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MULTI-FUNCTIONAL PIPELINE INSPECTION ROBOT

Master's Thesis

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

This dissertation addresses the computational challenges of robotic applications along with integrating sensors. One of the most challenging fields for robotics applications is pipeline-based applications which have become an indispensable part of life. Proactive monitoring and frequent inspections are critical in maintaining pipeline health. However, these tasks are highly expensive using traditional maintenance systems, knowing that pipeline systems can be largely deployed in an inaccessible and hazardous environment. Thus, we propose a novel cost-effective and a semi-autonomous sensor-based robotic system called Multi-Functional Pipeline Inspection Robot. It combines robot based technologies with sensing technologies for efficiently locating health-related events and allows active and corrective monitoring and maintenance of the pipelines.

The experimental results show that this method could be one of the solutions which can do proactive monitoring of the pipeline.

The English language is used in this thesis, 7 chapters, 35 figures, and 12 tables.

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List of abbreviations and terms

MLF:	Magnetic Flux Leakage
CCD:	Charged Coupled Device
USB:	Universal Serial Bus
IDE:	Integrated Development Environment
AC:	Alternate Current
DC:	Direct Current
I/O:	Input/output
INR:	Indian Rupee
GBP:	Great Britain Pound
USD:	United States Dollar
PWM:	Pulse Width Modulation
SRAM:	Static Random-Access Memory
EEPROM:	Electrically Erasable Programmable Read-Only Memory
SPAD:	Single Photon Avalanche Diodes
VCSEL:	Vertical-Cavity Surface-Emitting Laser
I^2C:	Inter-Integrated Circuit
SPI:	Serial Peripheral Interface
SDA:	Serial Data Line
SCL:	Serial Clock Line
LGA:	Land Grid Array
TTL:	Transistor-Transistor Logic

1 Introduction

Pipes are introduced to the human a long time ago. Everything from water, gases, crude oil, sewage, etc. are transferred from location to another location by means of a pipeline. There are several ways to transfer water, natural gases, oil, sewage, etc. from all these ways there is one which is best for this application is the pipeline. The pipeline has been used from a long time ago by previous civilizations and it remains relevant up to date till current days and will be in future too. Before the pipelines were made of bamboo but growing over technologies in present days it made of plastic, steel, concrete, etc. [1]

As pipelines are of the efficient and economical way to transport water, natural gases, oil, sewage, etc. it requires frequent and proactive inspections from both inside and outside of it which one of the factors for the life of the pipeline. To prevent from any kind of hurt or harm to human or to the surroundings within the event of a leak, or associate explosion, blockage, burst, deformation or sudden stop within the delivery of pipeline systems would also cause shortages in products at the receiving finish of the pipeline and all this result cause financial losses, pollutions, etc. [1]

Figure 1: Problems in the pipeline

There are several methods which have been developed by different pipeline industries for this kind of situation. Since pipelines are confined environments improper to human inspection, robots were developed to gather data and images of pipes. Nonetheless, some interesting points brought up by other researchers in pipe inspection robotic systems gave fuel to develop a specific solution to the general pipe inspection problem. Many existing pipe inspection robots suffer from the fact that they are tethered. While typically this scenario provides more control over the robot, it requires a manipulator on site and has a maximum range dictated by the cable length. [1] [2]

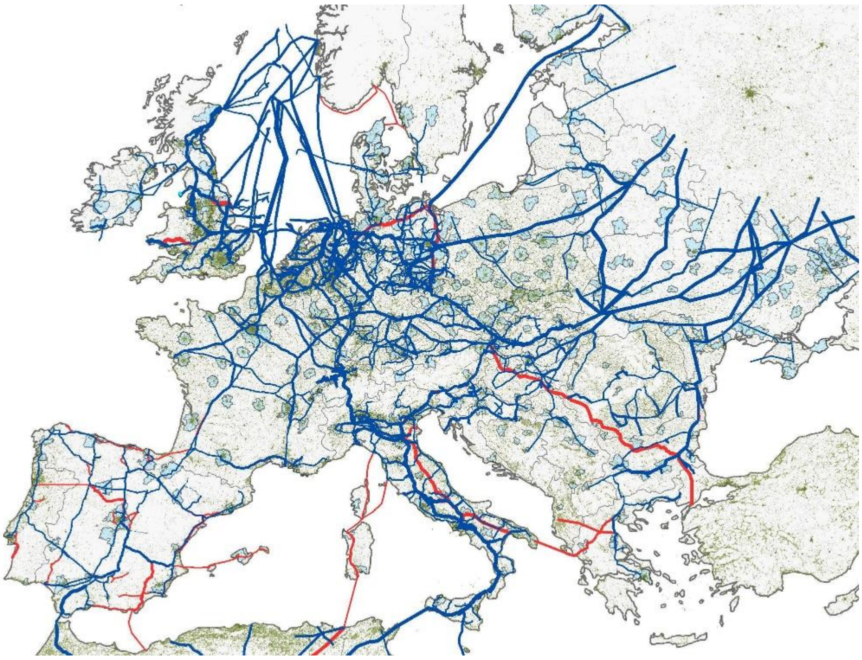


Figure 2: European natural gas pipeline network, blue indicate existing network while red indicates the planned network. (Image source: ETH Zurich)

1.1 Motivation and Objective

Pipelines are presented from a small house to complex industries such as petrochemical. Pipelines are vulnerable to both external and internal aspect such as cracking, leakage, blockage, deformation, etc. which make it lose its functionality. Maintaining pipeline in working condition as natural gas, crude oil, water, and sewer pipelines are a critical aspect because it has been an indispensable part of life. It requires frequent and proactive monitoring and inspection system to make it long term running.

In this thesis, we aim to design a cost-effective pipeline inspection system. This system would allow frequent inspection, early detection of problems, and controllable from a remote location and would perform planned recovery measures such as removing the blockage by drilling mechanism. The system combines with sensor technologies, robot techniques along with communication technologies which all together integrated into the system and goes inside the pipeline for inspection and sending all the parameters to control station.

1.2 Thesis Structure

Chapter 2: Background

This chapter gives an overview of the pipeline and the robot domain.

Chapter 3: Literature review

In this chapter, different sensing and inspection method is briefed and also drive mechanism used in pipe inspection robot is evaluated.

Chapter 4: Market Analysis

Chapter 5: System Design

In this chapter, system requirements, concepts, the hardware used is discussed along with the method of how an inspection is done.

Chapter 6: Experimental Results

In this Chapter, the system is taken under test setup and the result is analyzed and evaluated.

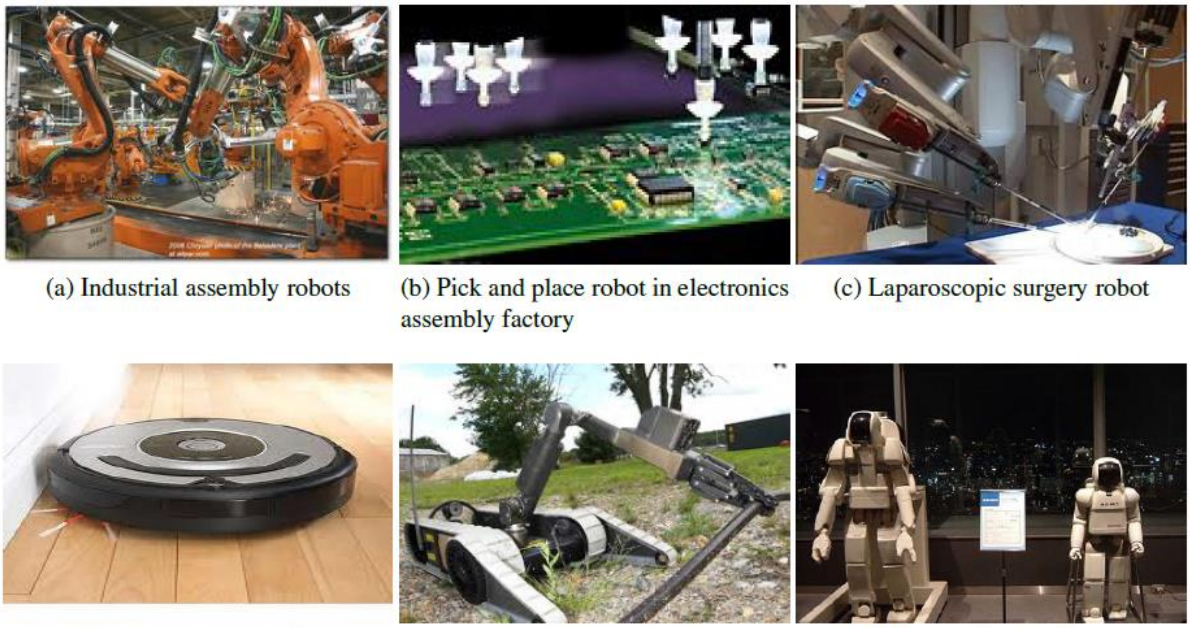
Chapter 7: Conclusion

In this chapter, future work and summary of this thesis are briefed.

2 Background

2.1 Robot Domain

It was difficult to imagine an automatically operated machine which would substitute for human effort, either to appear or to perform human functions. Robot engineering deals by extension with robotic design, building, and operation. A robot is an artificial mechanical or virtual agent that has its own brain. Usually, in practice, it is an electric-mechanical system that transmits a sense that its own purpose or agency by its appearance or movements. The robots are commonly used in commercial and industrial applications and perform precise and reliable rather than human beings. One category comprises tasks that can be more productively, with greater accuracy or durability than people, and the other category involves dirty, dangerous or painful jobs which are unwanted to humans [3]. Some examples of different types of robots, which are currently in service shown in figure 3.



(a) Industrial assembly robots (b) Pick and place robot in electronics assembly factory (c) Laparoscopic surgery robot

(d) Floor cleaning robot (e) Military robot (f) Humanoid robot (Asimo)

Figure 3: Different types of robots working in a different area

2.2 Robot Autonomy Based Classification

Autonomy as the word itself leads to compromise the different types of sensors, additional hardware and computing devices that the robot might need for its complete autonomy. Every robot can be classified as non-autonomous, semi-autonomous or completely self-contained, depending on its functionality.

2.2.1 Non-Autonomous Robots

A non-autonomous robot usually acts as a medium to control the area where it cannot reach the operator. The human operator operates the robot remotely and the robot control signals are normally delivered via a tied-up cable. By examining the output of the sensor data usually pictures from the camera attached to the robot. The human control system determines the conditions in the pipeline under pressure. These non-autonomous robots are generally used for the inspection process of commercial plumbing [3].

2.2.2 Semi-Autonomous Robots

The pipeline evaluation is not entirely left to the human operator in semi-autonomous robots. The robot often has modules, so the robot can perform actions that are normally programmed in advance on the robotic modules. However, the human operator must still issue controls to start these operations. Then the robot becomes semi-autonomous [3].

2.2.3 Non-Autonomous Robots

Compared to other robots, fully autonomous robots are one such field in which the research and development are comparatively less than other robots. A Fully autonomous robot usually includes all required modules to evaluate and process the pipeline condition. These are usually untethered robots so that all controls are transmitted via a radio connection. Robotic navigation and decision on the paths to be followed by the robot are usually controlled on the onboard calculation devices. Each time, the human inspector or an intelligential artificial unit is told all status messages via the radio link so that if adjustments are made, the robot can be communicated so that the robot can adjust those adjustments in the future by the robotic controllers. The data collected can be analyzed on the robot itself and/or transmitted for further processing by the remote inspector [3].

2.3 Pipeline Domain

The robot can be substituted for human robots in many areas; one of the most challenging areas are pipelines. In major utilities, pipelines have long been used. Robots are employed by people over millions of places from big plants to a single house. However, there have been many problems in pipelines such as aging, corrosion, erosion, cracks, and physical damage caused by others. In order to keep the pipelines functional, maintenance is therefore essential and furthermore, the costs for these activities are increased. Even with the problems in the pipeline mentioned above, people still prefer them. The reason is that in the transport of substances through a single pipe, pipelines are used. Liquid and gas are most frequently transmitted via pipes. There are also useful pneumatic tubes to carry solid capsules with compressed air. Like gases and fluids, a pipeline can transmit any chemically stable substance. Therefore, the pipelines exist for water, slurry, and even beer. It can be classified pipelines with this knowledge in relation to the substance that they contain. The materials used in pipes are stainless steel or plastic tubes typically 4 to 48 inches in diameter. The majority of pipelines are buried at a traditional depth of 3 to 6 feet underground. The fluid is kept in movement through the pipeline pump stations, which usually flow at a specific rate. [1] [2]

2.4 Navigation within Pipelines

To maintain their functionality, pipelines must be properly maintained while their material and structural engineering have significantly improved their durability. In addition, because of the increased pipeline length, maintenance costs have risen tremendously. Most sewer pipelines are furthermore buried or concealed within walls to protect them and to cover them up in the surrounding area. The accessibility of pipelines for human maintenance operations is therefore very limited, as many of them are too small to work for humans. Even if it is only a small number once, people do not want both dirty and dangerous to work inside.

Figure 4: Troubles in pipeline failure

Sewerage water, for instance, can be overflowed by sludge or dirty things blocking the sewer pipelines. Blockages from the pipe must be removed in this case. Alternatively, dirty water can spoil all areas by exhaust water. These things can be removed in a number of ways. In the first place, a long stick or wire can penetrate the blocked pipes, but if pipelines are tilted, it is very difficult. Secondly, air pressure may be used to remove blocks, but they do not function when the pipe has drains or taps between the tension and the air pressure starting point. Thirdly, there are excavations on the area suspected of being blocked (Figure 4 shows some examples). The problem here is to find blocked areas and it takes too long and heavy money. In this situation, we can now consider a robot pipeline. If a pipeline robot is able to travel, find and remove this in pipelines, the costs for recovery and time can be reduced significantly. For those jobs, we can avoid manpower. A pipeline robot can, therefore, be a highly recommended solution for the maintenance of the pipeline. [4]

3 Literature Review

In this chapter, various sensing and inspection method will be evaluated. And pipe inspection robot locomotion methods will be evaluated.

3.1 Sensing

In this section, various sensing device which is typically used in pipe inspection is highlighted. Some of them are magnetic flux leakage sensors, cameras, lasers, ultrasonic sensor.

3.1.1 Camera

Pipes are commonly inspected by visual means through a camera. This can be done by having a live monitor that shows the instantaneous images as they are being taken by the camera on the inspection robot or the robot records images and videos during the inspection to analyses later. While these methods are straight forward and arguably the easiest inspection method to implement, they rely on human supervision and therefore have inherent uncertainty.

Figure 5: Pipeline Inspection Robot using Camera

Some advantages of camera inspection of a pipeline include the small size of the device itself and low energy requirement. Newer cameras of small sizes can record good quality images and videos and at a relatively small cost. This makes the camera a good redundant inspection device. It requires little energy and space, at the expense of giving more qualitative than quantitative results.

Some disadvantages of camera inspection are the time required to analyze the gathered results. If human work is required, then the inspection of long pipelines might be costly in time and salary. Also, videos and images tend to take a lot of memory space. Even if digital memory has been shrinking in size for many years, it could be an issue on the untethered robot.

3.1.2 Proximity Sensor Inspection

Pipe distance measurements can also be made using the proximity sensor method. In this method, the theory of light beams is used. More specifically, a laser beam is emitted from a source, bounces on a reflective surface and is returned to a receiver. Thus, knowing the speed of a laser beam in air and the time it took to come to the emitter, it’s possible to get the distance from the sensor to the measured surface [5]. The process is shown in Figure 6.

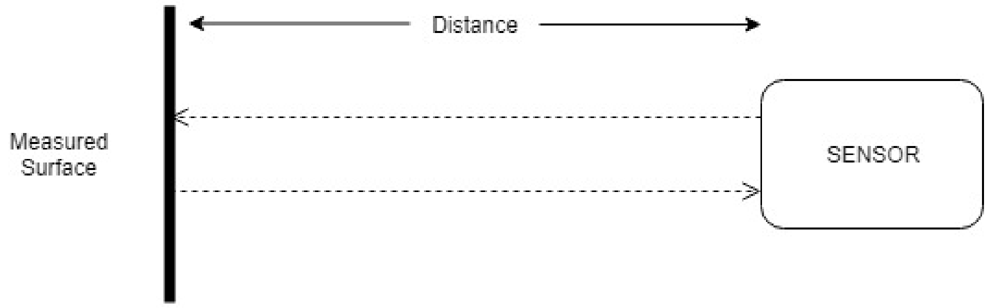


Figure 6 : Proximity sensor measurement principle [1]

However, this method yields only a single measurement data point, the distance of a laser dot from the sensor. Therefore, the idea with this method of inspection to get more data is to have many sensors working simultaneously or have fewer sensors being rotated around the pipe axis to gather data for the whole circumference of the pipe. Similarly, as with the previous method, an encoder is required to know at what speed the robot is traveling to match the measurements with distance traveled by the robot. In many laser sensors are used, then it can get costly and would increase the overall size of the robot. On the other hand, if one laser sensor is rotated around the pipe axis, fewer parts are required, but a motor and an encoder are needed. This method also requires the robot to remain centered on the pipe axis.

3.1.3 Ultrasonic Sensor Inspection

This method, explained by Beller, uses acoustic emitters and sensors to measure the pipe wall thickness, noticing variations where defects are present [6], whether the defects are inside the pipe or outside the pipe as it is shown in Figure 7. The emitted ultrasound will go through the material and bounce back from the outer wall. This echo can also be monitored by the receiver to measure the thickness of the pipe by knowing the distance to the front wall and the distance to the back wall.

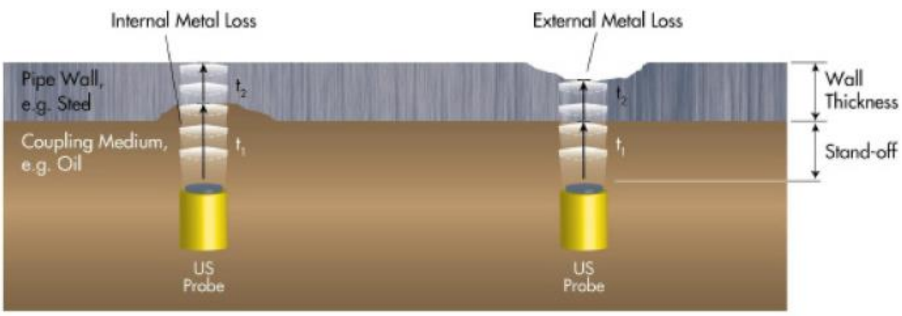


Figure 7: Ultrasonic sensor used for pipe inspection [2]

One of the advantages of this method is that it can be used in almost all pipe environments and materials and can also detect cracks as well as corrosion. However, like laser inspection, ultrasonic sensors get only a single data point at a time of distance to the nearest obstacle. So multiple sensors are needed to gather data in different directions, or the sensor must be moved, which can increase the size or the complexity of the robot. Finally, the ultrasonic inspection can be complicated on curved pipe walls, as the ultrasonic wave tends to bounce off the walls erratically.

3.1.4 Magnetic Flux Leakage Inspection

The quality of a pipeline can also be assessed using magnetic flux leakage technology. More specifically, this technology uses a strong magnetic field to carry a magnetic flux into the pipe wall. The flux created is strong enough so that the pipe wall is saturated, and the remaining flux leaks out. At this point, hall effect sensors measure the density of the leaked magnetic flux as they travel along the pipe with the robot [7]. This method has been used for the inspection of pipeline wall from within and from the outside on exposed pipelines [8].

Generally, robots that use this method of inspection to inspect from within using a circular array of hall effect sensors distributed evenly around the pipe axis. These sensors then measure the variations in the magnetic flux. If the wall of the pipe remains of even thickness, the flux density stays the same. Therefore, if there is a change in flux density, it means that the material is thinner or thicker. So, these variations in thickness can possibly mean erosion in some parts of the pipe or damage or a weld joint for instance. The intensity of the flux leakage is proportional to the change in thickness, or to the size of the gap if there is one. The magnetic flux leakage technology allows the measurement of a pipeline quality without the need for propulsion since this method works even when the fluid in the pipeline is flowing. However, it also comes with a loss of control over the speed of the robot and therefore also on the resolution as well. Typically, large robot gathering data using magnetic flux leakage carry multiple sensors to counter this limitation, which is not possible on small robots inside small pipelines, because of the lack of physical space. Lastly, MFL technology works with magnetic fields and is necessarily limited to ferrous pipelines.

3.1.5 Laser Inspection

Laser inspection technology makes use of lasers to inspect or measure the interior of a pipe. This can be done in different ways. The laser can be projected on a cone and then be reflected on the pipe wall [9] or by actually filming two lasers being projected on the pipe wall at different angles [10] or by using a laser proximity sensor to detect the distance between the robot and the wall, [5], among many other methods. Even though all these methods make use of lasers, their data collecting methods differ greatly. Two methods will be explored in further details.

Conical Triangulation One way to measure the quality of a pipe interior with a laser is with conical triangulation. Is this method, a laser beam is reflected on the surface of the pipe using a conical mirror and the resulting ring of light is analyzed through a camera. The process is illustrated in Figure 8.

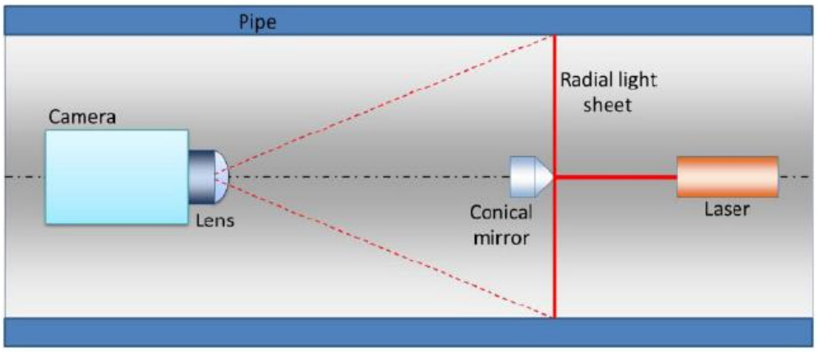


Figure 8 : Principle of conical triangulation [5]

This method has been used to evaluate the quality of a pipe interior [9] [10]. This method links two methods of inspection in one. A laser beam is projected on a surface and a camera gathers the data. This method can be precise to less than 1 mm but necessitates some other important details to function properly [11]. The robot moving through the pipe must be perfectly centered with the pipe axis and the laser beam must be reflected exactly at a right angle to the pipe surface to take useful data. Otherwise, the ring of light would be distorted and yield poor results. In addition, a camera usually gathers images that are distorted and needs calibration. It's possible to see how a typical image is distorted by a camera lens in Figure 9.

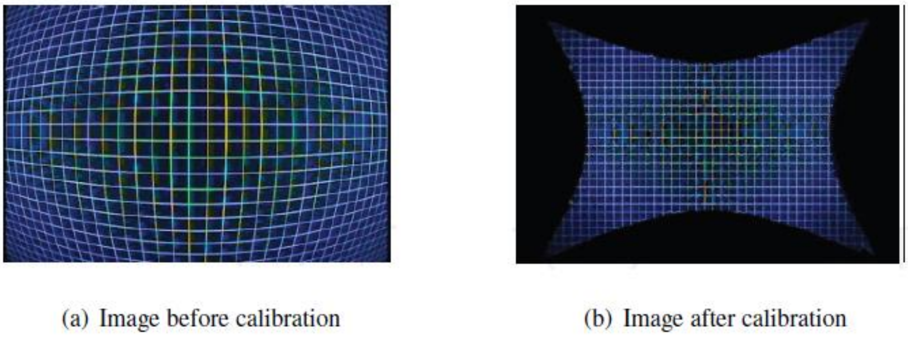


Figure 9: Typical camera image calibration process [6]

Also, typically on these robots, an encoder measuring the distance traveled by the robot is used to tell the robot to take a picture of the ring of light after a certain distance to get data that are evenly spaced. However, encoders are susceptible to slippage of the wheel and some other sort of encoder would need to be used independently of the wheel encoder to measure the traveled distance of the robot. So even though this scenario requires many parts and critical adjustment, it gives very precise data that can be analyzed rapidly.

3.2 Robot Architecture and Locomotion

This chapter is based on the study of different types of robot locomotion architecture used in pipeline inspection.

Over the past few years, there has been a lot of development on pipe crawling robots and man y researchers
have come up with very different ways of powering and steering their robots in pipes. The main concepts of design are the line, the wheel triangle and the track triangle. In addition, some other original designs were suggested and will be discussed. Since the designs studied above all address the same problem of efficiency, other research has been done on the subject to incorporate wheels into these designs to maximize efficiency during long journeys inside pipes. These designs are separated in two different categories: Vehicle robot [12-18] or Train robot [19-21].

The main difference between the two robot types is their number of wagons or sections. A vehicle robot only has one driving section or module, whereas a training robot has multiple sections each equipped with the same locomotive device. Both have their advantages and inconveniences. Usually, vehicle robots are lighter and more efficient while they can be limited in the type of environment in which they can be placed. Under difficult conditions, such as a 90-degree L - turn or T - junction in a pipe, The main advantage of a train - like a vehicle is that it can be driven by other wagons when the first wagon or head wagon faces such a situation. The following section presents the different design ideas or architectures surrounding wheeled robot.

3.2.1 Line Type Robot

The line type robot is a design consisting of an opposite set of wheels providing the robot with traction, as shown in Figure 10. This slender design allows more space and good steering capabilities to mount cameras on the side [14]. This design can also be adapted to different pipe diameters and is highly versatile as some obstacles in the pipe can be avoided. It preferably requires spring loaded arms and DC motors on both sides. In addition, this structure is rather simple and open and thus has room for other components, such as sensing devices. The most prominent foreseeable problem with this design is the possible difficulty faced in a pipe bend by this type of architecture. In sharp corners or other such scenarios, the low number of contact points between the wheels and the wall may cause singularity configurations.

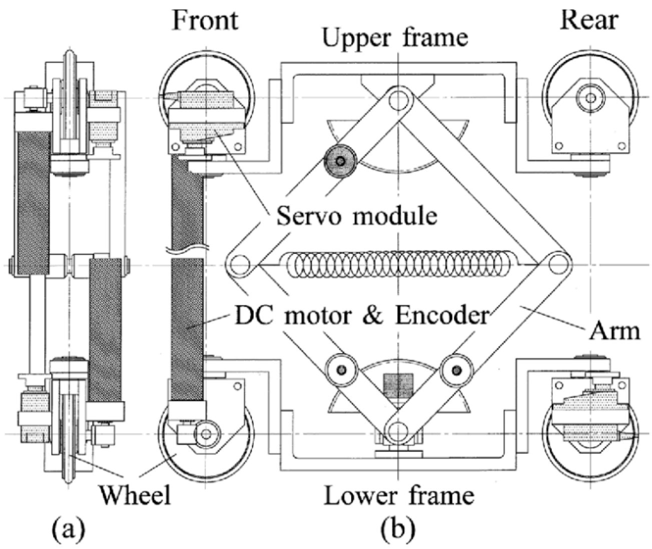


Figure 10: Line Type Robot [14]

3.2.2 Three wheel type robot

Similar to the type of line, the triangle design is more common. It consists of three wheelsets equally 120 degrees. This concept was developed by many various researchers [13] [22] [23]. Figure 11 shows an example of a wheeled triangle robot design. They share many advantages as it is the same general idea as the previous line type. The addition of an extra set of wheels, however, necessarily increases the number of robot components and size. The tracked triangle style [24] [25] [26] is another variation of this subcategory of robots. Tracks are used in this design instead of wheels. The use of tracks enables almost any type of pipes to be inspected as they can handle damaged pipelines, large obstacles and different diameters [16]. This can be done because tracks are less efficient than wheels at the expense of more energy consumption. Otherwise, this design has similar characteristics to the wheeled triangle design: it can adapt to different diameters, carry sensors and if desired, can be used as a training robot.

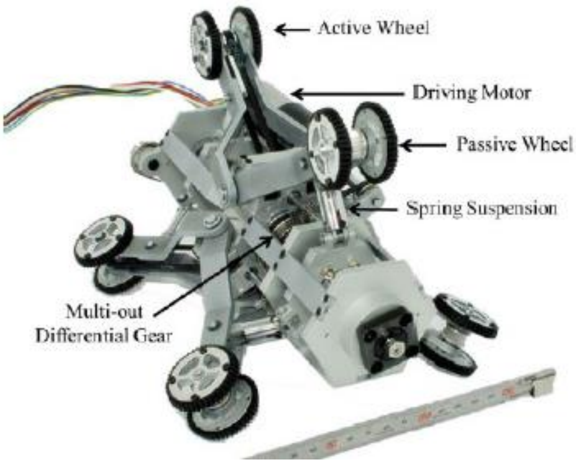


Figure 11: Three wheel type robot [23]

3.2.3 Four-wheel type robot

Some designs with four wheels are also built. These robots gain stability but are less energy efficient as there is one more wheel on the pipe wall that causes friction and requires continuous loading of multiple springs to adapt to different configurations of the pipe. This design may be useful in situations leading to possible unique configurations as more wheels may stay in contact with the wall. However, this very flexible design comes with the drawback of possibly being more difficult than other designs to use as a train - like a robot. Mostly because there are four directions where the robot can move. However, if multiple instances of this design are not impossible to connect to travel inside the pipeline. This design is also not meant to go Along the pipe axis. Although this is not a problem in itself, if onboard sensors need to be aligned with the axis of the pipe, it may cause problems. This design, on the other hand, can adapt to different diameters of the pipe and has room for certain sensors.

4 Market Analysis

In this chapter pipeline inspection robot from three different companies are evaluated in terms of price and feature.

4.1 Auto PTZ Pipe Inspection Robot

Figure 12: Auto PTZ Pipe Inspection Robot [27]

This solution is made by Shenzhen JTECH CO. LTD, China. This solution cost for one unit is $ 35000 is equals to € 30762.39 (1 USD equals to 0.90 Euro, exchange rate was taken from www.xe.com on 01 May 2019). This solution is used for pipe size ranging from 300 mm to 2000mm. It is used to measure holes, other abnormalities and also generates 3 dimensional XYZ data of pipeline using CAD software. It is applicable in sewage pipeline, gasoline pipeline and nuclear pipeline [27]. Product specifications are formulated in the table below.

Feature	Detail
Model Number	JT-C300
Sensor	CCD
Waterproof	IP68
Camera Head	90 mm electrical PTZ camera
Image Sensor	¼ Sony CCD
Display	12 inch Touch Display
Controller	Joystick controller box
Working Voltage	24 Volt
Working Temperature	-20°C to 55°C
Creeping Speed	35 m/min
Battery Type Used	Lithium
Battery Backup	5 hours
Connection with a control station	Cable

Table 1: Features of Auto PTZ pipe inspection Robot [27]

4.2 Pipe Line Inspection Robot Crawler

Figure 13: Pipeline Line Inspection Robot Crawler [28]

This inspection robot is made by Oaasa Technology, West Bengal, India. The solution cost of one unit is Indian rupees 550000 which is almost equal to € 7061. (1 INR equals 0.013 Euro, exchange rate was taken from www.xe.com on 01 May 2019). It is suitable for pipe having a diameter ranging from 150 – 800 mm. it is used for both wet and dry underground or overhead pipelines, duct line or tunnels. The exact temperature and moisture of the working environment can be felt. The ratio of carbon monoxide gas (CO), methane gas (CH_4), LPG, alcoholic dangerous fumes that are present in the operating environment can be analyzed. Fire & smoke can also be detected in the field. In the presence of fire, the fire alarm is activated. Water or dust can be cleaned or pumped off [28].

Feature	Detail
Sensor	Camera, Gas, Temperature
Working Voltage	12V / 24V DC or 220V/230V
Working Temperature	-20°C to 60°C
Crawler Weight	5 Kg
Battery Charging	9 to 10 hours
Battery Backup	8 hours
Connection with the control station	Cable
Storage Disk Device Size	500 GB to 1 TB
Crawler Body Material	Stainless Steel / Aluminum Alloy
Crawler Peripherals	Local Control Station : Hi-Speed Processing PC (1 Unit),Cable Station : Cable length 100 meter (1 Unit) ,Charger : 3 Units. (220AC / USB / Solar)

Table 2: Specification of Pipeline inspection Robot [28]

4.3 VT100 Vertical Crawler

Figure 14: VT100 vertical crawler [29]

Produce by Inuktun Services Ltd, Canda and price quote by this company for this product is £125,000 which is equal to € 144834 (1 GBP to 1.16 Euro, exchange rate was taken from www.xe.com on 01 May 2019). VT100 Vertical Crawler can perform complicated inspections in almost all directions across a range of pipe sizes. Independent track control allows the vehicle to easily travel over distances of up to 180m/600 ft in multiple bends and vertical pipe segments. High-quality video captured by onboard cameras is complemented by auxiliary LED lighting, and real-time sensors show tube dimensions and expansion power. Built of anodized aluminum and stainless steel of marine quality, the VT100VC is extremely durable and fully submersible for underwater uses [29].

Feature	Detail
Depth Rating	30m / 100ft
Maximum Tether Length	180m / 600ft
Maximum Speed	9m / 30ft per minute
Vehicle Payload	up to 18kg / 40lb
Front Facing Camera	Spectrum 45
Optional	Rear-facing Mini Crystal Cam® camera
Operating Temperature	0°-50° C / 32°-122° F
Vehicle Weight	10kg / 22lb
Vehicle Dimensions	437mm / 17in length with variable diameter depending on pipe size

Table 3: VT100 vertical crawler Specification [29]

5 System Design

This chapter describes the system design, overview of the system, major hardware proposed in system design.

5.1 System Requirements

Two main activities should be carried out by a pipeline monitoring and maintenance system. First, it inspects the health of the pipeline and reports to the control station(s) on a regular basis. Second, it helps to restore the health of the system from any leakage, damage, or corrosion. It is necessary to maintain pipelines regularly. Maintenance costs, however, continue to increase, as well as the pipeline scale. Thus, the following requirements should be fulfilled by a cost-effective and scalable pipeline monitoring and maintenance system:

- It should be scalable: since most pipelines could extend over thousands of kilometers, it should work for any pipeline length and topology and should be regardless of pipeline characteristics (for example shape, size, material) and topology. The systems should also be designed to be scalable.
- The system should be easily customizable: a generic solution for various applications, such as health surveillance for a wide range of pipeline types, should be provided with minimally activity and modification.
- The system should be vibrant. The system should include capability and software that enables the pipeline to be dynamically inspected and that problems can be detected in a practical way. It should provide solid performance in order to address the variability of possible problems.
- Proactive control and recovery measures should be implemented: before any faults occur, the system can identify any faults in the unhealthy pipeline under control. It should be able to analyze incidents correctly and take swift action to recover.
- The power consumption of the system should be kept to a minimum: the components of the system should provide for efficient communication and data transfer activities which will consume low energy.
- The system should be cost-effective: the system should reduce the pipeline monitoring and servicing, operational and maintenance costs. System components should be low-power general purpose tools, able to transfer and receive data relating to events, and able to take simple physical measures to achieve cost-effectiveness.
- Efficient localization techniques are to be implemented in the system: Efficiency requires that the inspection and incident discovery entities in the pipeline are able to identify incidents with controllable mistakes and themselves.
- The major system components should be independent: the main system components should function autonomously and work together. During the implementation of their tasks, they should not be controlled manually. We should not rely on external energy and should have enough energy to fulfill tasks.

Feature	Detail
Movement	Horizontal
Operating DC Voltage	5 to 12 V
Pipe Size	150 mm to 600 mm
Operating Temperature	-40 to 100°C
Operating Pressure	5 PSI to 100 PSI
Data Transfer time	Less than 10 millisecond
Data transfer through	Universal Serial Bus Cable
Protection	IP68
Driver Mechanism	Chain-track belt drive
Control Anatomy	Semi-auto
Visual Inspection	Camera
Battery Backup	Should be not less than 5 – 6 hours

Table 4: System Requirements

5.2 System Overview

The proposed system consists of multiple sensors for inspection of the pipeline from inside. The major inspection function of this system consists of deformation detection, leakage or crack detection, blockage detection controlled over wire along with data transfer from a control station. System design is more focused over electronics design along with rover type localization for movement inside the pipe. The system also consists of a drill mechanism for removing the small blockage. In order to thoroughly inspect detected incidents, the robot can stop and reverse motion in the pipeline.

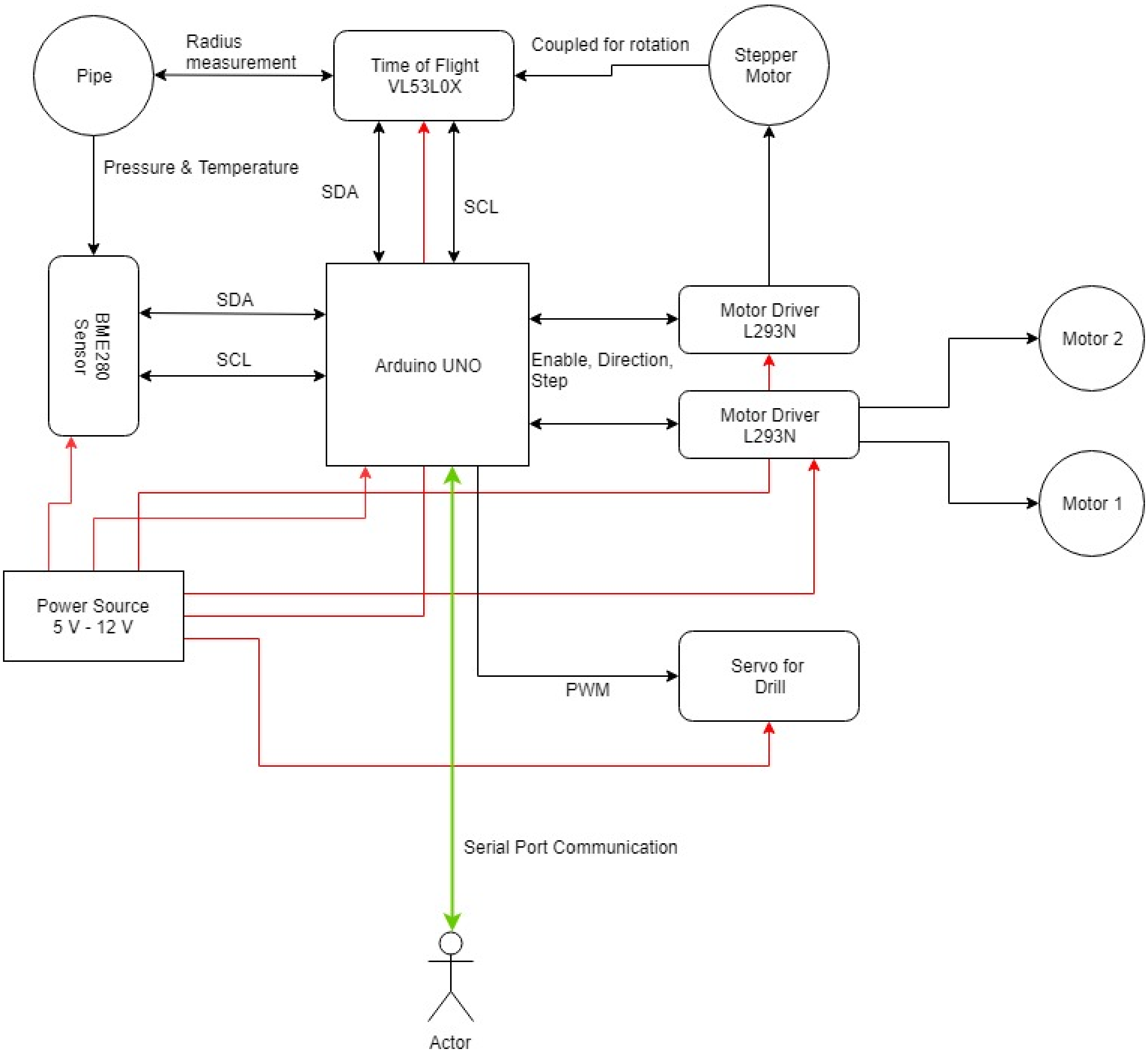


Figure 15: Block Diagram of System Proposed

The above block diagram shows the overall system proposed. The user can communicate with Arduino over USB and send the command to do all the task and also control the movement of the robot. It consists of two L293N one to the driver stepper motor and another for the locomotive function of the robot.

5.3 Hardware required for the proposed system

This proposed system consists of the following hardware

- Arduino Uno
- Time of Flight Sensor (VL53L0X)
- Pressure and Temperature Sensor (BME280)
- Motor Driver (L298N)
- Servo Motor (FS90R)
- Stepper Motor (NEMA 8-size)
- Zumo Chasis Kit
- Geared DC Motor

5.3.1 Arduino UNO

Figure 16: Arduino Uno [30]

Arduino is a company which design and produce signal-board microcontroller for building an embedded system, it is open source hardware and software. Arduino UNO board is based on 8-bit AVR microcontroller ATmega328P.Arduino boards can be programmed by with Arduino Software IDE. ATmega328P comes with preprogrammed with a bootloader which allows uploading code without any use of an external hardware programmer. Arduino Uno communicates using the STK500 protocol [30]. Technical specification of Arduino UNO is listed in Table 5.

Feature	Detail
Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	7-12 V
Digital I/O Pins	14 (of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz

Table 5: Arduino UNO technical Specifications [30]

5.3.2 Time of Flight Sensor (VL53L0X)

Figure 17: VL53L0X sensor and Breakout Board [31]

Time of flight sensor is based on laser-ranging and uses an infrared signal to measure the distance of the object, based on the time difference between the emission of a signal and its return to the sensor. With the help of this absolute distance of 2 meters can be measured. VL53L0X is designed by STMicroelectronics, integrates SPAD array. It is 940 nm VCSEL emitter, coupled with internal physical infrared filters it enables longer ranging distance, higher immunity to ambient light, and better robustness to cover glass optical crosstalk [31]. Evaluation board consisted of VL53L0X is used in this system which is made by Pololu Robotics and Electronics. Technical specification of VL53L0X is listed in Table 6.

Feature	Detail
Package	Optical LGA12
Size	4.40 x 2.40 x 1.00 mm
Operating voltage	2.6 to 3.5 V
Resolution	1 mm
Operating temperature	-20 to 70°C
Infrared emitter	940 nm
I^2C	Up to 400 kHz (FAST mode) serial bus

Table 6: VL53L0X Technical Specification [31]

5.3.3 Pressure and Temperature Sensor (BME280)

BME280 is an integrated environmental sensor which is capable to measure temperature, pressure, and humidity in an 8 pin metal lid 2.5 x 2.5 x 0.93 mm^3 LGA package, manufactured by Robert Bosch GmbH. Full site operating modes provides the flexibility to optimize for power consumption, resolution and filter performance. The sensor provides both I^2C and SPI data transfer protocol. Block diagram of BME280 is shown in figure 12 and technical specification is tabulated in table 7.

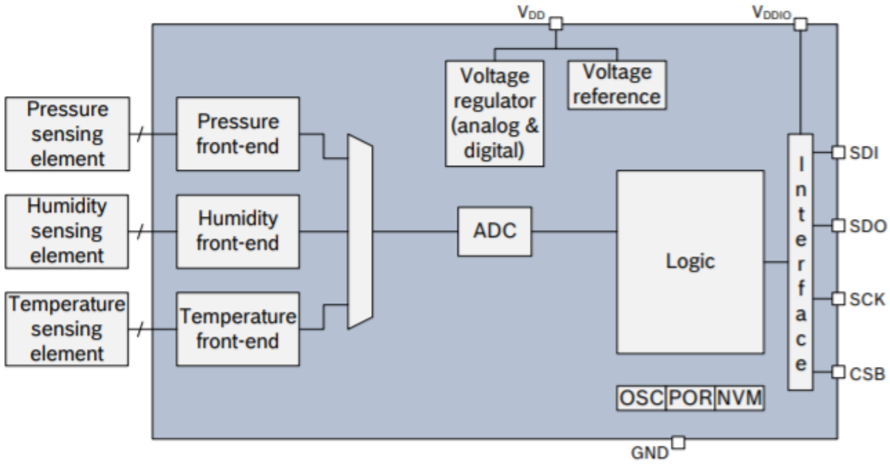


Figure 18: Block Diagram of BME280 [32]

Feature	Detail
Operation range (full accuracy)	Pressure: 300 - 1100 hPa Temperature: -40 - 85°C
Interface	I²C and SPI
Supply voltage V_{DDIO}	1.2 - 3.6 V
Supply voltage V_{DD}	1.71 - 3.6 V
Average current consumption (1Hz data refresh rate)	2.8 µA @ 1 Hz (P, T)
Package dimensions	8-Pin LGA with metal 2.5 x 2.5 x 0.93 mm³

Table 7: Technical specification of BME280 [32]

5.3.4 Motor Driver (L298N)

L298 is an integrated monolithic circuit in a 15- lead Multiwatt and PowerSO20 packages. It is a high voltage, double-powered fully bridge driver designed to support standard TTL levels of logic and drive inductive loads like relays, solenoids, DC, and motors for steps. There are two allowable inputs that allow or disable the device regardless of input signals. The emitters of each bridge's lower transistors are joined together and the appropriate external endpoint can be utilized for an external sensing resistance connection. Additional input is provided to allow the logic to function at a lower tension. [33]

5.3.5 Servo Motor (FS90R)

Figure 19: FS90R Micro Continuous Rotation [34]

The FS90R is a servo micro-sized, which was specifically built by the FEETECH servo for continuous rotation. The servo can be controlled via the direct connection to a single I / O Line microcontroller. The resting point default is 1.5 ms. [34]. Below table gives technical specifications of FS90R.

Feature	Detail
Operating Speed	110RPM (4.8V) 130RPM (6V)
Stall Torque	1.3kg.cm/18.09oz.in(4.8V) 1.5kg.cm/20.86oz.in(6V)
Operating Voltage	4.8V~6V
Control System	Analog
Operating Angle	360degree
Required Pulse	900us-2100us

Table 8: Technical Specification of FS90R [34]

5.3.6 Stepper Motor (NEMA 8-size)

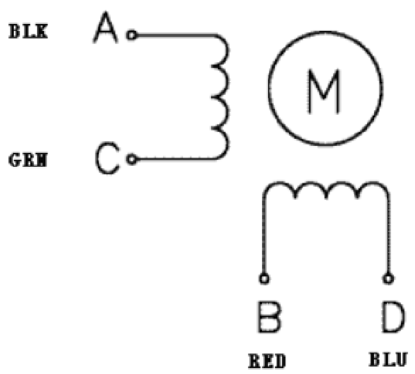


Figure 20: stepper motor winding [35]

This is a small hybrid bipolar stepping motor with a step angle of 1.8 ° (200 steps/revolution). The holding torque at 3.9 V is 180 G-cm (2.5 Oz-in) at 600 mA in each phase. The motor has four bare-leaded color-coded wires: black and green connect to one coil; red and blue connect to the other. An appropriate H-bridge (one for each spiral) can control the motor [35].

Feature	Detail
Shaft Type	4 mm “D“
Current Rating	600 mA
Voltage Rating	3.9 V
Holding Torque	2.5 Oz.in
Steps Per Revolution	200
Resistance	6.5 Ohm
Inductance Per Phase	1.7 mH

Table 9: Specification of Stepper Motor [35]

5.3.7 DC Geared Motor

Figure 21: DC geared motor [36]

This is miniature brushed dc geared motor, used in this system for localization of the robot inside the pipeline. This motor consists of 75:1 gear ratio made of metal gear. The shaft of the transmission shaft is 9 mm long and 3 mm in diameter. It has a cross section of 10 X 12 mm [36]. Specifications of this motor are shown in Table 9. The performance curve of this motor is shown in figure 22.

Feature	Detail
Gear Ratio	75.81:1
No-load speed @ 6V	410 RPM
No – load current @ 6V	1.6 A
Stall torque @ 6V	1.3 kg.cm
Max output power @ 6V	1.4 W
Max efficiency @ 6V	40 %
The speed at max efficiency	340 RPM
Torque at max efficiency	0.23 kg.cm
Current at max efficiency	0.34 A
Output power at max efficiency	0.80 W

Table 10: Specification DC geared motor [36]

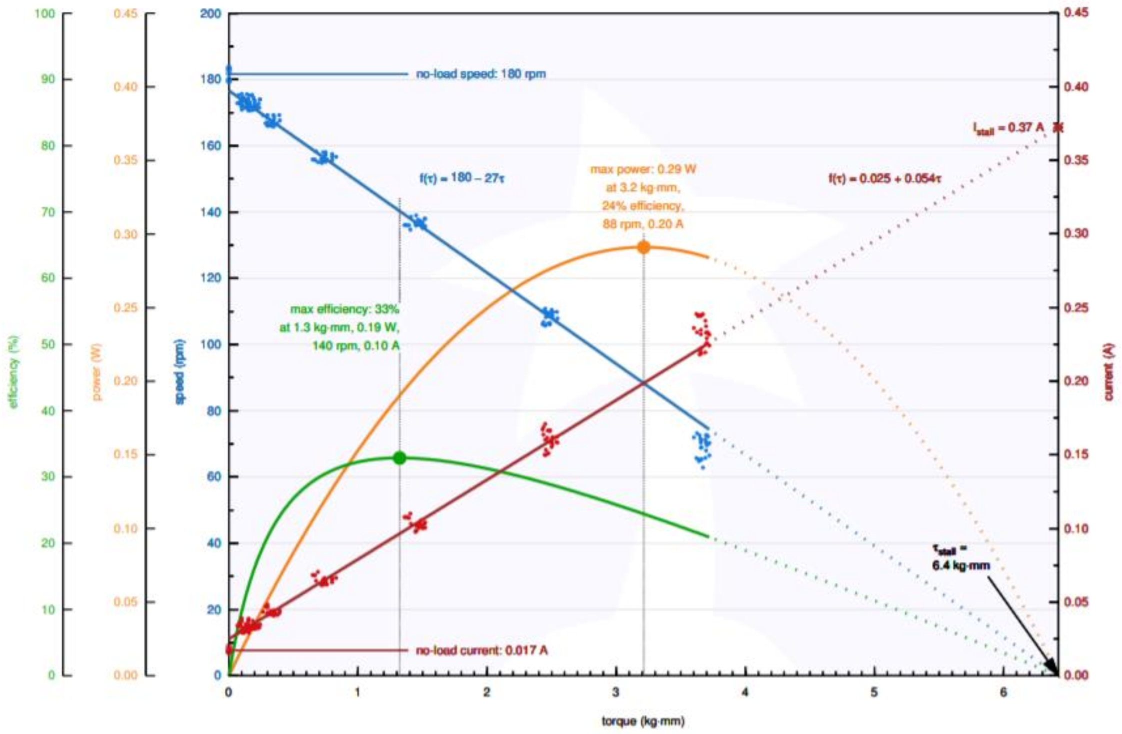


Figure 22: Performance Curve [36]

5.4 Method and Setup for Measurement

5.4.1 Deformation in Pipe

Deformation in the pipe is usually caused by load experienced on the pipe, which results in cause deformation and also lead to bursting in the pipe. The method to measure deformation is to measure the distance from the center of the pipe to its wall and after that plot, all the measured distance in circular, when it is fine circular pipe is in good condition when it is not then there is deformation in the pipe. Time of flight sensor is fixed to the shaft of the stepper motor to rotated in a complete 360 degree at some step angle. Sensor setup is shown in Figure below.

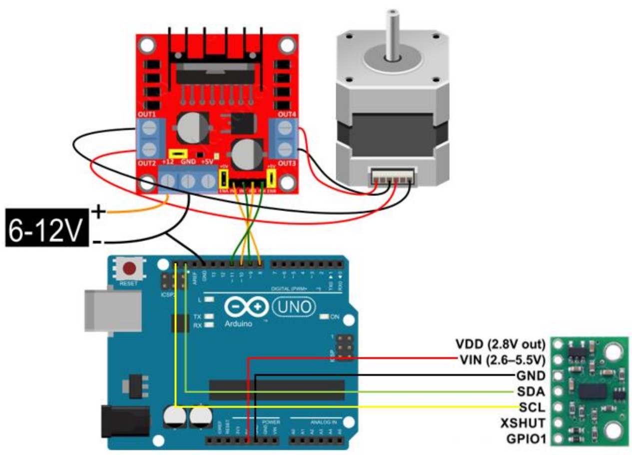


Figure 23: Connection Diagram for Deformation Measurement Setup

Arduino Uno digital pin 8,9,10,11 is connected to L293N IN1, IN2, IN3, and IN4 respectively. Arduino UNO 5V and GND pin are connected Vin and GND to time of flight sensor. While SDA and SCL are connected to SDA and SCL pin of Arduino.

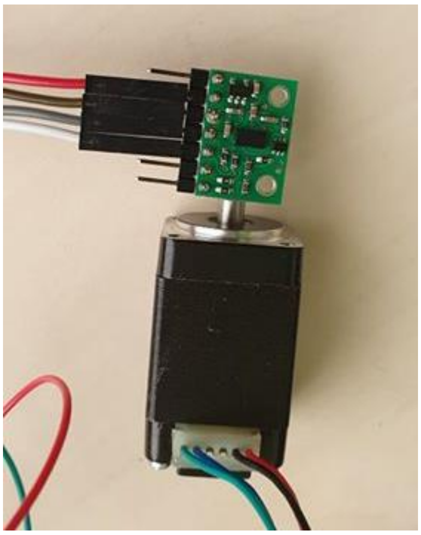


Figure 24 : Sensor setup for circular measurement

5.4.2 Leackage / Temperature in Pipe

Leakage in the pipeline can be measured by detecting the pressure drop in pipeline. There is a pressure difference where ever there is a hole or crack in the pipeline. Temperature is also one of the aspects which causes degradation of pipe quality. Suppose, there is a pipe where there no any kind of leakage or crack which corresponds to pressure “X1“. If there is any hole there is leakage of pressure so at that place let the pressure be “X2“. Therefore the pressure difference is given by

X = X1-X2

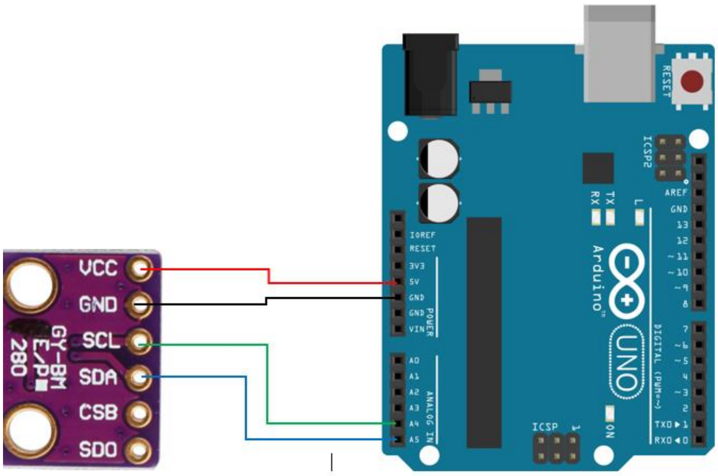


Figure 25: Connection Diagram for pressure & Temperature measurement

Vcc and GND pin of sensor BME280 are connected to Arduino pin 5 V and GND, while SCL and SDA pin of BME280 is connected to analog pin A4 and A5 of Arduino respectively.

5.4.3 Blockage Removeable

Blockage removable is activated by a user once the blockage is observed. It is a drill mechanism attached to servo 360 continuous rotation. Servo signal is connected to the digital pin 12. Along with drill fin attached to the servo.

5.4.4 Localization of Robot

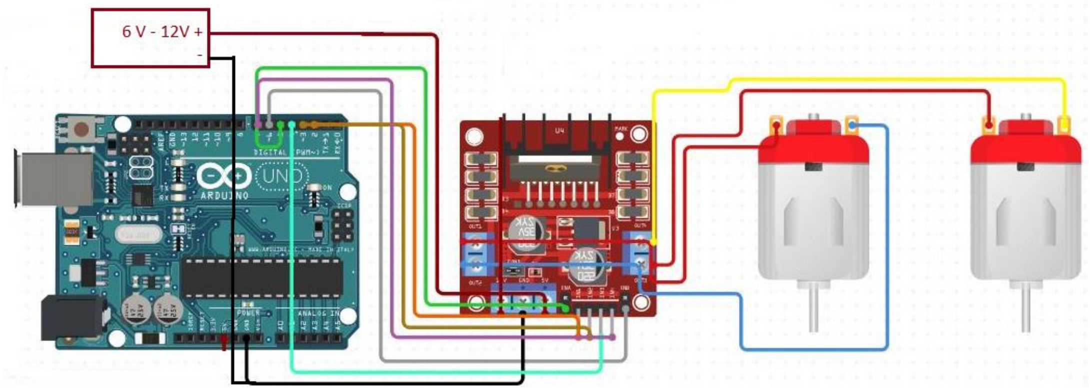


Figure 26: Connection diagram for motor drive

The above figure shows the connection diagram of the drive mechanism of the robot which consists of two dc geared motor along with motor driver L298N. Forward, reverse, left, right motion can be achieved by enabling motor according to desire movement by the user. Arduino Uno digital pin 3,4,15,6 is connected to L293N IN1, IN2, IN3, and IN4 respectively.

6 Experimental Results

This Chapter deals with the testing of concept design. Test setup, analysis of result are also evaluated.

6.1 Testing of Deformation

A pipe was taken for the measurement, the first pipe was measured without any deformation, and the reading was taken for further analysis. Then deformation was made in the pipe and it was again measured and the result was taken for analysis.

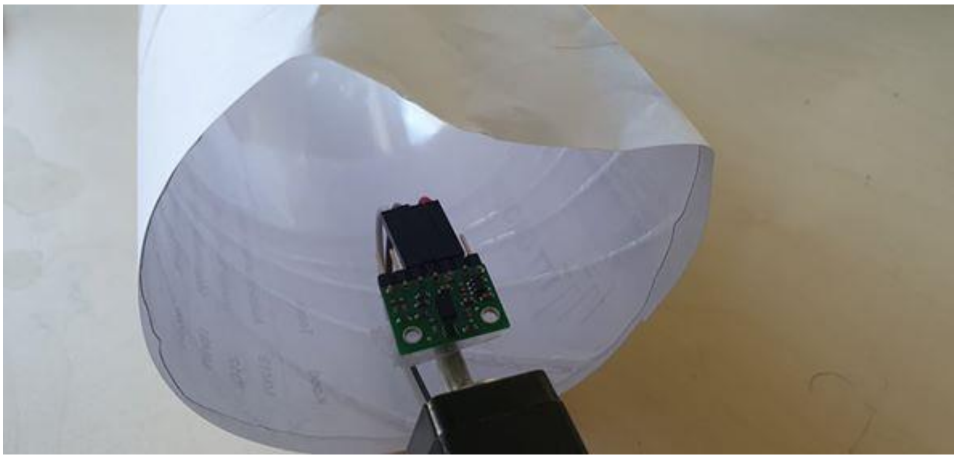


Figure 27: Measuring for deformation

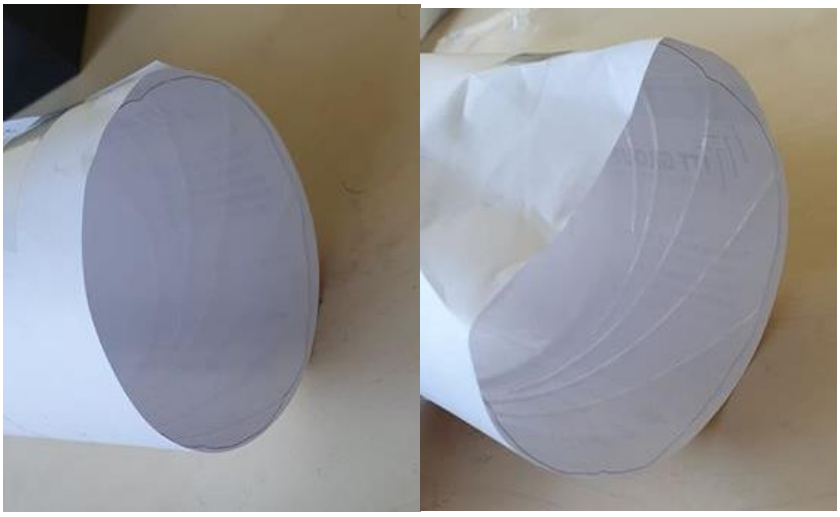


Figure 28: Left pipe without deformation, right pipe with deformation

Measured	Pipe without deformation	Pipe with deformation
Distance from Center (mm)	49	49
Distance from Center (mm)	49	50
Distance from Center (mm)	49	51
Distance from Center (mm)	50	50
Distance from Center (mm)	50	49
Distance from Center (mm)	51	49
Distance from Center (mm)	50	40
Distance from Center (mm)	49	39
Distance from Center (mm)	50	37
Distance from Center (mm)	49	35
Distance from Center (mm)	50	33
Distance from Center (mm)	50	36
Distance from Center (mm)	49	38
Distance from Center (mm)	49	39
Distance from Center (mm)	50	45
Distance from Center (mm)	50	49
Distance from Center (mm)	51	50
Distance from Center (mm)	50	51
Distance from Center (mm)	49	49
Distance from Center (mm)	50	50

Table 11: Measured data of pipe with/without deformation

The above data is plotted in the waveform to see, from the below graph we can see the pipe without deformation gives almost straight curve while pipe with the curve is bend from point 6 to 16.

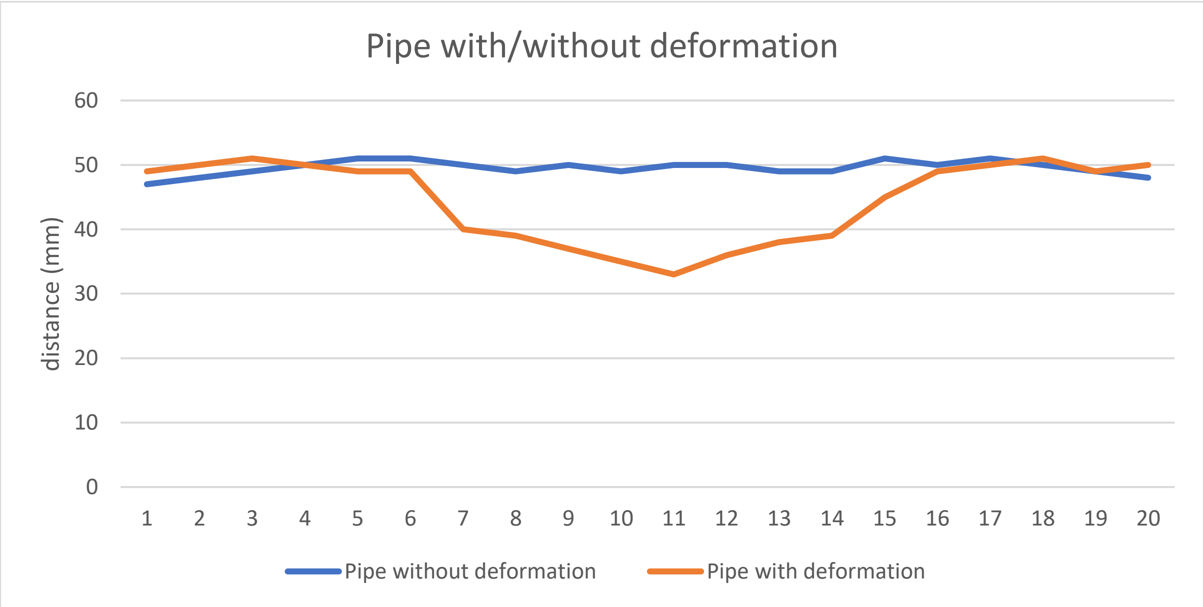


Figure 29: Graph for pipe deformation

The measurement point was used to make a 3D diagram of pipe with the help of SOLIDWORKS software (this 3D model was made with the help of a student from mechatronics department).

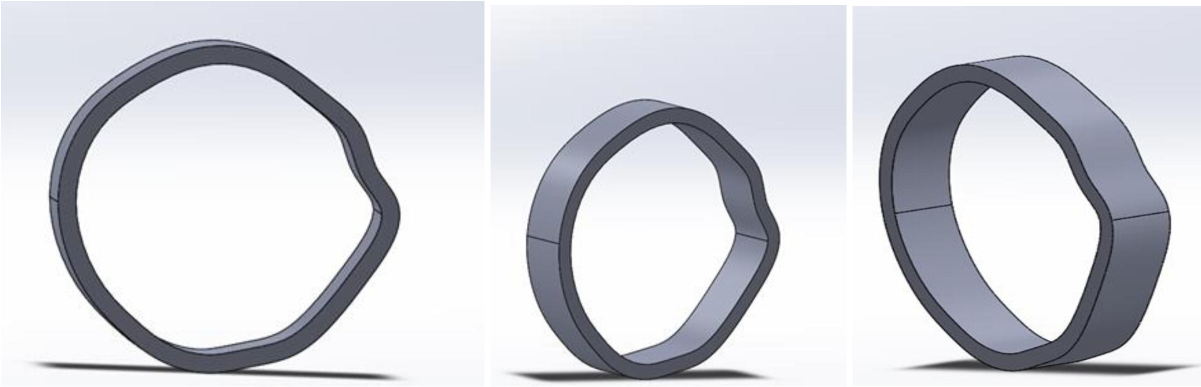


Figure 30: 3D diagram of pipe without deformation

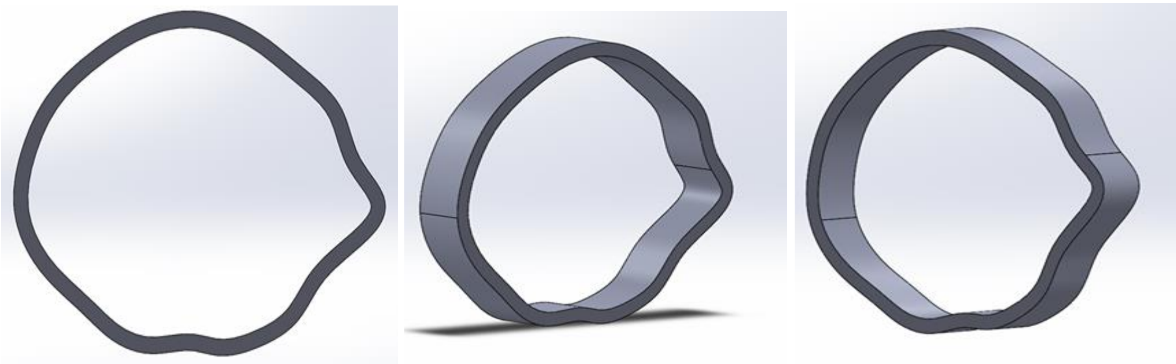


Figure 31: 3D diagram of pipe with deformation

6.2 Testing of Pressure and Temperature

For testing for leakage, a closed bottle was taken sensor was inserted in the bottle and pressure was noted, after a few moments later a small hole was created with help of pin to see the pressure drop.

Figure 32: Measuring for pressure

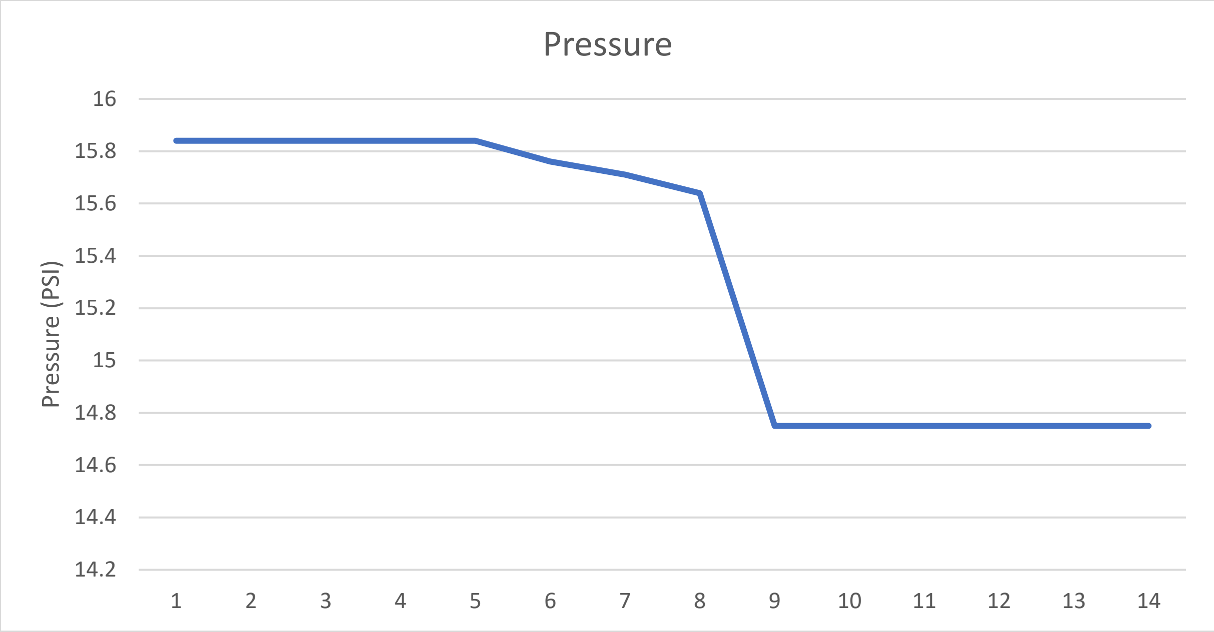


Figure 33: Graph for pressure

From the above graph, it’s clear that in starting the pressure was 15.84 PSI, and when the pressure was released pressure was 14.75 PSI. The drop in pressure is 1.09 PSI.

The temperature was tested by warming the sensor and allowing it to cool, the graph is presented show the temperature change.

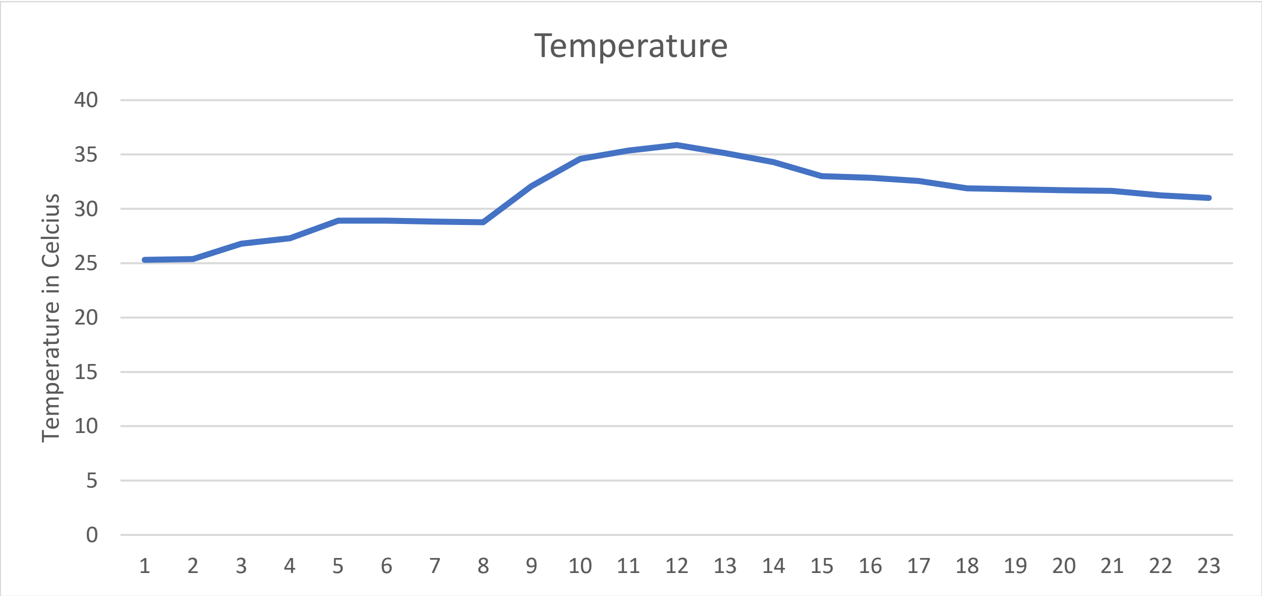


Figure 34: Graph for temperature

6.3 Testing of Localization

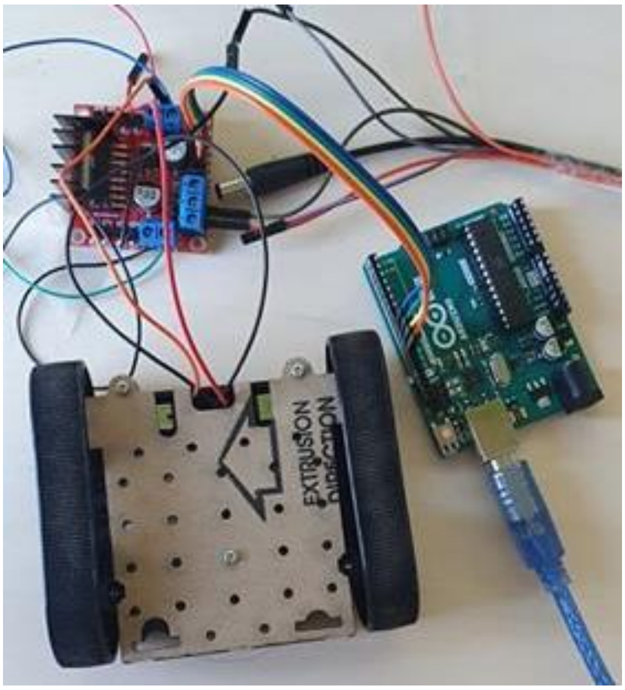


Figure 35: Testing for motor drive

Left, Right, Forward, Reverse movement was tested according to user input. But this test was done on a normal surface, it was not tested in any kind of pipe.

6.4 Power Required Calculation

Based on the voltage and current rating, the power required for this system is calculated which equal to 16.534 Watt. Calculation table is shown in table 11.

Components	Operating Voltage (V)	Operating Current (mA)	Power (watt)
Arduino Uno	5	30	0.15
VL53L0X Time of Flight Sensor	5	10	0.05
BME280 Pressure/Temperature sensor	5	2.8	0.014
L298N Motor Driver	5	600	3
L298N Motor Driver	5	600	3
Stepper Motor	4	600	2.4
Servo Motor	6	120	0.72
DC gear motor 1	6	600	3.6
DC gear motor 2	6	600	3.6
		Total Power Required	16.534

Table 12: Required Power Calculation

7 Conclusion

7.1 Limitations, Challenges, and Open Issues

Since the thesis is more like an attachment to the sensing side, it has to be studied and applied in order to limit the size of the pipe. The next step is to be fully autonomous together with wireless data transfer. It is semi-autonomous. One of the characteristics of the pipeline control robot should be the resistant liquid regardless of the type of liquid essential to implementation in the real world. During making the water robot resistant to various types of liquids as well as to pipeline pressure it should also be considered. And in different environments such as sizes, tube materials, goods transported through pipelines, pressures, etc, the robot agent should ensure secure mobility. The development of various types of the robot in pipeline networks for various conditions. And recovery measures are one of the major challenges for a robot. For different environments and tasks, there must be huge demands and numerous difficulties that can be endless challenges for robot agents. The robot also needs sensitive and powerful sensors to be inspected in detail to ensure the quality of the inspection. Along with all this, it also needs universal user control application software which can be installed on any computer system and connect to the inspection robot wireless.

7.2 Dissertation Summary

Based on the market research we found that the existing solution is used in different pipeline application at different industry segment. Most of the existing solution is based on a camera inspection method along with some sensor such as gas, temperature. Economically the existing solution price (in Euro) is more than 5000. And few of them are mechanically adjustable with the pipe size. All the existing solution is protected by IP 68. Coming to the battery and power device they are sharing almost the same 24V DC power supply and battery backup are varying for 2 to 3 hours solution to solution. The existing solution comes in a set of a control station, inspection robot along with its peripheral device, all the sub-systems are interconnected its high-speed data cable. From this, we can conclude that though they are adaptable with the pipe size, most of them are limited to the inspection method, there are a lot of things to sensing in the pipeline environment.

In this research, we have proposed a new, cost-effective and semi-autonomous robotics monitoring system integrated with multiple sensors and blockage removable mechanisms for the pipelines. It combines robot-based technology with sensing systems in which health-related events are efficiently located and a wide range of pipeline systems can be pro-actively and correctively maintained. The prototyping tests show the system's feasibility and excellent performance, its cost efficiency, and scalability, as compared to the current pipeline surveillance systems.

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Appendix

Firmware for Multi-Functional Pipeline Inspection Robot

```
#include <Wire.h>
#include <SPI.h>
#include <Servo.h>
#include <VL53L0X.h>
#include <Stepper.h>
#include <Adafruit_BMP280.h>

#define BMP_SCK 13
#define BMP_MISO 12
#define BMP_MOSI 11
#define BMP_CS 10

#define IN1 3
#define IN2 4
#define IN3 5
#define IN4 6

Adafruit_BMP280 bme;
Servo servo;
VL53L0X tof;
const int stepsPerRevolution = 200;
Stepper step_motor(stepsPerRevolution, 8, 9, 10, 11);
String input;
int a;

void setup() {
  Serial.begin(9600);
```

```
  if (!bme.begin()) { while (1);}
  Wire.begin();
  tof.init();
  tof.setTimeout(500);
  tof.startContinuous();
  step_motor.setSpeed(10);

  pinMode(IN1, OUTPUT);
  pinMode(IN2, OUTPUT);
  pinMode(IN3, OUTPUT);
  pinMode(IN4, OUTPUT);

}

void temp(){
  Serial.print("Temperature = "); Serial.print(bme.readTemperature()); Serial.println(" *C");
  Serial.println();
  delay(500);
}

void pressure(){
  Serial.print("Pressure = "); Serial.print(bme.readPressure()/6894.757); Serial.println(" PSI");
  Serial.println();
  delay(500);
}

void drill(){
  servo.attach(12);
}
```

```
void deformation(){
  step_motor.step(stepsPerRevolution);
  step_motor.step(-stepsPerRevolution);
  Serial.print("Distance = ");
Serial.print(tof.readRangeContinuousMillimeters());Serial.println(" mm");
  Serial.println();
  delay(500);
}

void loop (){
    while (Serial.available() > 0){
    input = Serial.readString();
//wait for the user input through serial port

switch (input){

    //if input is temp, start temp sensor
    case "temp":
        temp();
        break;
    //if input is presssure, start pressure sensor
    case "pressure":
        pressure();
        break;
    //if input is drill, start drilling mechanism
    case "drill":
        drill();
        break;
     //if input is deform, start deformation measurement mechanism
    case "deform":
        deformation();
```

```
    break;
//front input to move robot forward direction
case "fornt":
    digitalWrite(IN1, LOW);
    digitalWrite(IN2, HIGH);
    digitalWrite(IN3, LOW);
    digitalWrite(IN4, HIGH);
    break;
//back input to move robot backward direction
case "back":
    digitalWrite(IN1, HIGH);
    digitalWrite(IN2, LOW);
    digitalWrite(IN3, HIGH);
    digitalWrite(IN4, LOW);
    break;
 //left input to move robot left direction
 case "left":
    digitalWrite(IN1, LOW);
    digitalWrite(IN2, LOW);
    digitalWrite(IN3, LOW);
    digitalWrite(IN4, HIGH);
    break;
//right input to move robot right direction
 case "right":
    digitalWrite(IN1, LOW);
    digitalWrite(IN2, HIGH);
    digitalWrite(IN3, LOW);
    digitalWrite(IN4, LOW);
    break;
 //brake input to stop robot
```

```
      case "brake":
        digitalWrite(IN1, LOW);
        digitalWrite(IN2, LOW);
        digitalWrite(IN3, LOW);
        digitalWrite(IN4, LOW);
        break;
    //to stop all the task
     case "stop":
       Serial.print("all function stipped, enter task");
        break;
    }
  }
}
```