors were initially rejected during sensor selection in Chapter 3 as they cannot be used for distance measurements in small pipes, they are still helpful in detecting near by objects. Based on research conducted by (Reddy B. and C.M., 2019) ultrasonic sensors are highly effective when it comes to detecting cracks in the pipe. It is also capable of detecting the thickness of the wall of the pipe (Zhao et al., 2010). This information further helps in identifying if the measured thickness is similar to the initial wall thickness during installation or if the walls have been eroded. Determining this value helps in further determining if the pipe requires maintenance. Hence, ultrasonic sensors are highly useful in crack detection and in measuring the wall thickness of the pipe.
In conclusion, both the methods provide similar feature detection results. On comparing the outputs provided by both methods where in the number of points are reduced, it is seen that using lesser number of 1D LIDARs provide results which help in identifying the different fea-

tures efficiently. This method is preferred as it also reduces the weight of the sensors which are placed on the robot.

A Appendix 1

A.1 Sensor Fusion

As mentioned in Chapter 6, a combination of sensor data can provide more information and more accurate results. This is based on the sensor fusion technique. With technology developing at a fast rate the availability of various types of sensors have also increased. This has further led to the requirement of more information from a process which can be easily preserved by humans (Man Lok Fung and Chen, 2017). Hall and Llinas defined sensor fusion as a technique which combines data from various multiple sensors and other associated database information which helps in achieving a greater accuracy with more specific inferences which mostly cannot be achieved by only using a single sensor (Dr.V.S.Krushnasamy and Rashinkar, 2017). Some of the advantages of using Sensor Fusion:

- Representation: The processed information obtained though this method is at a higher level than the original input data set. This leads to a higher resolution and a richer schematic of the data when compared to the information when received from each individual source.

- Certainty: The signal to noise ratio of the output data is estimated to be improved and the probability of the data is also said to increase. These factors are said to increase the reliability of the information.

- Accuracy: The fusion method should help reduce the overall errors in the output and provide a more accurate data. The accuracy can also be related to the timing from the parallel processing of information from multiple sensors.

- Completeness: Different sensors provide various kinds of information which helps in providing a more thorough view of the whole process making the information more detailed and accurate (Man Lok Fung and Chen, 2017). Some applications of sensor fusion technique are in the fields of Automotive and Navigation, Quadrotors and Drones, Computer Vision, Virtual Reality/Augmented Reality and in the field of Healthcare (Dr.V.S.Krushnasamy and Rashinkar, 2017).

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