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DESIGN OF PIPE INSPECTION ROBOT WITH PID SPEED CONTROLER

MASTER'S THESIS

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4 Contents of the master's thesis

1. INTRODUCTION
2. LITERATURE REVIEW AND PROBLEM STATEMENT.
3. The Problems and Vulnerabilities to be detected.
4. Method of Detecting Pipe Vulnerabilities.
5. Deferent Pipelines Shapes and Forms (Pipe Bends and Joints)
6. Deferent Types of Pipe Inspection Robot.
7. Standard Diameters of Elbow and T Section.
8. Accurate Determination of the Maximum Allowable Operating Pressure (MAOP) of Oil and Gas Pipelines.
9. Cleaning Before the Inspection.
10. DESCRIPTION OF THE MECHATRONIC SYSTEM.
11. Deferent Modules of Pipe Inspection Robot.
12. Calculating the Dimensions of the Robot
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16. Calculating the Final Wight of the Robot
17. Calculating Maximum Torque of Each Motor
18. The friction coefficients and friction force and choosing the spring types
19. Calculating the maximum pressure applied by the robot

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ABSTRACT

This paper is about the steady and design of a pipe inspection robot. The robot should able to pass through the 508mm pipe. The robot should be also able to successfully go through vertical pipe rather than the horizontal pipe and be able to turn left, right, up and down according to the operator control. All the motors of the robot will have a speed control by using PID controllers.

CONTENT

INTRODUCTION

In the present day, many companies that work with deferent kinds of fluid production, like oil, gas, water or any chemical product, use the pipeline as transition medium. Those Pipes can be construct of a deferent kind of materials and in deferent shapes and diameters depending on the type of the fluid, pressure, distance, flow rate and even the surrounding environment.

The most common types of pipes used in these fields are the metallic pipes due to their reliability to endure the high pressure and the flow rate and they could be install in long distance with relatively good efficiency to stand against harsh environment for deferent amounts of time.

These pipes might face some problems due to deferent situations that makes them not fully functional or on threat to be not able to work in the future due to their current exited problems.

The method of inspecting and detecting these problems are sometimes not easy because installation of the pipe can be under water under ground and it is imposable for human to do that work.

Her the use of the robotic solution to drag the sensor unit can be most effective solution to go instead of conventional methods.

The history of robotics that is deals with pipeline inspection in very long and we will try to summarize some of that work make some comparisons and reach some conclusions.

Nowadays, the pipe inspection robot usually a designed of a several modules each one of those modules will has its own unique function.

The (fig. 1) will summarize the basics of the work of these modules.

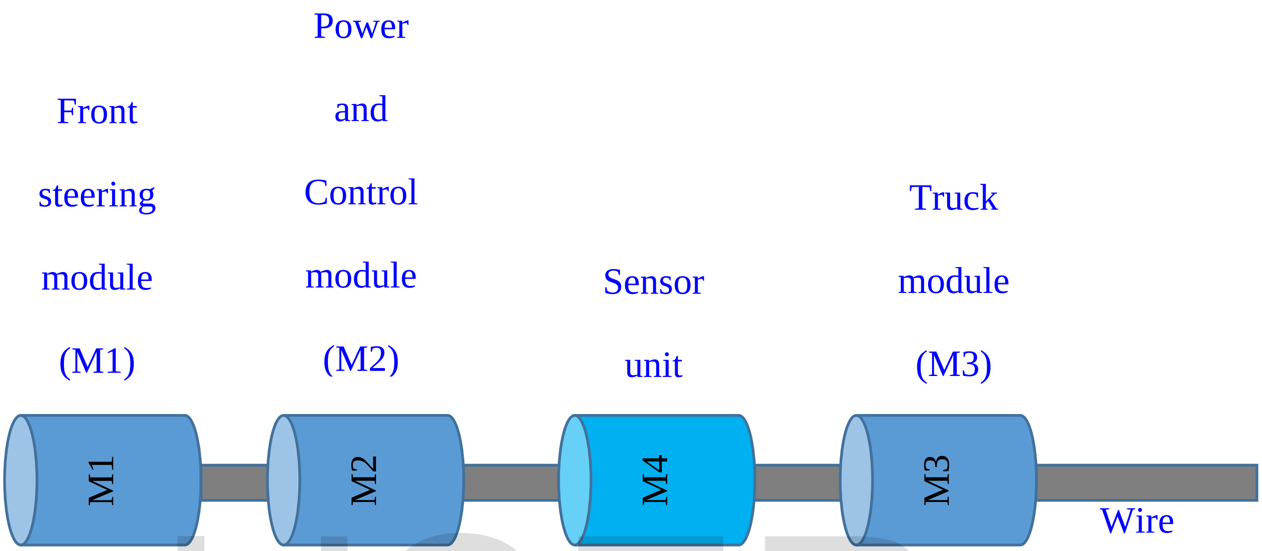


Fig. 1 – Schematic of pipe inspection robot’s modules

Front module is usually has the abilities to sense the change of the geometry of the pipe and the abilities to change the direction. Front module will be provide with a camera and light so that the operator will be able to monitor what happened inside the pipe visually.

The power and control module will provide the other modules with the power line and control signals. Truck module has the puss power to move most of the other robots weight. In some cases a battery unit could be add in other cases, a wire can be used to energize all other unit.

The wire will also be important to catty out the entire control signal from the operator rather than sending the reading of the sensor unit and the footage of the camera.

1. LITERATURE REVIEW AND PROBLEM STATMENT

1.1 The Problems and Vulnerabilities to be Detected

A lot of predicted and unpredicted problem might be happen to any pipeline that might led to failure in their operation.

Some of these problems might be a caused by human infarction like the mistakes in installation or damages due to strike of heavy or light tolls. Moreover, these problems might happen due to the environment effect on the pipes during any amount of time. For that, we need to understand these vulnerabilities to choose the best sensor unit for the robot. The most common problems are corrosion, deformation, and cracking. Each one of those problems will explained bellow.

1.1.1 Corrosion

Corrosion may be the most consistent integrity challenge facing operators of cast iron and steel pipelines. While other concerns can be considered incidental and only affect certain sections of pipeline, corrosion constantly affects every inch of pipeline. Corrosion is a natural phenomenon that occurs whenever a metal is exposed to the surrounding environment.

This electrochemical process pulls ions from the surface of the steel pipe to dissimilar metals (i.e. more passive metals) in the soil, water, or air. As ions are pulled from the steel pipelines by these dissimilar metals, oxygen can bond and create rust. Left unchecked it can eventually degrade the structural integrity of a pipeline. Although pure oil does not present a corrosion risk to the pipeline, sediment and water carried by crude can cause internal corrosion.

Corrosion generally results in minor leaks from small holes in the steel pipeline [1]. As shown below in (Fig. 2) some pipes with corrosion with deferent intensity

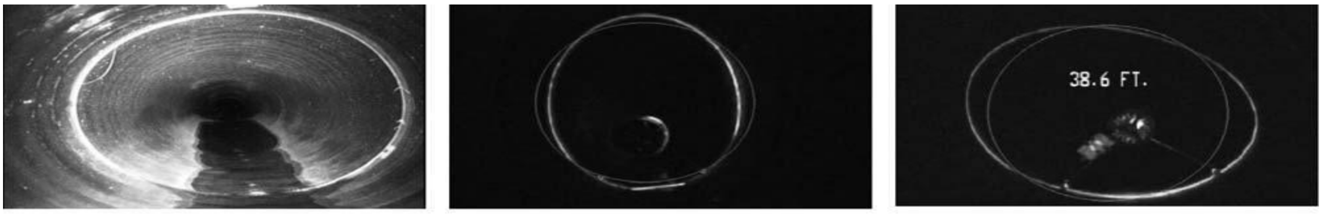
Fig. 2 – Pipes with corrosion

1.1.2 Deformations

The most common causes of deformations in steel pipelines are environmental incidents and human interference; human interference is the more common of the two. When heavy equipment or rocks strike the steel pipe, they can make dents or gouges that change the internal geometry of the line.

Changes in the internal geometry alter the distribution of internal pressure by focusing it on certain sections of pipeline. Overtime these deformations may result in pipeline failure. Deformations are often accompanied by a loss of coating, which increases the risk of corrosion [1].

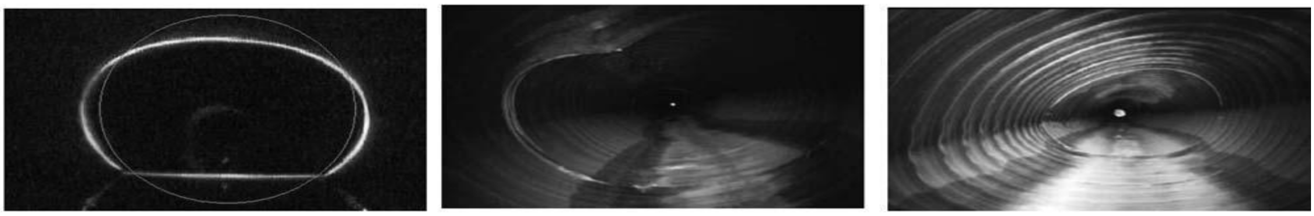
As shown below in (Fig 3) some pipes with Deformation with deferent Kinds; (a) symmetrical deformation along the horizontal X axis (b) symmetrical deformation along the horizontal Y axis (c) Ovality (Racking) deformation (d) Crown Flatting deformation (e) Inverse Curvature (f) Bucking Deformation.



a) Symmetrical deformation along horizontal X axis

b) Symmetrical deformation along Y axis

c) Ovality (Racking) Deformation



d) Crown Flattening

e) Inverse Curvature

f) Buckling Deformation

Fig. 3 – Pipes with deformation

1.1.3 Cracking.

Steel is generally a strong and malleable metal. However, improper installation and/or maintenance of steel pipelines can lead to stress induced separation of the metal or cracking. Stress is a physical quantity measured in Pascal’s that describes the force per unit area acting on a material. Stress generally leads to cracks in oil pipelines in three ways: cyclic fatigue, stress corrosion, or manufacturing error. Cyclic fatigue is the structural damage that occurs when the steel pipeline is subjected to fluctuating internal pressures. Stress-corrosion cracking occurs where pipe is under tension and exposed to corrosive elements. Cracks that are built into the pipe tend to be too small to cause pipe failure but are usually detected nevertheless.14 Cracks generally cause leaking but severe cracks can lead to a burst pipe [1]. In the below (Fig. 4) the picture shows a wall of a pipe with cracks.

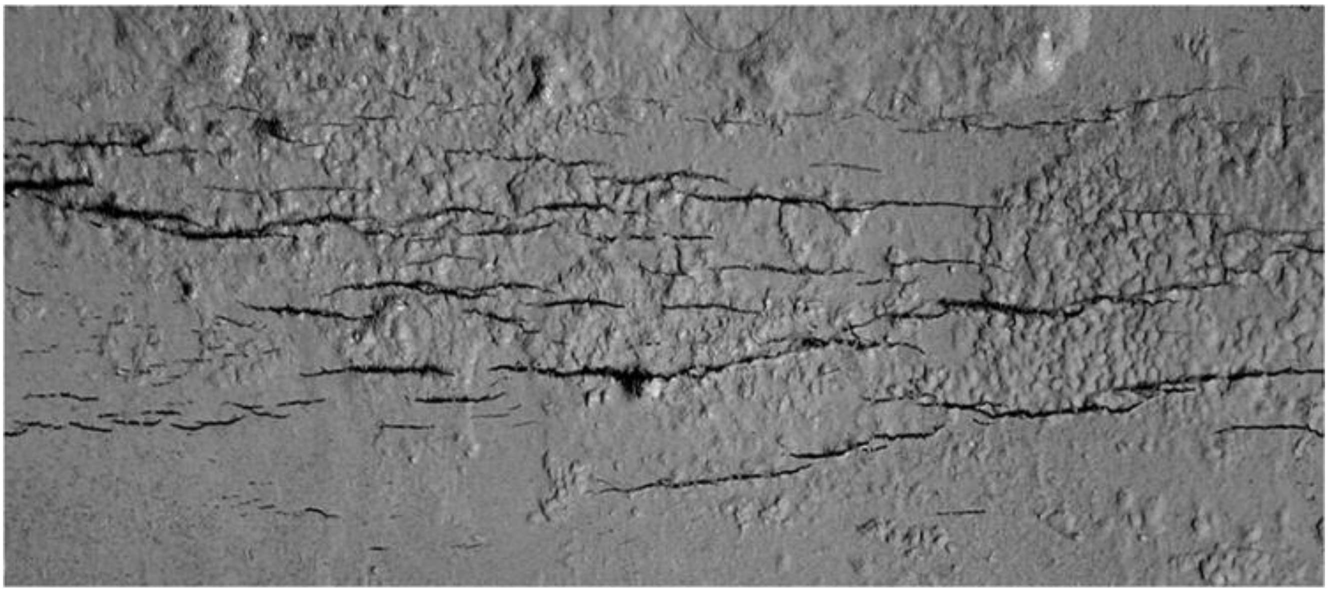


Fig. 4 – Pipe cracking

1.2 Method of Detecting Pipe Vulnerabilities

There are deferent technique to detect the pipe vulnerabilities such as cracking, corrosion and deformation. The most common two technique are ultrasonic wave test and magnetic flex leakage test.

1.2.1 Ultrasonic Wave Test

Ultrasonic testing (UT) utilize the sound waves of a high frequency that is typically from 0.5 MHz to 15 MHz rang. A common pulse-echo UT for the system of inspection in composed of several unit like pulsar/receiver, transducer and display device.

Pulsar/receiver is an electronic device that can produce high voltage electronic pulses. The transducer in responsible for creating ultrasonic energy with a high frequency. The energy of the sound is travels through the materials in waveform. When the wave hits the crack it will cause a discontinuities in the path of the wave so part of the energy will reflect back from the surface. The reflected wave will be transformed by the transducer into electrical signal and appeared in the screen. It is important to know the velocity of the wave and travel time because this is can directly related to the signal travelled.

Advantages of Ultrasonic wave test:

1- Sensitive to both surface and subsurface discontinuities.

2- It need to access a single side only.

3- Has a high accuracy.

4- Provide instantaneous result.

Disadvantages of Ultrasonic wave test:

1- Surface must be accessible to transmit ultrasonic waves

2- It normally requires a coupling medium to carry sound waves to the specimen.

3- Linear defects oriented parallel to the sound beam may be goes undetected.

4- Material that is rough or irregular in shape are difficult to inspect.

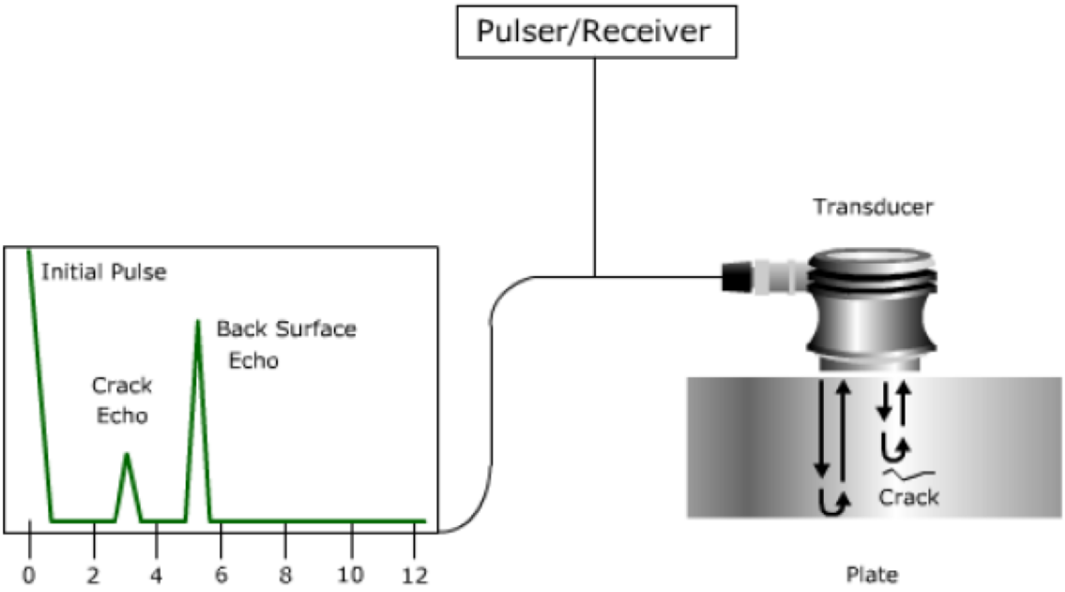


Fig. 5 – Ultrasonic test principle

1.2.2 Magnetic Flex Leakage Test

Magnetic flex leakage work on magnetising the component to a level at which the presence of a significant local reduction in material thickness causes sufficient distortion of the internal magnetic field to allow flux lines to break the test surface at the site of the discontinuity. In the case of traditional MPI, a ferromagnetic powder, in wet or dry form, is used to mark the spot so that it is readily visible by the inspector. With MFL, suitable sensors are used to give an electrical signal at the leakage site. This signal may operate an audible or visual alarm to alert the inspector, or may store the event for computer mapping of the area. Thus both techniques require two basic things, a method of magnetisation, and a method of detecting the leakage field.

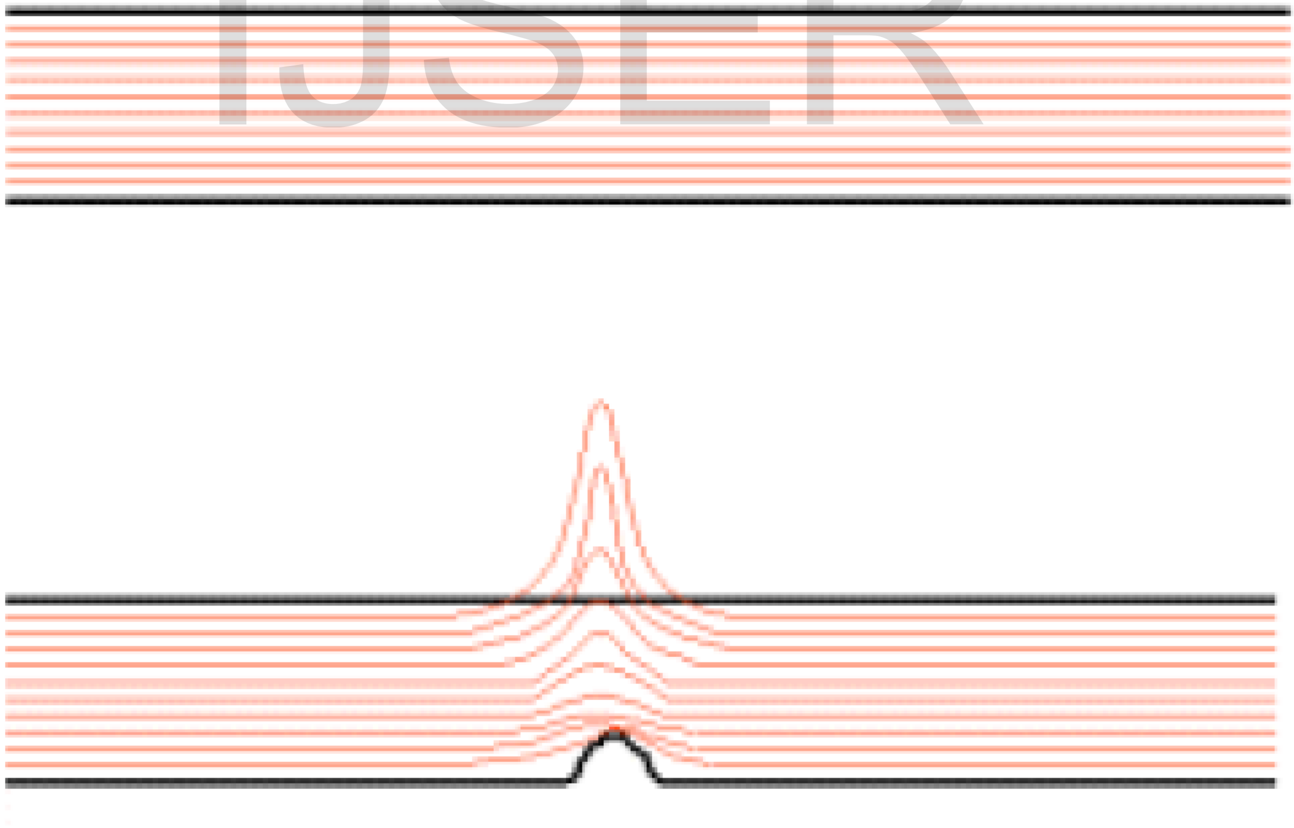


Fig. 6 – Magnetic flex leakage test result

1.3 Deferent Pipelines Shapes and Forms (Pipe Bends and Joints)

Unpiggable pipe networks vary in diameter range, material, and fluid type and can be joined in various methods and configurations. Categorised pipe joint configurations are shown in (Fig 8)

1- Horizontal sections (Fig 7A) are considered the baseline for in-pipe complexity; any in-pipe robot should be able to navigate these. Configurations B to F are more complex; passing through them requires advanced motion planning techniques.

2- Valves are particularly difficult as designs such as plug valves (Fig 7B) can split the cross-section in two hindering full-bore robots.

3- Changes in diameter (Fig 7C) are a common occurrence in unpiggable systems, many robots take measures to prepare for this obstacle specifically.

4- Vertical sections (Fig 7D) require a traction method that must also overcome gravity.

5- Elbows (Fig 7E) are very commonly encountered and are often described in terms of their bend radius; lower radius bends are tighter harder to navigate.

6- T-Sections (Fig 7F) are extremely challenging obstacles due to their lack of wall support; only sophisticated robotic platforms can navigate these [2].

Each of these in-pipe obstacles can be found in any orientation and possibly even back-to-back e.g., encountering two consecutive bends. Developing a single robot to solve all of these problems in a wide range of diameters is currently unheard of and often requires a fleet of multiple systems in different class sizes. In this review significant robots that have furthered the research field will be presented. Current state-of-the-art methods of in-pipe travel and inspection are discussed as well as the future abilities of in-pipe robots. By analysing the barriers facing current technology and the methods being employed to overcome them, breakthroughs can be made towards universal in-pipe inspection. This review addresses in particular the problems surrounding shape adaptability, fleets, and system classes and their role in universal pipe inspection.

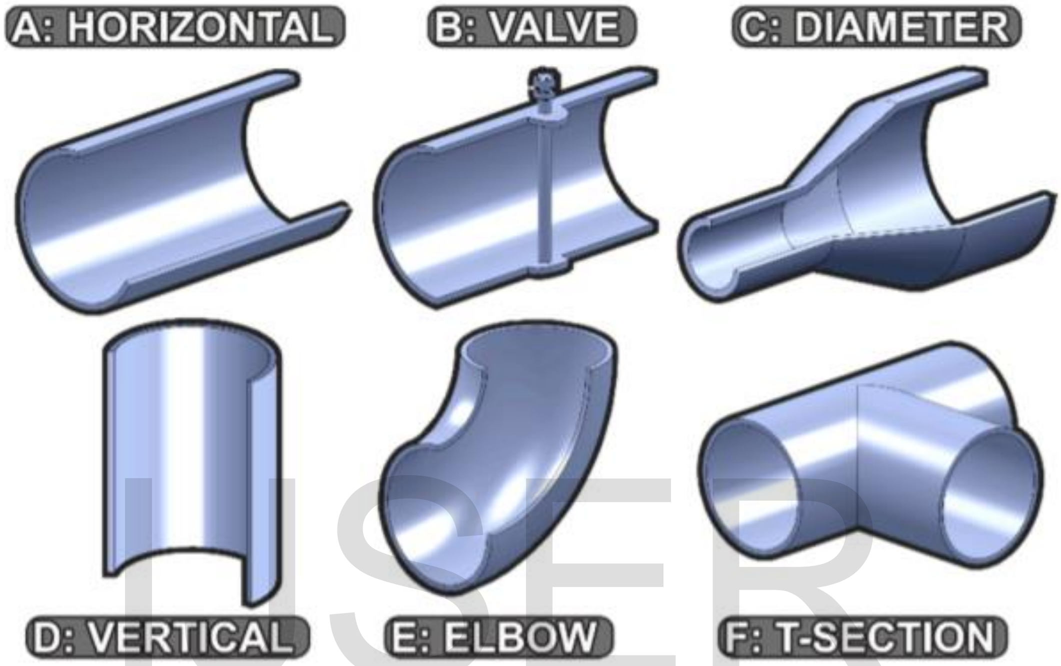


Fig. 7 – Deferent pipelines shapes and forms

1.4 Deferent Types of Pipe Inspection Robot

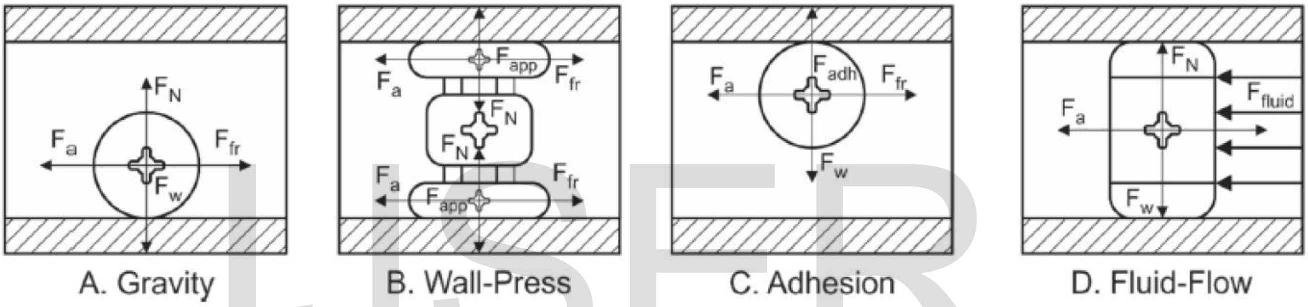
A pipe inspection robot should have the abilities to preform deferent sort of manoeuvres to go through the network of pipeline. The building of the pipe inspection robot should starts with deciding of which type of traction method that the robot will use interact with environment of the pipeline. During the past type many methods have been invented to make the inspection robot able to pass through all kind of obstacle that faces it in the unpiggable pipeline some of the appeared in (Fig 8).Those methods are ;

A) Gravity (Fig 8A) that relied only on the gravity to make the robot attract to the bottom of the pipe. This type restrict the robot to work on Horizontal pipes only.

B) Wall-Pressing (Fig 8B) utilizing the reaction of one side of the pip's wall to create attraction force applied on another side .This method is useful with claiming vertical pipes and foe carrying have load.

C) Wall Adhesion (Fig 8C) usually work with metallic pipeline to create a magnetic force that causes the adhesion.

D) Fluid Flow (Fig 8D) uses the pushing force of the medium for moving



A. Gravity B. Wall-Press C. Adhesion D. Fluid-Flow

Fig. 8 –Traction methods of in pipe inspection robot

Table 1 – Deferent kind of attraction methods and their aspects

Ability to	Gravity	Wall-pass	adhesion	Fluid-flow
claim vertical pipe	no	Very good	good	good
decide to turn	yes	yes	good	no
existence of medium	no	no	no	good
carry heavy load	good	Very good	no	good
speed control	good	Very good	good	no

At the beginning of the issues of the need of pipe inspection robot all idea were simple weal robot that is depend on the gravity force as an attraction. By the time, go on this idea developed to provide the robot with more abilities to pass through deferent pipe shapes and become more adaptable to any geometrical change. In (Fig 9) all common types of inline inspection;

A) PIGs (Fig 9A); this device utilize the flow of the fluid inside the pipe for its movement .It is good in direct horizontal pipes but not good with complex network of pipeline.

B) Wheeled robot (Fig 9B); It is one of the most comment types of the inline robot .The wheel robot uses deferent methods of attraction to make it able to do a certain kinds of manoeuvres.

C) Track robot (Fig 9C); instead of the wheel the track robot (caterpillar robot) uses the large aria of roll that surround the moving wheel. This method is very affective to prevent the robot slipping and makes the robot able to carry a relevant big loud.

D) PIGs (Fig 9D); use a spiral inspection path, they perform well in vertical sections and are resistant to slip due to their angled approach, even against an in-pipe flow.

E) Snack robot (Fig 9E) it uses the length of the pipeline to make itself adaptable deferent changes of pipe geometry.

F) Inchworm robot (Fig 9F) relevantly it considered a slow inline inspection robot with the ability to carry a good amount of laud.

G) Propeller base robot (Fig 9G) utilize the medium to transport inside the pipe. It does not depend on the wall attraction. Since it is basically swimming in fluid that will make it unstable and very heard to control.

H) Walking robot (Fig 9H) utilize a set of legs with deferent degree of freedom to do the manoeuvres [2].

Fig. 9 –The eight main elements of in-pipe robotic devices `

Some robots uses the combination of two or more of the eight technique above to make a hybrid robot that gathers the advantages of this combination. It is important to understand the environment of pipeline, geometry and complexity of the network to decide what is require from the robot to achieve. Fig. 10 –History of in-Pipe Robot Publication.

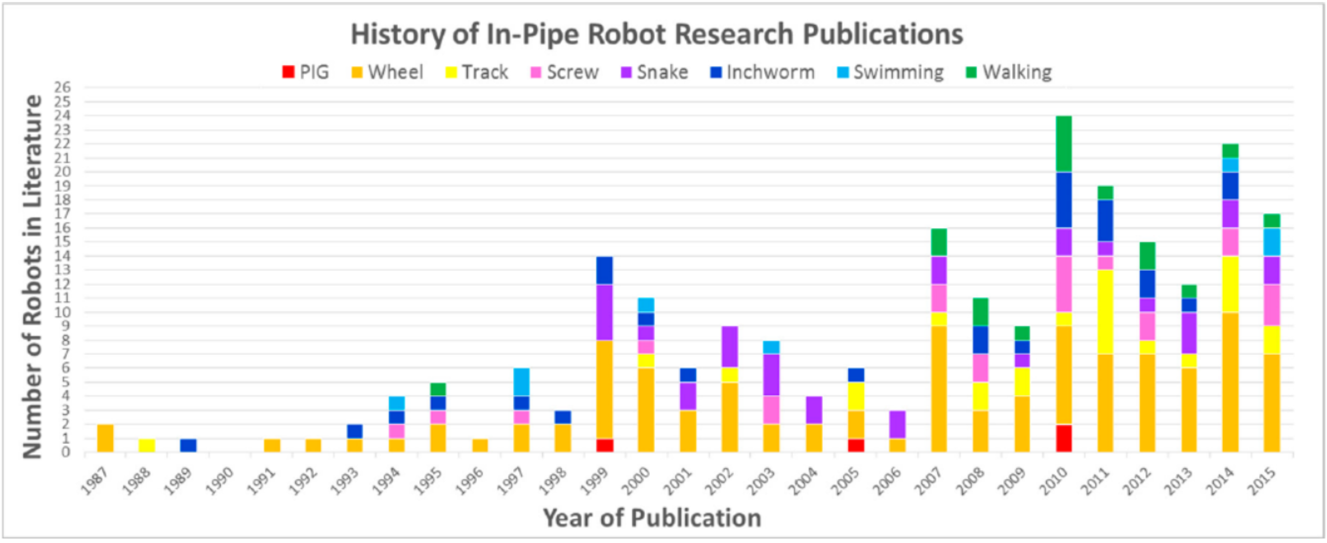


Fig. 10 –History of in-Pipe Robot Publication

1.5 Standard Diameters of Elbow and T Section

A) Elbow

Elbows are categorized based on various design features as below:

- Long Radius (LR) Elbow is also called LR elbow – means the radius is 1.5 times the pipe diameter
    - L/R 45°Elbow: Long radius 45 degree elbow changes the direction by 45 degrees.
    - L/R 90°Elbow: Long radius 90 degree elbow changes the direction by 90 degrees.
    - L/R 180°Elbow: Long Radius 180 degree return bend allows complete reversal of flow.
- Short Radius (SR) Elbow is also called SR elbow, – means the radius is 1.0 times the pipe diameter.
    - Short radius 45°Elbow: Short radius 45° elbow changes the direction by 45 degrees.
    - Short radius 90°Elbow: Short Radius 90° elbow is same as LR90 except for the measurement between end of elbow to center line is 1 x NPS.
    - Short radius 180° Elbow: Short Radius 180° return bend allows complete reversal of flow [15].

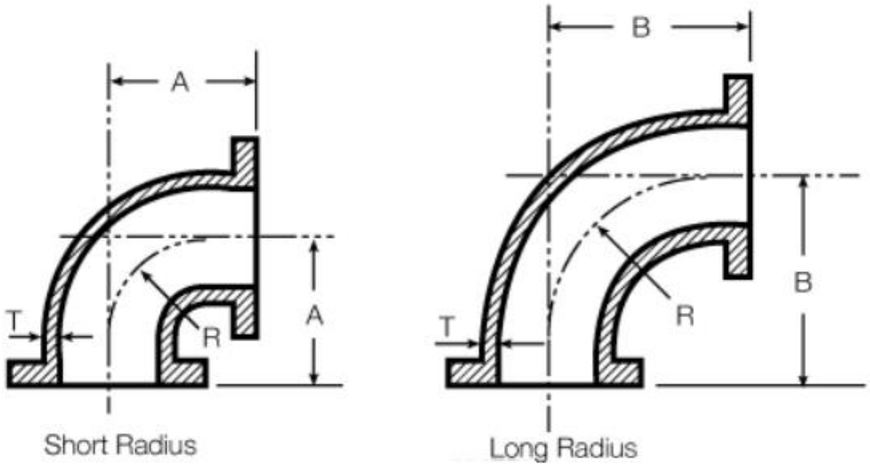


Fig. 11 – Slandered dimensions of elbow

B) T-Section

T-section are categorized based on various design features to equal Tee and unequalTee .In our study we are interested in the equal Tee that shown in (Fig 12) [15].

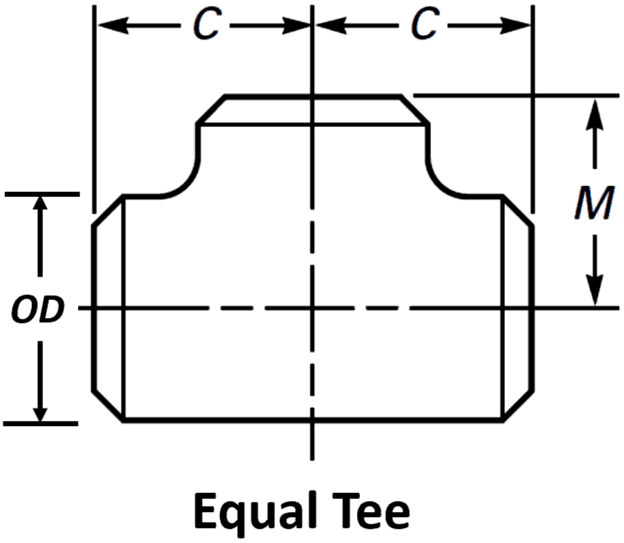


Fig. 12 –Slandered dimensions of equal T-section

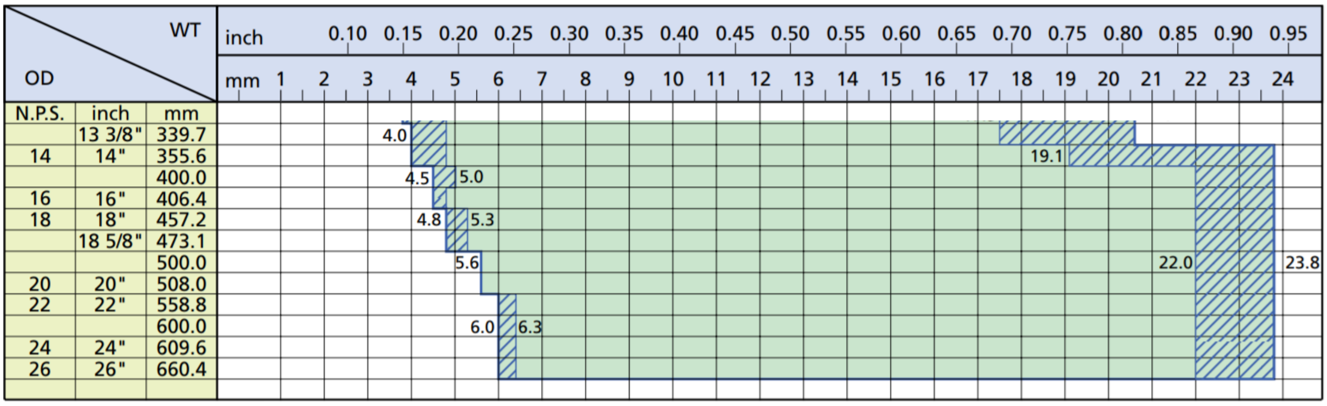
Table 2 – Slandered dimensions of equal T-section for deferent sizes

NOMINAL PIPE SIZE	OUTSIDE DIAMETER	CENTER TO END	LENGTH
Inch.	OD	C	M
18	457.2	343	343
20	508	381	381
22	559	419	419
	All Dimensions are in mm		

1.6 Standers for Oil Pipeline Sizing and Dimension

Understanding the pipe sizing and dimension is important before starting to design the pipe inspection robot. The overall dimension of the robot will be determined by the inner diameter of the pipe. The thickness of the pipe's wall (WT) and the Specified Minimum Yield Stress (SMYS) are very important to calculate the Maximum Allowable Operating Pressure (MAOP) of Oil and Gas Pipelines. This is important when calculating the pressure applied by the robot to make it within the acceptable rang. The below table is shown the relationship between the out diameter (OD) and the allowable wall thickness rang by JFE steel corporation [14].

Table 3 – Slandered relation between oil pipe wall thickness and their sizes



N.P.S.	inch	mm
	13 3/8"	339.7
14	14"	355.6
		400.0
16	16"	406.4
18	18"	457.2
	18 5/8"	473.1
		500.0
20	20"	508.0
22	22"	558.8
		600.0
24	24"	609.6
26	26"	660.4

Since the pipe we selected to inspect by the robot is of 508mm diameter the wall thickness will be 12.7mm.

In addition, we need to consider the minimum yield strength of the A200 SA 209 pipe. That has 195 Mpa .

Table 4 – Parameter of A200 SA 209

Specification Code	Grade Designation	Manufacturing Method	Chemical Requirements										Tensile Requirements		
			C	Mn	P max	S max	Si	Ni	Cr	Mo	V	other	Tensile strength (Mpa)	Yield strength (Mpa) min	Elongation GL=2in min %
A 209 SA 209	T1 a	Seamless process, hot finished and cold finished	≤0.14	0.30~0.80	0.025	0.025	0.025			0.44~0.65			365	195	30

1.7 Accurate Determination of the Maximum Allowable Operating Pressure (MAOP) of Oil and Gas Pipelines

Maximum allowable operating pressure (MAOP) is the maximum pressure a pipeline can safely operate. The pipe wall thickness (WT), Specified Minimum Yield Stress (SMYS), and pipe outer diameter (OD) are used to calculate the MAOP of a pipe as shown below.

$$\text{MOAP} = (\text{Factors of safety} \times \text{SMYS} \times \text{WT}) / (\text{OD}) \tag{1}$$

It is very important to understand that the fact that each pipe can endure a certain amount of pressure. For any reason if the internal pressure exceeded the MAOP the result will be the damage of the pipe Therefore, a margin of safety is used in the calculation of MAOP. Accurate determination of MAOP is a serious problem for undocumented pipelines. Examining Equation () above, the factors of safety are chosen from the US Code of Federal Regulations.

SMYS: The specified minimum yield strength (SMYS) is the yield strength specified for the steel when purchased and must be documented in the grade certification. When a pipeline is constructed the operator specifies the SMYS required for the project. The actual pipe received often exceeds the minimum because pipe manufacturers make multi-grade pipe joints with a single certificate specifying multiple grades

Grade: Is determined by the chemical composition and mechanical properties of a specific pipe steel. The chemical composition of steel used in the manufacture of pipe must conform with standards defined in the American Petroleum Institute (API) Specification 5L (API 5L) [3].

Let’s assume Factors of safety= 25%

Thickness = 0.0127 m

Outside diameter = 0.508 m

Minimum SMYS =195 MPa

Maximum pressure (Pa) = $(0.5 \times 0.0127 \times 195 \times 10^6) / 0.508 = 1228422.6$ Pa = 12.2 bar

1.8 Cleaning Before the Inspection

For so many reasons the pipe should be cleaned before the operations. A dirty pipe environment will lead to some problem to any pipe inspection robot especially in the cases of vertical pipes. The oil that sticks to the wall will decrease the friction coefficient. Moreover, the existence of any soled peaces will lead to the possibility of stopping the robot. Pipeline cleaning methods vary from pipeline to pipeline and depend on many factors such as pipe product, service, diameter and length. These methods are basically divided into three categories such as mechanical, hydraulic and chemical cleaning. Mechanical cleaning includes the techniques such as Rodding, Balling and Power Bucket. Hydraulic cleaning includes Flushing, Jetting and Scooter techniques. Chemical cleaning deals with Foaming, Dusting and Liquid application. Pipe cleaning schedules and maintenance programs are based on the age of the pipe and the problems it encounter [18].

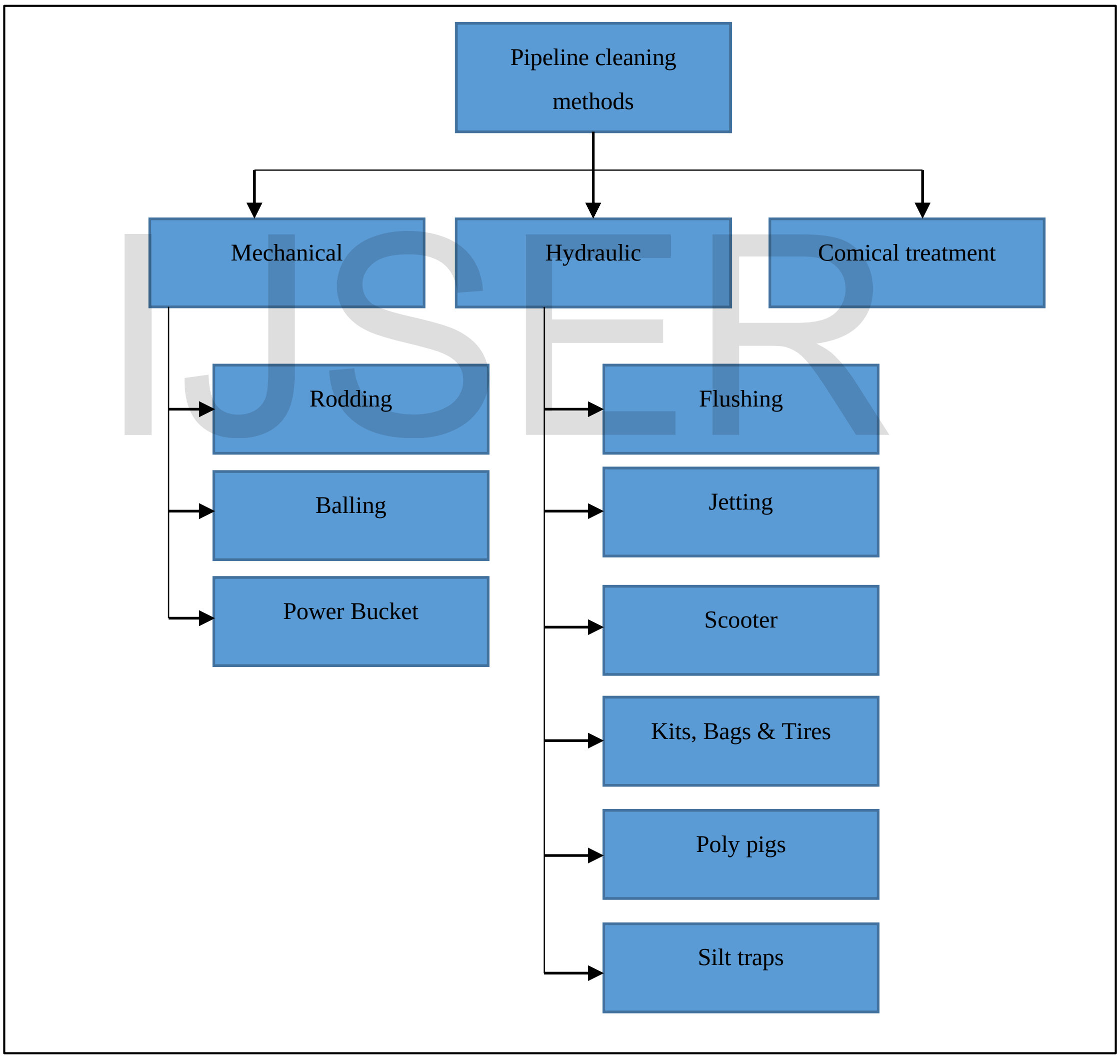


Fig. 13 – Oil pipe cleaning method classification

1.8.1 Mechanical

A) Roding: This method is used to break up grease deposits, cutting roots and debris loosening. It is also used for emergency removal of blockages to create way for TV inspection equipment in the pipeline

B) Balling: This equipment consists of sewer balls to fit different diameters of pipes, a tag line, winch, cable, reels, water source and a dump pick up. When the balls are passed in to the sewer, water will be forced with high pressure and velocity to clean the pipe. Balling is effective in removing heavy concentrations of sand, grit, rock and grease from the sewers. This method is not suggested for basement fixtures and pipe having steep grade.

C) Power Bucket: Power bucket is used to remove debris, roots, grease or sediments from main line sewers. A bucket machine is equipped with a set of specialized winches that pull a special bucket through a pipe to collect debris. The captured materials are then physically removed from the pipe [13] .

1.8.2 Hydraulic

A. Flushing: Flushing is the oldest and effective pipe cleaning technique, cleaning an existing pipe inexpensively. It helps to remove disinfectant residual, expel harmful bacteria, remove suspended sediment, and clear up other problems of water discoloration.

B. Techniques of Flushing: There are two techniques available in flushing which are conventional flushing and unidirectional flushing. Conventional flushing is nothing but opening up one or more fire hydrants and allowing the water to run in to the sewers until the sediments, bio films and poor quality water are removed. Unidirectional flushing is a technique in which valves are closed and fire hydrants are opened in a systematic way. Initially, the water travels towards hydrant in a single direction.

C. Jetting: Hydro jetting is the process of using water under high pressure to scour the pipe walls. It also helps in cleaning of grease, debris deposits, roots, sand or dirt and flushes it all away downstream

D. Scooter: This method is also a hydraulic method for cleaning of a sewer line. This is effective to remove heavy debris in large diameter sewers. These are also suitable for storm drains of large diameters. Precautions should be taken in case of basement fixtures and steep grades. This equipment consists of scooter assembly, dump pick-up truck, power winch, water tank truck, and a tag line.

E. Kites, Bags and Tires: This method is similar to the balling technique. These are more suitable for cleaning large sanitary sewers. Rigid rims on bag and kite induces scouring action. The kite’s shape creates a forward jet of water that scours the pipe wall. It is very effective in moving accumulations of decayed debris and grease downstream.

F. Poly Pigs: Poly Pigs provide a fast, simple and economical way to clean water mains and are frequently used to clean pressure pipes. According to Purinton (1984) poly pigs are mainly classified into two types mechanical and jelled chemical pigs which are used to remove scale inside the pipe. The pig works like a hydraulic ram to remove deposits and tuberculation from the main. They can be launched in a line through an existing fire hydrant or by removing a section of the main.

1.8.3 Comical Treatment

In this method, some chemical pushed along the pipe from inside to clean the pipe. Deferent kinds of chemical used depending on the type of dirt to clean and the composition of the pipe’s slab.

2. DESCRIPTION OF THE MECHATRONIC SYSTEM

In this chapter of this paper, the overall mechatronics system of the pipe inspection robot will be explained. Each individual part will be chosen, analyzed and explained from a mechanical perspective.

2.1 Deferent Modules of Pipe Inspection Robot.

Pipe inspection robot will be consist of deferent modules. Modules have to go in the pipe one by one like the trailers of the train. Each module has his own unique function according to its ordering and position. The ordering of the unit is considered according the direction of movement whether it is go away from the entering point (the opposite direction of the wire) or going backward (the direction of the wire).

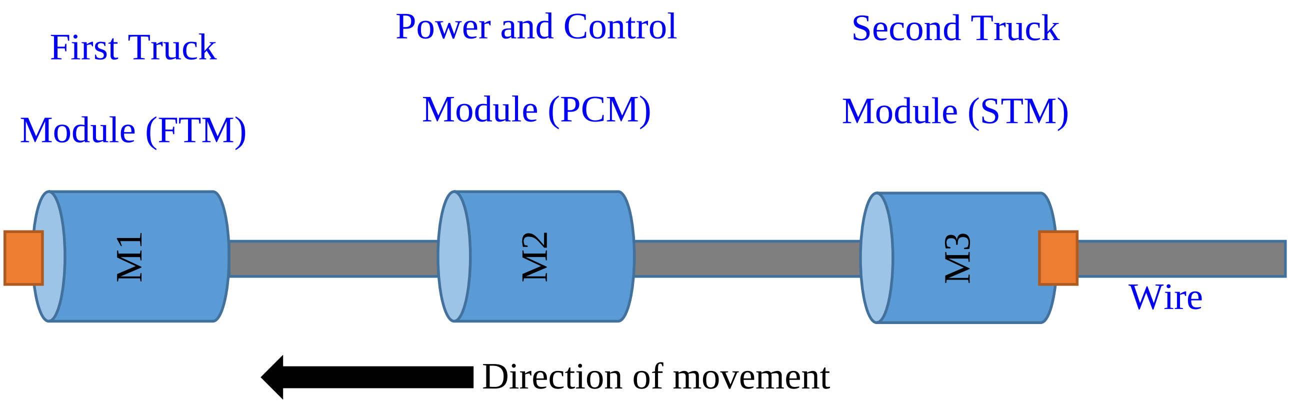


Fig. 14 – ordering Modules of pipe inspection robot

1- First Truck module (FTM): it is the first module that it goes in to pipe. The First truck module has tree motors to provide the robot with the push power and it also has 12 spring which work on creating the attraction power with the pipe walls. The front face of First truck module will be provided with a camera and light to provide the operator with visual of what happened inside the pipe it will also be provided with and set of sensor to sense the change of the geometry of the pipe. This unit is similar the Back Truck module in the design. When the robot is in going forward mode the module that is away from the wire the first module will act as master truck module and its sensor will start to work on detecting the changes in the pipe geometry. The second truck unit will act as slave truck unit and it will be synchronized according to the first truck unit movement.

2- Power and control module (PCM): this module is located between the first and second Truck module .The responsibly of this unit is energized all other unit and send all control signals. This unit does not have motors built with in so it has no pushing power. The main two components of the Power and control module are the PLC and the servo control amplifier

3- Second Truck module (STM): this module Identical in the mechanical and electrical design to First Truck module the deference that it is installed face to the back. When the robot is going the forward mode this unit will be synchronized according to the first truck and act as support to its pushing force. When the robot is going backward mode the vice versa happens.

2.2 Calculating the Dimensions of the Robot

Pipeline configurations give geometric limitations and the size of a robot should be. Determined to satisfy the limitations. In an elbow, the robot can be modelled as a cylinder and the relations can be derived among the diameter of the elbow, the curvature, and the size of the robot. The worst placement of the robot is when it is inclined with 45 degrees, as illustrated in (Fig 15).

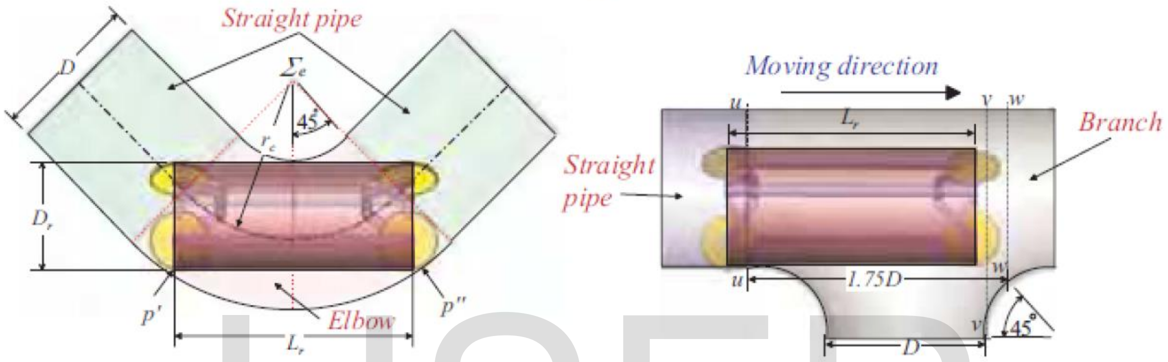


Fig. 15 – Size of the robot. (a) Size of the robot for negotiating the elbow. (b) Size of the robot for negotiating the branch

In this situation, two different cases can be considered: (a) the diameter of the robot D_r is relatively smaller than the height h, and both ends of the robot p' and p'' are located on the region of the straight pipeline. (b) Both ends of the robot are included in the elbow. Depending on the situation, constraint equations are derived to determine the size of the robot.

In the case of (a),

D_r has the range of

$$0 < D_r < \{\left(r_c + \frac{d}{2}\right)\sin 45 - \left(r_c - \frac{d}{2}\right)\} \tag{2}$$

The length of the robot L_r is given by

$$L_r = 2\sqrt{2}\{\left(r_c + \frac{d}{2} - \frac{d}{2} + D_r\right)\cos 45\} \tag{3}$$

Since r_c is represented as 1.5D in fig () the length of the robot L_r is rewritten by

$$\frac{3}{2}\sqrt{2d} \le L_r < \left(3\sqrt{2d} - 1\right)D \tag{4}$$

In the case of (b) the rang of D_r is obtained by

$$\left\{\left(r_c + \frac{d}{2}\right)\sin 45 - \left(r_c - \frac{d}{2}\right)\right\} < D_r < D \tag{5}$$

Thus, the length of the robot L_r becomes

$$L_r = 2\sqrt{((r_c + \frac{d}{2})^2 - (r_c + \frac{d}{2} + D_r)^2)} \tag{6}$$

And rewritten by

$$0 < L_r < \frac{3}{2}\sqrt[2]{2}\,D \tag{7}$$

Eqs. (7), (6), (5), and (3) provide the basic constraint equation so that the robot can moves in pipelines connected with elbows.In the branch, the size of the robot determines whether turning is possible or not. For example, when the length of the robot is a little longer in Fig. 7(b), the robot cannot turn in the branch though the robot has the proper size for moving in the elbow. When the *front wheel set* of the robot is placed in the branch and the *rear wheel set* has contact with the inner side of the straight section of the pipeline, the *rear wheel set* is confined absolutely to the straight section of the pipeline. The *rear wheel set* is kept from steering though the robot tries to turn. Thus, to turn in the branch, the *rear wheel set* should pass over the line *u*-*u* from which the area of the branch is. The robot should start turning before the *front wheel set* reach the line *v* -*v*. If the *front wheel set* passes over the line *v* -*v* and the robot tries turning, then separation and isolation will occur. However, the robot can turn in the branch until the *front wheel set* reaches to the line *w*- *w* if the body of the robot except wheels does not have contact with the wall. Therefore, the length of the robot should be shorter than 1.75D. On the other hand, the robot could turn easily but could not drive straightly because it would be isolated in the turn drive space if the length of the robot is shorter than the diameter D of the pipeline[4].

Thus, the length of the robot

L_r for negotiating branch is given by

$$D < L_r < 1.7D \tag{8}$$

Consequently, to determine the useful length of the robot in the elbow and the branch, Eqs.(4), (7) and (8) should be incorporated. From Eqs. (4), (7) and (8), L_r can be determined with Eq. (14) since D_r in (Fig 15) is flexible. Since we are working on 0.5 M inner diameter pipe, we will choose the robot length 0.55m

2.3 Mechanical Connection between Modules

Since the robot should be able to turn to all direction up , down , left and right so it need a spatial kind of connection .The (Fig 16) shows the universal join is consist of two join. The first join is with ability rotate around the z-axis makes the robot able to turn left or right. . The second join is with ability rotate around the y-axis makes the robot able to turn up or dawn. The combination of these two joins will make the robot able to perform the all the necessary manoeuvre as the same time prevent it from rotating around the x-axis (movement direction). The dimension of the join is suitable to make each module length to stay within the acceptable range of the robot dimensions.

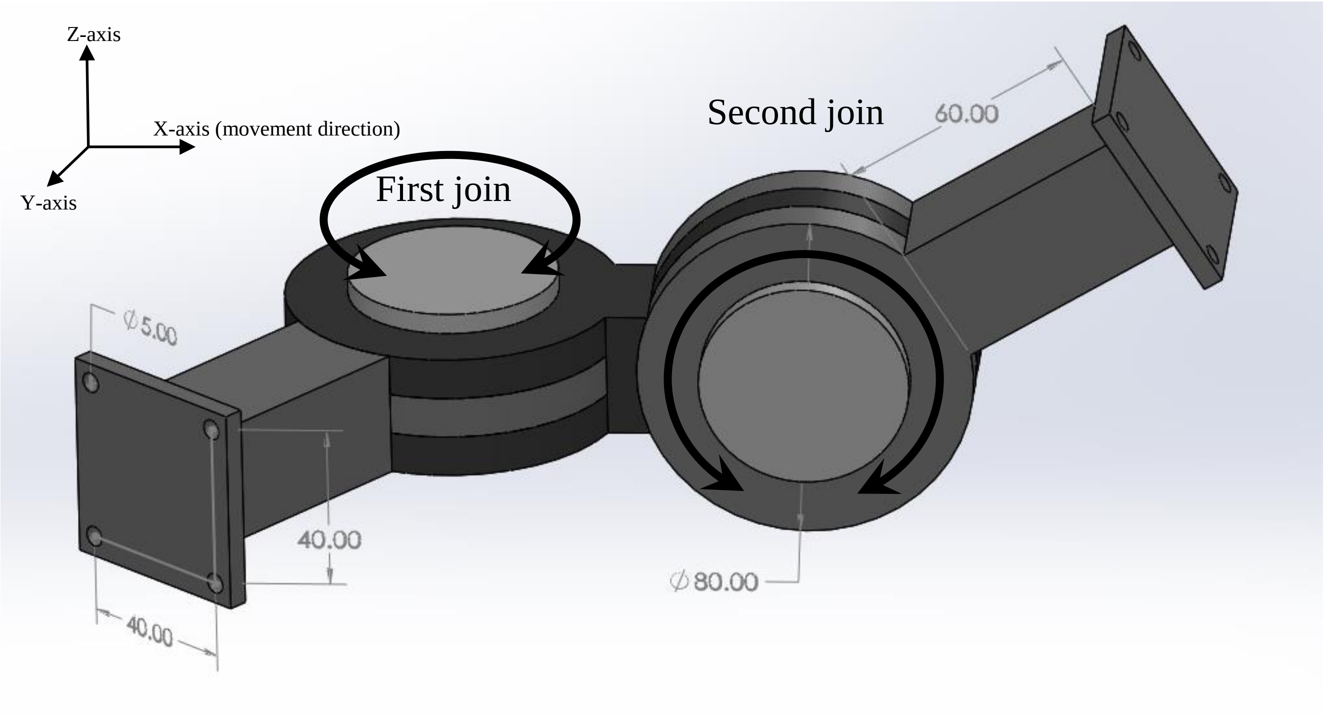


Fig. 16 - 3D design of universal connection between modules

2.4 Mechanical description of The Truck Module

A truck module is a responsible for moving the robot and keep it from slipping when going on the vertical pipe. The robot will be consist of three leg group align with 120 degree from each other. One group will be upward (Upper leg group) and the other two groups will be on the left (left leg group) and right (Right leg group). In this way, the centre of weight will be always on the middle part of the robot. During the robot movement, the three-leg group will apply a pressure force on the inner sides of the pipe. This will create the attraction power that prevents the robot from slipping when going in vertical pipe. Each leg group has the same component and design as shown in (Fig 17).

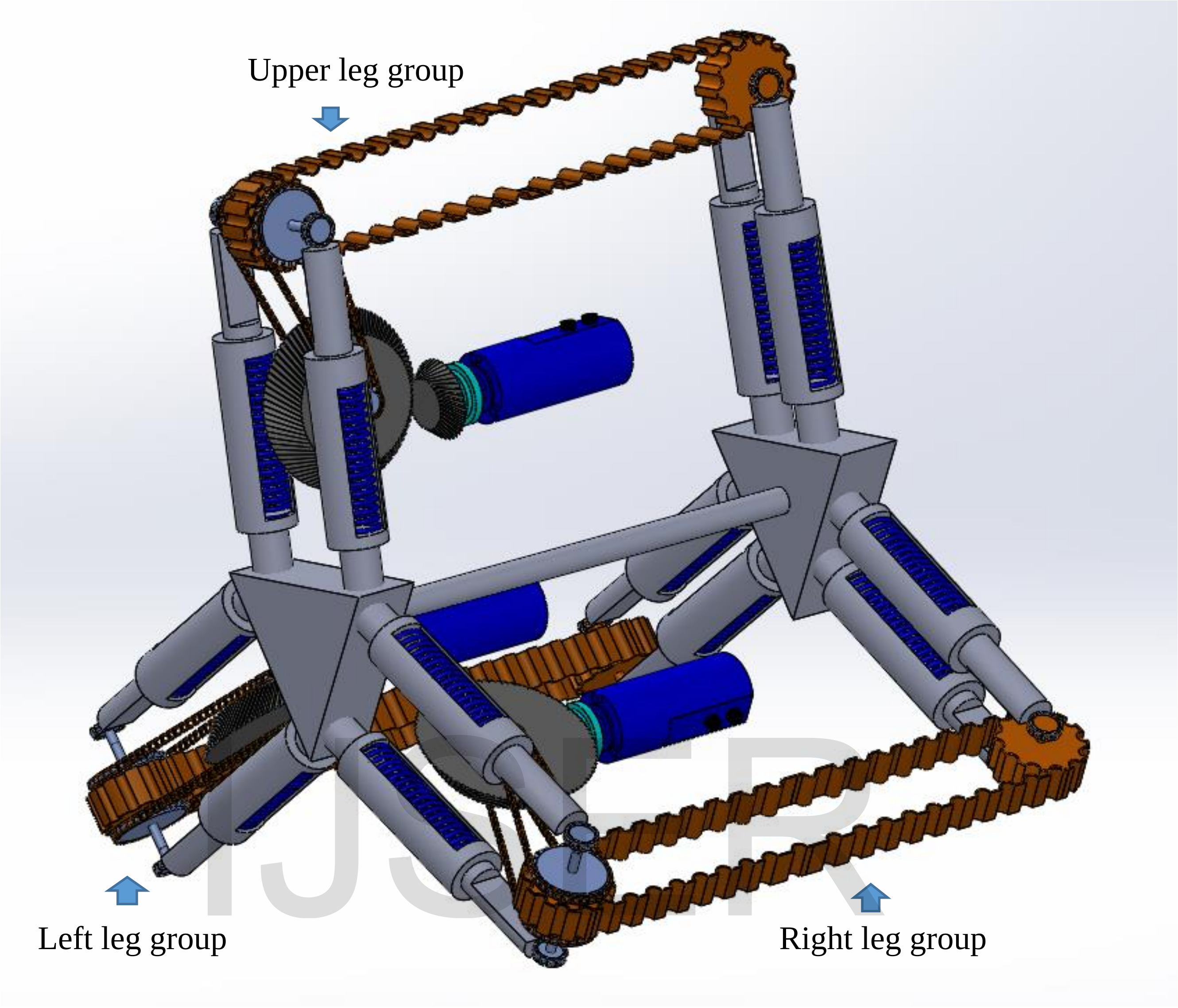


Fig. 17 - 3D design of the truck module

The component of each leg group will be listed as shown in (fig 18)

1- Permanent Magnet DC motor with encoder built inside

2- Gluch

3- Bevel gear of 4 diameter and of 12 diameter

4- Chain wheel sprocket

5- Four springs

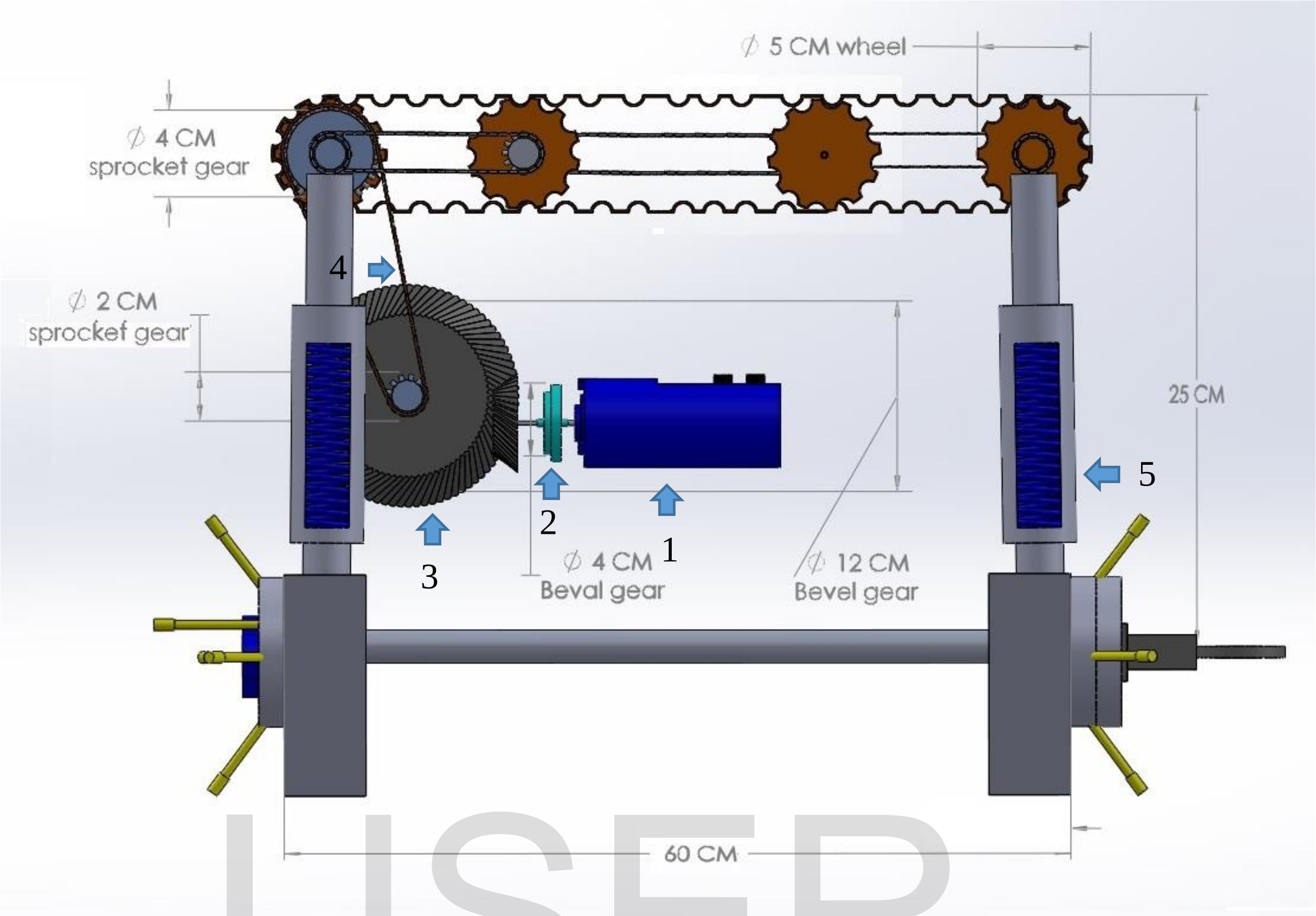


Fig. 18 - 3D design of one leg group with dimensions

2.4.1 Permanent Magnet DC Motor

Choosing a motor in any mobile macaronic robot is depend on the weight. Calculating the weight is important because it is directly affect the minimum and maximum load torque. To choose the right motor it is necessary to adjust the equilibrium between the motor continues stall torque and the final weight because both of them will has the effect on each other. The method of Calculating the motor maximum torque will be explained in more details at the end of this chapter after the final weight is calculated. (Fig 19) shows the cycler process of choosing the motor.

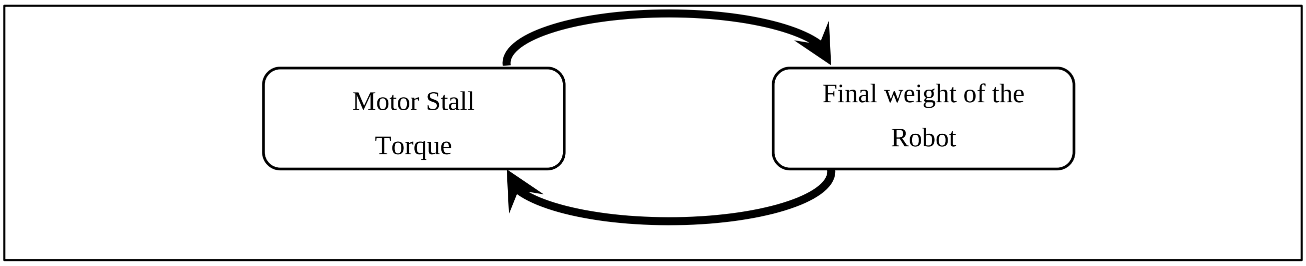


Fig. 19 - Cycler process of choosing the motor

BALDOR Co. is to provide the best quality products and solutions. We make constant improvements in the quality of our PMDC servomotors and drives. The chosen motor is MEB-4070-ANACE. This motor has 500 PPR encoder built inside as well as internal brake[8].

Fig. 20 - DC Servomotors and Drives by BALDOR

The MEB-4070-ANACE is a member of M4000 family of BALDAR motors. The M4000 family has common bore diameter of 16mm as show in (Fig 21).

Table 5 – Mechanical Parameters MEB-4070-ANACE

general		
Continuous Stall Torque	N-m	3.16
Continuous Current	amps	9.2
Peak Torque	N-m	14.1
Peak Current	amps	36.97
Viscous Damping	amps	0.181
Thermal Resistance	°C/watt	1.3
Thermal Time Constant	Min	65
Mechanical Time Constant	msec	9.76
Electrical Time Constant	msec	3.33
Rated Speed	rpm	2300
Rated Voltage	volts	100
Electrical		
Torque Constant	N-m/amp	0.382
Voltage Constant	v/r/s	0.382
Resistance	ohms	0.9
Inductance	mH	3
Mechanical		
Inertia	Kg-cm2	15.82
Maximum speed	rpm	2500
Weight	Kg	5.9

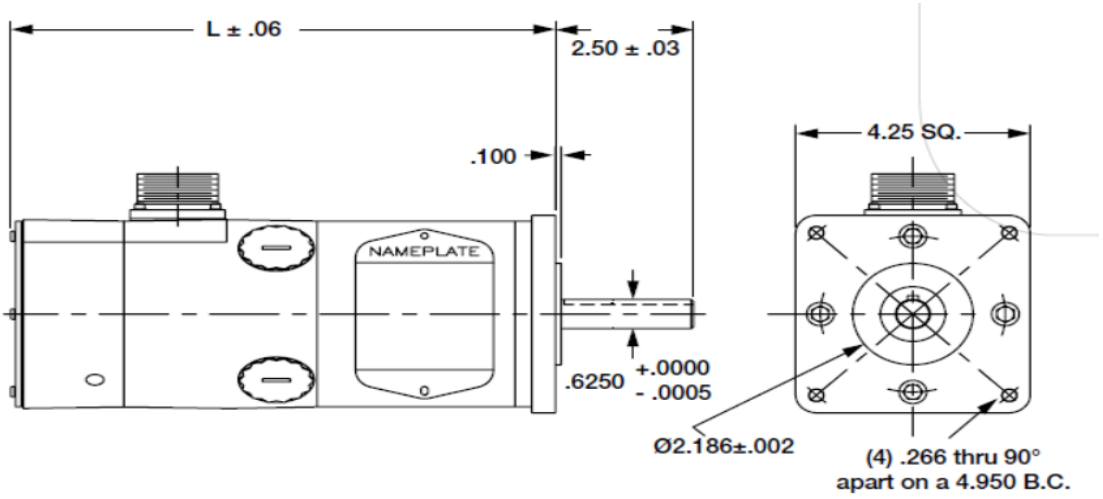


Fig. 21 - Dimensions of M4000 PMDC motor (all dimensions in inch)

According to the order number that we chose to out motor (MEB-4070-ANACE) the motor will have a brake and encoder built inside all the motor .Table 6 and 7 summarize the parameters of them

Table 6 – Parameters of the Brake

motor family	Holding Torque	Brake
	N-m	Watts
M4000	5.08	12

Table 7 – Parameters of the encoder

Specification	Description
Resolution(ppr)	100 / 500 / 100/ 1024 /2000 / 2500 / Custom
Output	Differential Line Driver Logic “1” Vcc = 2V (min) 4 ma Max Source Current Logic “0” Vcc = 0.4V (max)8 ma Max Sink Current
Voltage	Voltage 5 VDC ± 5% @ 80 ma
Inertia	0.0001 oz - in - s2
Frequency Response	200 KHz
Index	Non-gated There is no specific alignment between index and channels
Vibration	50 to 2000 Hz. @ 10 G's
Shock	30 G's for 11 ms

2.4.2 Clutch

Clutches are devices used to channel or isolate the motor rotational movement to the mechanical system. The Basic concept of their design and operation is simple. The Clutches is often composed of two equal sized gears with thread on their side. The first gear will be connected to the motor to rotate together with it. The second gear will be connected to the mechanical system (load).The second gear can be moved by solenoid to or the first gear or away from it. When the second gear is moved toward the first gear “by the solenoid force” their threads attached together. This action will channel the rotational movement from the motor to the mechanical system. When the solenoid is powered off the second gear will go back to its original position and due to that, the rotational movement of the motor will be isolated from the mechanical system. The clutch is useful to the pipe inspection robot when something wrong happened and it stops moving. The clutch then can be used isolate the movement from the motor and the robot can be pulled back by the wire.

Fig. 22 - Clutch picture

The clutch we chose is produced by INERTIA DYNAMICS Co. The SL, BSL and FL clutches are designed for parallel shaft mounting and will connect to the load via a chain or belt drive. The clutch can be mounted to either a driving or a driven shaft [5].

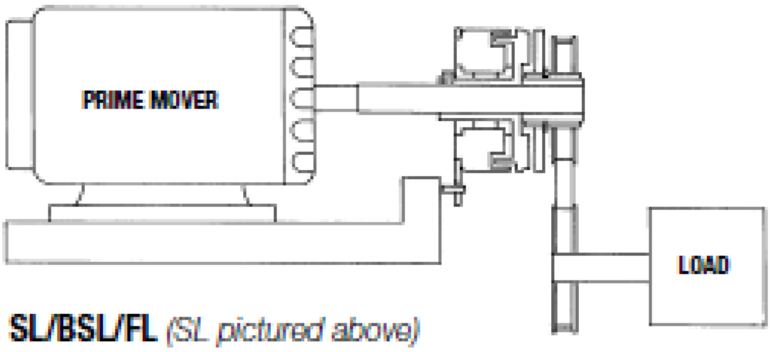


Fig. 23 - SL/BSL/FL Clutch mounting

Table 8 – Parameter of SL26

Mechanical					
Model No.	Static tongue N-m	Inertia Kg-cm2		WEIGHT kg	BORE
		ROTOR	ARM & HUB		10H9
SL26	9.04	1.062	0.855	0.794	15H9
Electrical					
Model No.		24 VDC			
SL26		AMPS		OHMS	
		0.358		67.1	

2.4.3 Bevel Gears

The gears we will used our robot will triple the value of the output torque and at the same time reduce the output speed to the third. We have in our system 2 kind of bevel gears 4 Cm that will be connected to the bore of the motor and 12 Cm. The gears we chose will be from KHK stock gears Co [10].

Table 9 – Parameter of KHK SMSG2-20RJ16 gear (For 4 Cm gear)

Catalogue Number	SMSG2-20RJ16	**Pressure Angle**	20°
Material	S45C	**Tooth Surface Finish**	Ground
Module	2	**Heat Treatment**	Gear teeth induction hardened
Speed Ratio	1	**Tooth Hardness**	50-60HRC
Number of Teeth	20	**Mounting Distance (mm)**	37
Pitch Diameter (mm)	40	**Tooth Type**	Spiral Teeth
Bore Diameter (mm)	16 keyway&screw hole	**Direction of Spiral**	Right
Bending Strength (Nm)	7.83	**Helix Angle**	35°
Surface Durability (Nm)	6.78	**Shaft Angle**	-
Precision Grade	JIS 2	**Weight kg**	0.13

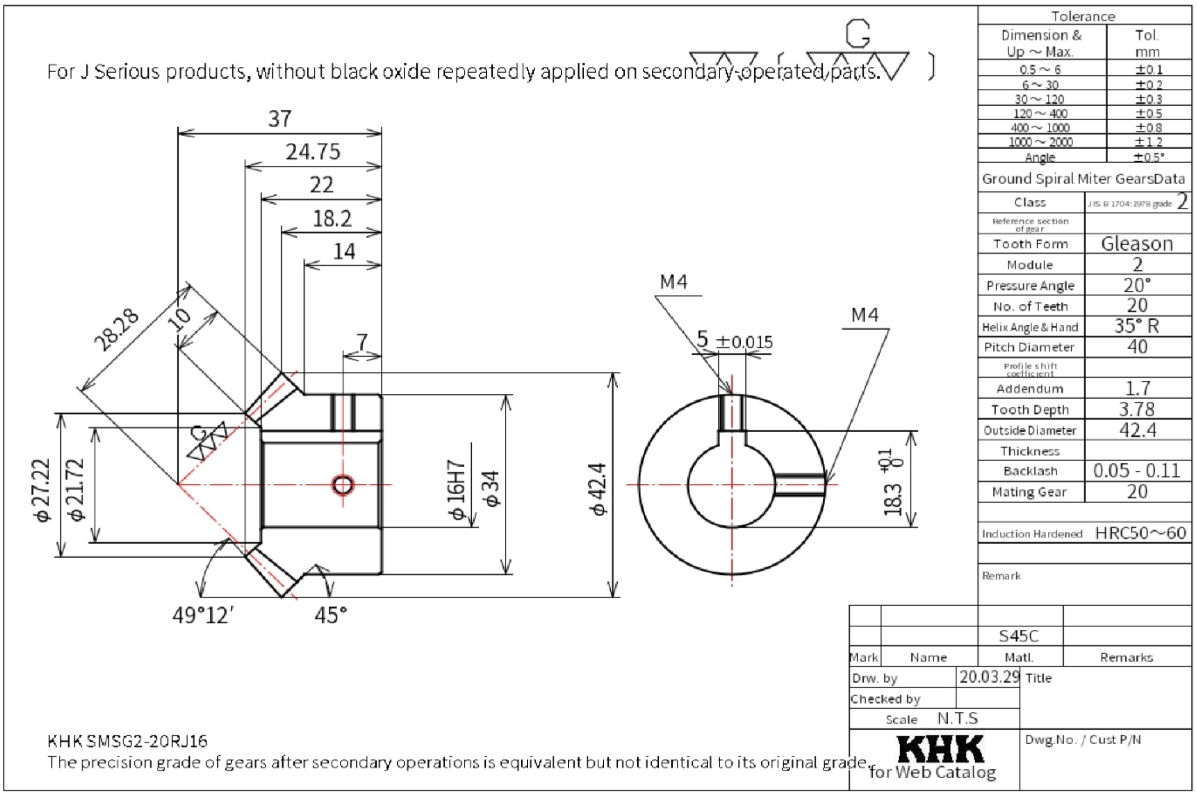


Fig. 24 - KHK SMSG2-20RJ16 gear dimensions

Table 10 – Parameter of KHK SBS2-6015R gear (For 12 Cm gear)

Catalogue Number	SBS2-6015R	**Pressure Angle**	20°
Material	S45C	**Tooth Surface Finish**	Cut
Module	2	**Heat Treatment**	Gear teeth induction hardened
Speed Ratio	4	**Tooth Hardness**	50-60HRC
Number of Teeth	60	**Mounting Distance (mm)**	42
Pitch Diameter (mm)	120	**Tooth Type**	Spiral Teeth
Bore Diameter (mm)	15	**Direction of Spiral**	Right
Bending Strength (Nm)	42.5	**Helix Angle**	35°
Surface Durability (Nm)	30.9	**Shaft Angle**	-
Precision Grade	JIS 4	**Weight kg**	1.59

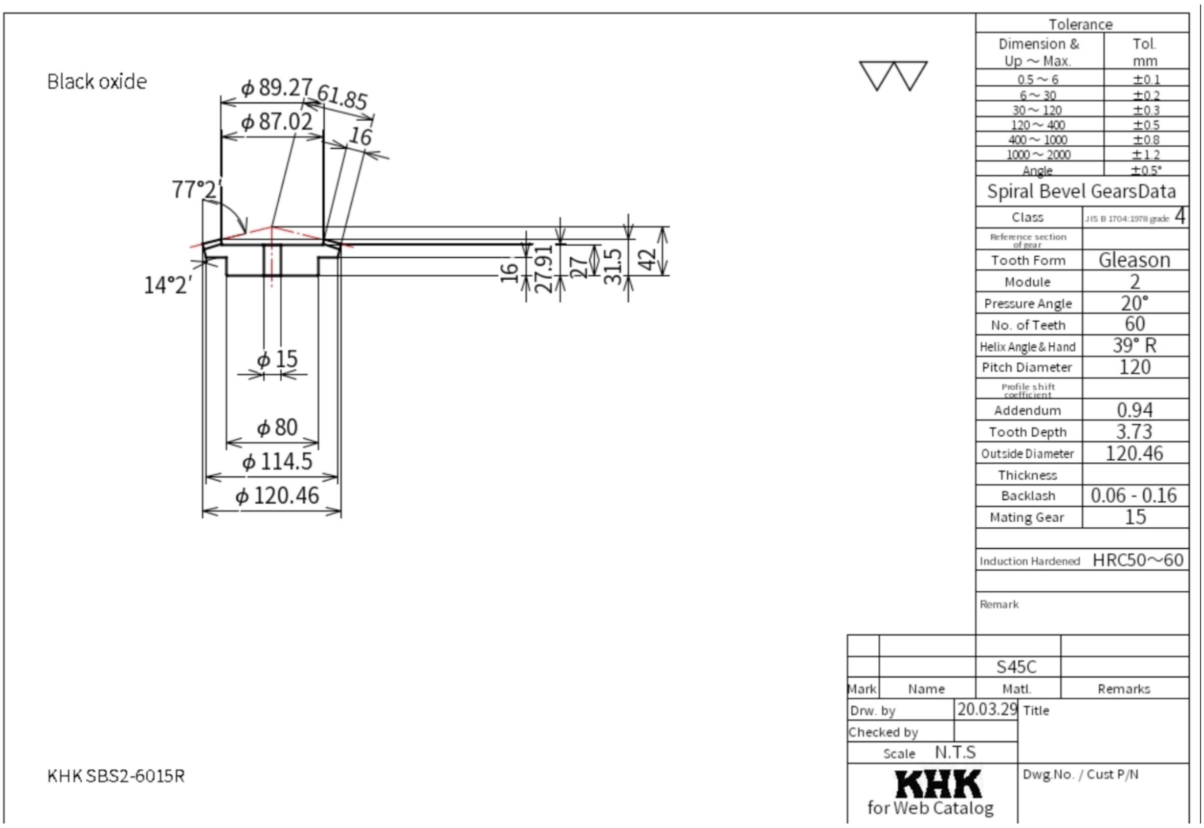


Fig. 25 - KHK SBS2-6015R gear dimensions

Fig (26) shows the logo of the KHK Co.

KHK®
STOCK GEARS

Fig. 26 - KHK Stock Gears

2.4.4 Sprocket

Our connected Sprocket will double the value of the output torque and at the same time reduce the output speed to the Half. The diameters will be 2 Cm and 4 Cm.U.S. Tsubaki SPROCKETS Co. will be the next catalogue that we will use . The first sprocket of 2 Cm from catalogue number 25B10 and the second sprocket 4 Cm 25B20.

Fig. 27 - Sprocket gears

2.4.5 Springs

The spring function is to keep the robot attached to the wall when claiming vertical pipe by Appling the vertical force in the wall. The spring will be installed inside a metallic cylinder and on the tope a screw shape shaft is used to make the length of the leg adjustable.

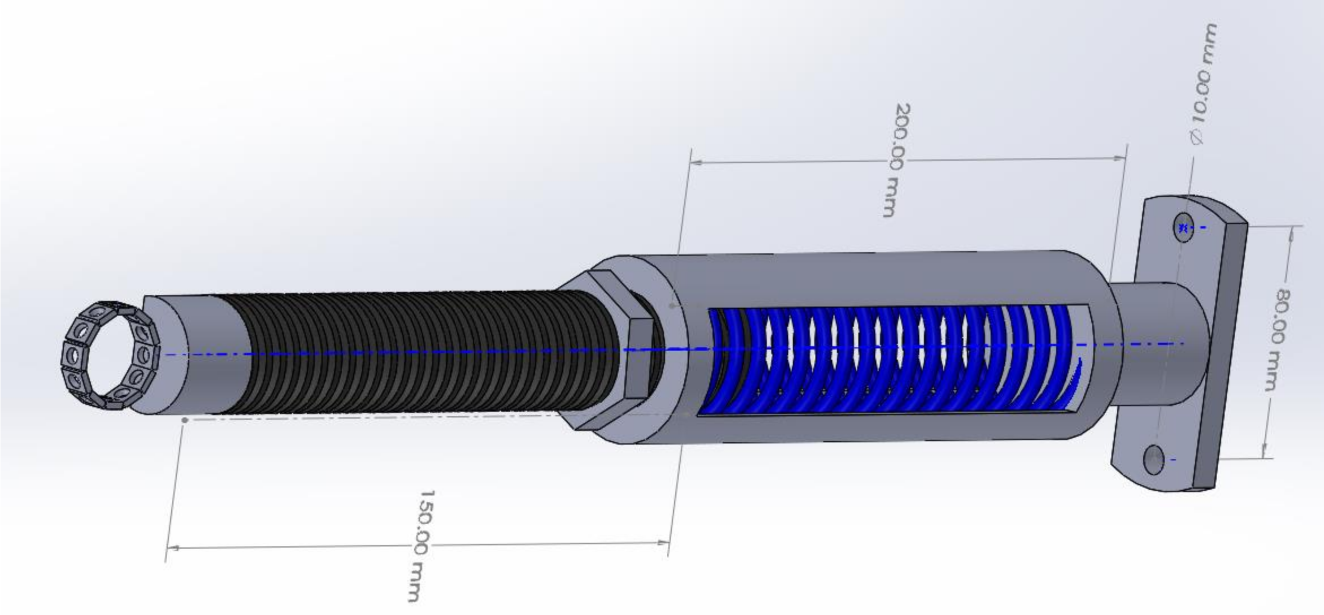


Fig. 28 - One Leg spring group

Century Spring Corp will provide us with the necessary spring below. The method of calculating the spring force will be discussed in the end of this chapter after we calculate the final weight of the robot [6].

Table 11 – Parameter of S-3231 spring

OD	CENTURY STOCK NUMBER	FREE LENGTH	I.D.	RATE	SUGG. MAX. DEFL.	SUGG. MAX. LOAD	SOLID LENGTH	WIRE DIA.	TOTAL COILS	MAT'L	Star	FINSH
21.03	S-3231	153.2	12	35	21	730	112.4	4.5	25	SST	G	N

2.5 Power and Control Module

The Power and control module will be responsible for providing the first truck and second truck module with the electrical power and also control signal. It will be consisted of two main component PLC and Servo Amplifier.

2.5.1 PLC

In our robot we will use Siemens S7 1215 DC/DC/Rly with one to additional analogue output modules. The weight of the PLC and the additional modules will be less than one kilogram and with update speed of 1 KHz. More Details about choosing the PLC and its properties in chapter 3.

2.5.2 Servo Amplifier

Six servo amplifier (M1525-BL Brushless Servo Amplifier) will be installed inside the power and control unit .Each one will be responsible for controlling one of the motors. The weight of each one is 0.7 Kg. All other electrical details will be explain in chapter 3.

2.6 Calculating the Final Wight of the Robot

Calculating the weight of robot will help us calculating the Max load torque and the required frictional force when claiming vertical pipe.

1- Calculating the final Weight Truck module

The weights of all the equipment built inside the truck module are summarized in Table 11.

Table 11 – Weight summery of the truck module

Item	Weight(Kg)	Qun.	final Weight(Kg)
Motors	5.9	3	17.7
12 Cm gear	1	3	3
4 Cm gear	0.1	3	0.3
Sprocket gear 2 CM	0.015	6	0.09
Sprocket gear 4 CM	0.1	6	0.6
well	0.4	12	4.8
spring	0.2	12	2.4
Clutches	0.9	3	2.7
Additional weight			8.4
Final Weight			40

2- Calculating the final Wight Power and control module

The weights of all the equipment built inside the Power and control module are summarized in Table 12.

Table 12 – Weight summery of the Power and Control module

Item	Weight (Kg)	number	final weight (Kg)
Motors	1	1	1
12 Cm gear	0.7	6	4.2
Additional weight			4.8
Final Weight			10

3- Calculating the final Wight of the robot

The weights of all the Modules built inside the Robot are summarized in Table number 13.

Table 13 – Weight summery of the Robot

Item	Weight (Kg)	number	final weight (Kg)
Truck Module	40	2	80
Power and control	10	1	10
Additional load			30
Final Weight			120

2.7 Calculating Maximum Torque of Each Motor

As shown in the figure bellow we will see one leg group of three groups in total each one of them have the same equipment and same design.as we see in the figure below the weal diameter is 0.05M so if want to calculate the torque on all legs we will have.

$$(\text{Max Weight} * 9.8) * 0.05 = 29.4 \text{ Nm} \quad (9)$$

$$(120 * 9.8) * 0.05 = 58.8 \text{ Nm} \quad (10)$$

Since we have three legs in each one of the two truck modules, so the torque in each leg will be,

$$58.8 / 6 = 9.8 \text{ Nm} \tag{11}$$

As we see that, we have gears that change the movement from 0.4M diameter gear to 0.02M diameter gear .and then from 0.12 M gear to 0.04 M gear .so the final torque applied on the motor will be

$$9.8 * (0.02 / 0.04) * (0.04 / 0.12) = 1.63 \text{ Nm} \tag{12}$$

2.8 The friction coefficients and friction force and choosing the spring types

To the friction coefficients, we need to know about the tow materials and their statues. Usually the pipe is made of steel and the real chain in our robot is made of steel too. Their statues is usually lubricated. From the bellow website, we will find the coefficient [9] https://www.engineeringtoolbox.com/friction-coefficients-d_778.html

Table 14 – Frictional Coefficient between steel and steel

Materials and Material Combinations		Surface Conditions	Frictional Coefficient	
			Static - μstatic -	Kinetic (sliding) - μsliding -
Steel	Steel	Lubricated and Greasy	0.16	-

For lubricated and greasy, steel to steel, we have 0.16 friction coefficient

For horizontal pipe position, we need to calculate the vertical power of the spring to make the robot able to claim

$$F_f = \mu * \text{spring force} *6 \text{ (because we have six leg group)} \tag{13}$$

$$1200 = 0.16 * \text{springs force} \tag{14}$$

$$\text{Springs force} = 120 / (0.16*6) = 1250 \text{ N} \tag{15}$$

Each leg group has two springs. So each spring should supply a force of 1250/2 = 625 N

2.9 Calculating the maximum pressure applied by the robot

Our force will applied on the bottom of three connecting chains of 0.55 M length and 5 cm width so the maximum pressure that the robot will make

Max pressure = (Springs force + Truck module weight/2) / (Aria of the belt) (16)

Max pressure = (1250 + 200) / (0.6 * 0.05) = 50909.09 Pascal = 0.509 bar (17)

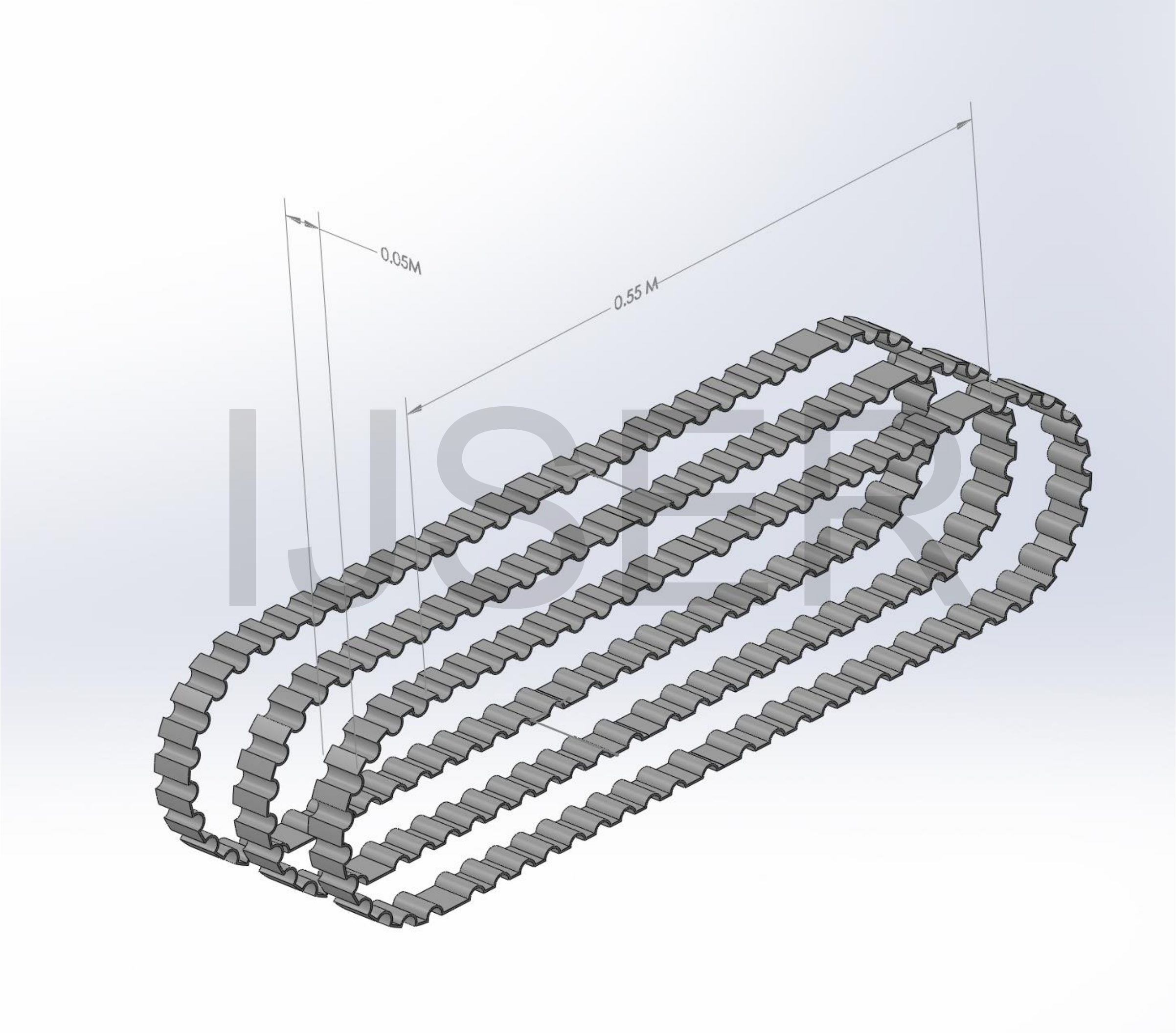


Fig. 29 - Pressure Aria of the Belt

3 DESCRIPTION OF THE ELECTRICAL CONTROL SYSTEM

In this chapter, we will explain the electrical circuit connection methods and how that is can be a big part of the automation and control. The method for choosing the PLC will be explained in detail also.

3.1 Automation scheme

Automation scheme is shown in the (fig 30). The automation will be consist of three part the part is inside the power and control unit. This part will be consist mainly of the PLC and the servo amplifiers. The other two part will be inside the truck modules one and two. The main equipment to control inside the truck modules is the motors. In addition, we need to control the clutches and the breaks. The truck modules will send the signals of the electro photo sensors.

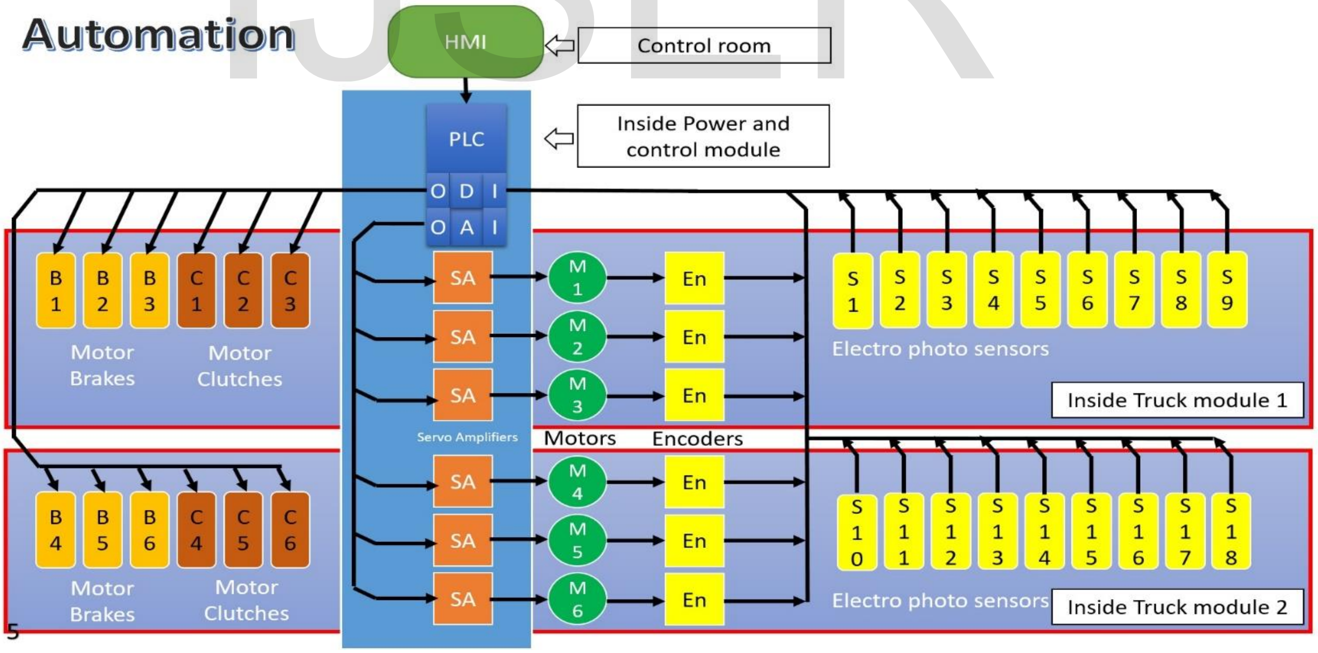


Fig. 30 - Automation scheme

The power and control module will have inside one PLC and six servo-amplifier. The PLC will work on controlling the motors by sending the analog signals to the servo-amplifier. The servo-amplifier will amplify the analog signal to match the motor voltage. The controlled voltage will be sent to the motors to control their rotational speed as shown in (Fig 31). The digital output of the PLC will control the breaks of the motors as well as the clutches. The digital input will read the signals from the photoelectric sensors and read encoders reading.

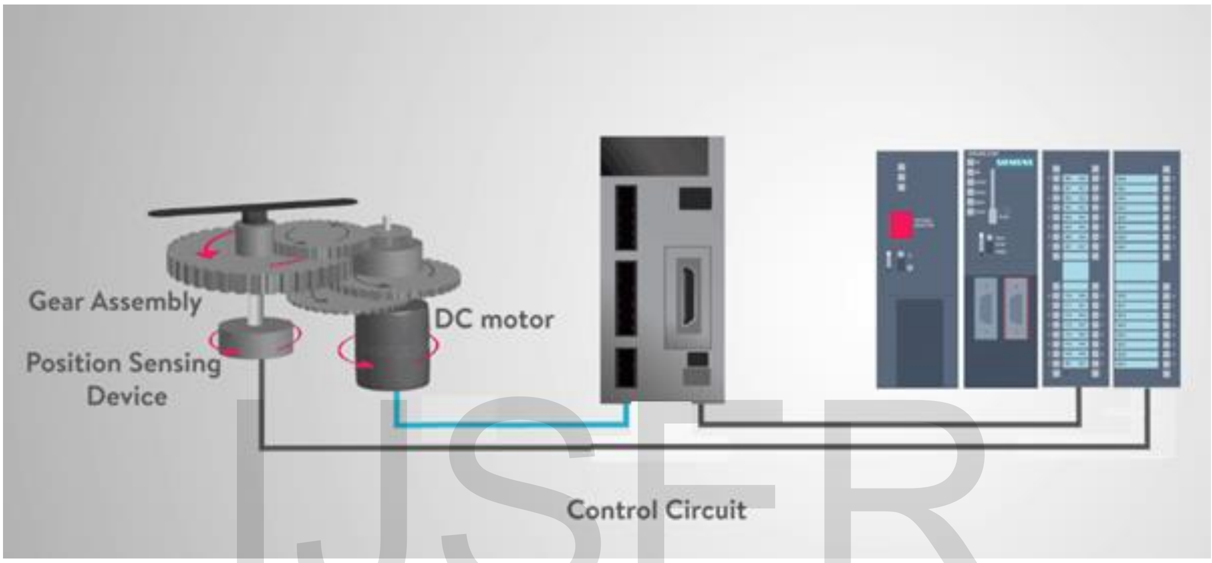


Fig. 30 - Servo Control method

3.2 Selection the Suitable PLC

Choosing the PLC for the pipe inspection robot is depending on so many criteria's. We already explained about the weight of the PLC in chapter two so now we will explain the choosing the PLC from electrical and control requirement perspective.

To select an approximate PLC for this automation systems, firstly, we need to determine the signals in this system.

1- Digital Inputs

a) Eighteenth digital 24VDC inputs produced by eighteenth photoelectric sensors.

b) Six digital 24VDC inputs produced by six encoders for measuring the speed of the six motor we have on both truck modules.

2- Digital Outputs

a) Six digital 24VDC Outputs to control the breaks of each motor on both module.

b) Six digital 24VDC Outputs to control the Clutches of each motor on both module.

3- Analog Outputs

Six Analog +-10VDC Outputs to control the breaks of each motor on both module.

4- One PROFINET interface for communicating with HMI.

5- The PLC should be able to provide at least six PID controller to enhance the response of the motor.

The SIMATIC S7-1200 controller is modular and compact, versatile, a secure investment, and is powerfully fit for a full range of applications. A scalable and flexible design, a communication interface that fulfils the highest standards of industrial communication and a full range of powerful integrated technology functions make this controller an integral part of a complete and comprehensive automation solution. The new modular SIMATIC S7-1200 controller is at the core of our new offering for simple but highly precise automation tasks[12]. The optimized performance of our SIMATIC HMI Basic Panels, designed for seamless compatibility with this new controller and the powerfully integrated engineering system, ensures simplified development, fast start-up, precise monitoring and the highest level of usability. It‘s the interplay between these products and their innovative features that give you an unprecedented level of efficiency for small automation systems. Up to 16 PID control loops with auto-tune functionality are possible in the SIMATIC S7-1200 controller for simple closed-loop process control applications.

The PLC we choose is SIMATIC S7-1200 with CPU 1215 and type DC/DC/Rly. The work memory is 25 KB; It has a 24VDC power supply with DI8 x 24VDC SINK/SOURCE, DQ6 x relay and AI2 and AQ2 on board. It also has a 16 high-speed counters (expandable with digital signal board) and 2 pulse outputs on board. In addition, it has a PROFINET interface for programming HMI and PLC to PLC communication. What's more, signal board expands on-board I/O; up to three communication modules for serial communication; up to 2 signal modules for I/O expansion; 0.1 ms/1000 instructions;

Since we need 10 digital 24VDC inputs, we have to add an additional DI4 signal board with 4 digital 24VDC inputs into the PLC to expand the input number[11].

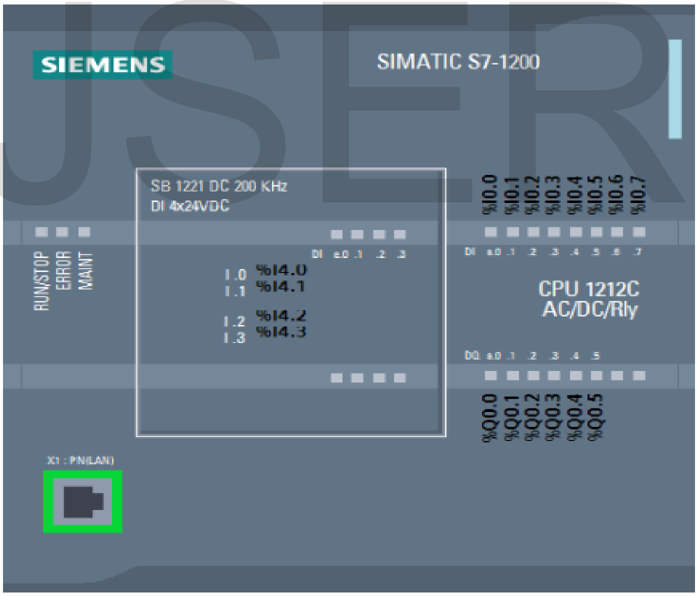


Fig. 31 – SIMATIC S7-1200 controller

3.3 The Choosing of the Suitable Servo Amplifier for the Motor

The servo amplifier function is to amplify the out voltage from the PLC to make it suitable for running the motor. To choose the Servo Amplifier we need to consider that its control signal should match the analog output of the PLC. In addition we need to make sure that its output matches the input voltage requirements of the motor. Since the analog output of our PLC (+- 10 volts) and the required voltage of our PMDC motor is 150 VDC the M1525-BL Brushless Servo Amplifier from MIDWEST MOTION PRODUCTS will as suitable for our design because it has the required characteristics [16].

Fig. 32 – M1525-BL Brushless Servo Amplifier

Table 15 – Parameter of M1525-BL Brushless Servo Amplifier

Performance Characteristics	
Peak Power	3.75 kW
Peak Output Voltage	+ -150 VDC (shut off @ 205 VDC)
Peak Output Current	+ -25 amps (1 sec.)
Max. Continuous Current	+ -15 amps (50 C), 19 amps (25 C)
Internal Shunt Regulator	55 W continuous, 2.4 kW peak for 0.2 seconds
Encoder or Hall Comumutation	(activates at 190 VDC)
Dead Band	Zero
Electrical Characteristics	
Input Signal Voltage	+ -10 VDC (typ), + - 35 VDC (max)
System Gain	0 to 5100 amps/volts - velocity mode
	0 to 10.0 amp/volt - torque mode
Input Impedance	40 K Ohms
Typical Input Drift	10 u V/C
Bandwidth	3 kHz with 1.2 mHy Inductance
Dead Band	Zero
Electrical Characteristics	
Input Voltage	60 - 170 VDC
Adjustments	
Peak Current Limit	0 to 25 amps
RMS Current Limit	0 to 19 amps
Signal Command Input	Scaling
Balance	Zero velocity offset
Compensation	System response
Tachometer	Scaling
Physical Characteristics	
Module Dimensions	7.6 in. x 1.0 in. x 5.7 in.
Weight	1.4 lbs.
Ambient Temperature	0C to 50C
Shutdown Temperature	80C at heat sink
Relative Humidity	5 - 95% non-condensing

3.4 Electrical Control Circuit

The connection of the electrical circuit is shown in (Fig 33) that shows an example of connection of each item. The main Items of the electrical circuit are the power cable, Transformer, photoelectric sensor circuit, motor drive circuit, controller circuit and other.

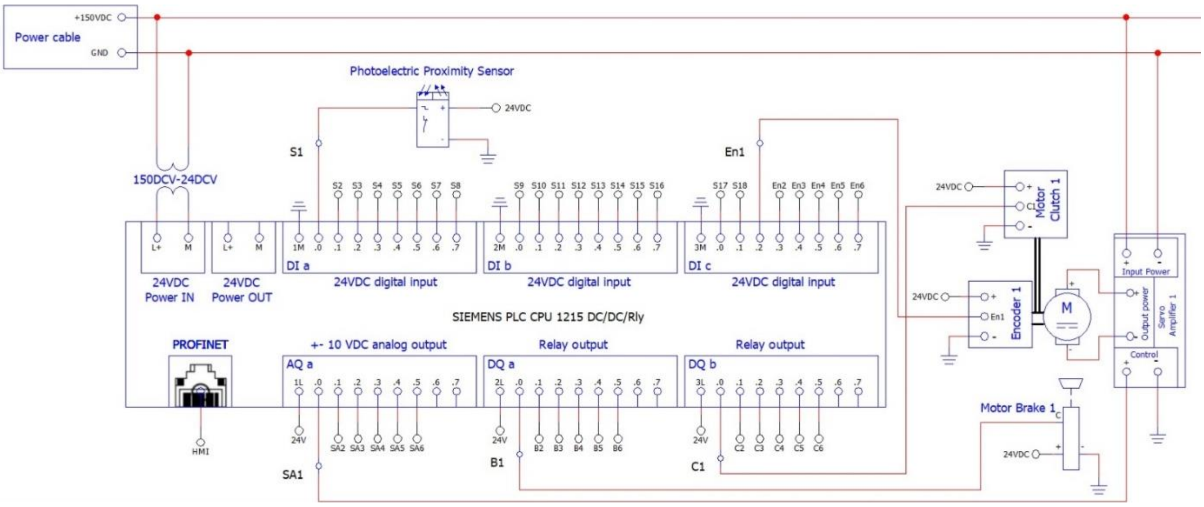


Fig. 33 – Connections of the electrical circuit

1- Power Cable

The Power Cable will send the power to the entire system. The power required in our system 150 VDC.

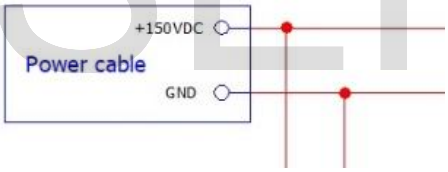


Fig. 34 – Power Cable

2- Transformer

The Transformer will work on changing the voltage from 150 VDC to 24 VDC .The 24 VDC is required to provide the power for the sensors ,clutches, break and PLC . We will choose for our robot 150 VDC mini maxi transformer.

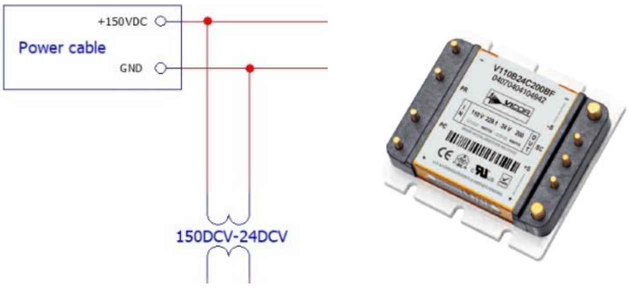


Fig. 35 – 150 VDC to 24 VDC Transformer

3- photoelectric sensor circuit

The input of photoelectric sensor is 24VDC from STOP and the output of which is PNP type with 150mA maximum current. When the photoelectric sensor switch on, it output high voltage signal. When the photoelectric sensor switch off, it output low voltage signal[16].

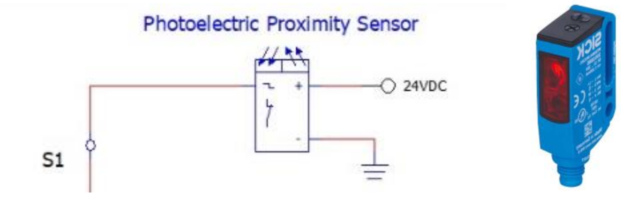


Fig. 35 – NPN photoelectric sensor

4- Motor Drive Circuit

The motor drive circuit is start with the servo amplifier that receive its power from the power line directly. The motor works with 150 VDC maximum so the servo amplifier will provide the necessary voltage according to the control signal that comes from the PLC.

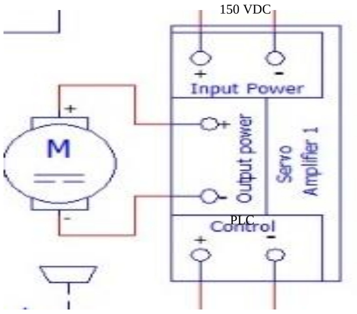


Fig. 36 – motor drive circuit

5- Encoder circuit

The transformer will provide the encoder by 24 VDC to energize it. The output of the encoder will sent directly to the PLC.

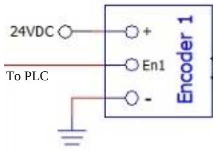


Fig. 36 – Encoder sensor

6- Clutches circuit

The transformer will provide the clutch by 24 VDC to energize it. The input control signal of the clutch will come directly from the PLC.

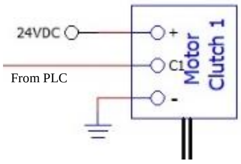


Fig. 37 – Clutches circuit

7- Clutches circuit

The transformer will provide the motor break by 24 VDC to energize it. The input control signal of the clutch will come directly from the PLC.

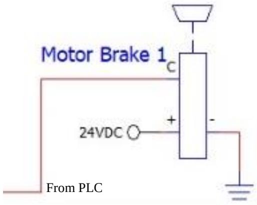


Fig. 38 – motor break circuit

4. FUNCTIONAL SIMULATION IN MATLAB

MATLAB(matrix laboratory) is a multi-paradigm numerical computing environment. A proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python.

To validate the performance of the packaging system, we use MATLAB to analyze the mathematical model of the system and perform simulation analysis in MATAB combined with the system's operational logic.

4.1 Simulating the PMDC motor of the truck module

To create a block diagram representing the PMDC motor’s behavior, the main equations associated with the PMDC motor are first converted to the Laplace domain. For example, the equation for the armature voltage:

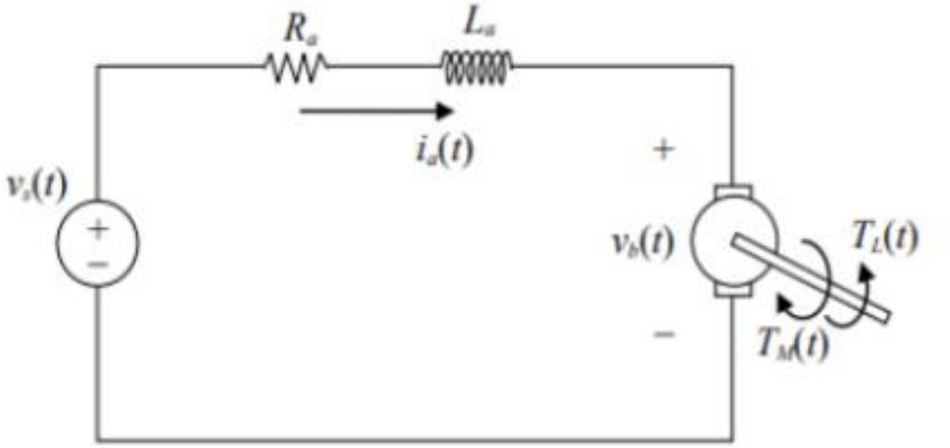


Fig. 38 – Simulation of motor circuit in time domain

$$v_a(t) = e_a(t) + R_a i_a(t) + L_a \frac{di_a(t)}{dt} \tag{18}$$

Transforms into the following equation in Laplace domain:

$$V_a\,(s) = E_a\,(s) + R_a I_a\,(s) + s\,L_a\,I_a\,(s) \qquad (19)$$

Where the principle that a derivative in the time domain equates to multiplication by $s = j\omega$ in the Laplace domain was used. Solving this equation for the current, which is the variable we want to control, results in the following:

$$I_a\,(s) = \frac{V_a(S) - E_a\,(s)}{R_a - sL_a} \qquad (20)$$

Similarly, start with the equation for the PMDC motor’s electromagnetic torque:

$$T_{em}\,(t) = T_L\,(t) + B\,\omega_m\,(t) + T_f + J_{eq}\,\frac{dW_a\,(t)}{dt} \qquad (21)$$

Then ignore the frictional losses, convert the equation to the Laplace domain, and solve for the speed (which we want to control) to obtain the following:

$$\omega_m\,(s) = \frac{T_{em}(S) - T_L\,(s)}{sL_{eq}} \qquad (22)$$

The behaviour represented by equations (1) and (2) above can be put into block diagram form as shown in Figure

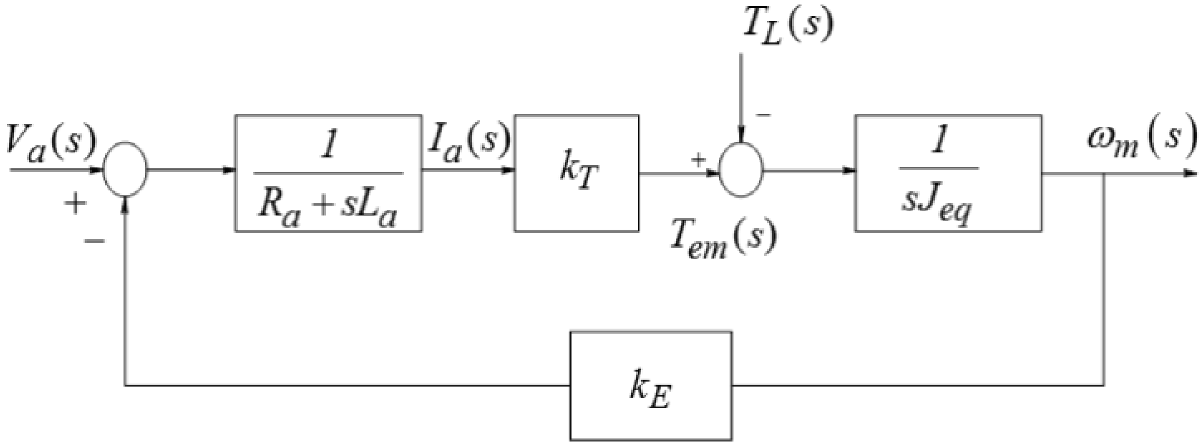


Fig. 39 – Block diagram of the PMDC motor’s transfer function

4.2 PID tuning

In 1942 two methods for tuning the parameters of P-, PI- and PID controllers were published by Ziegler and Nichols. One for open loop and the other for second loop.

The Ziegler-Nichols' open loop method is based on the process step response. The PID parameters are calculated from the response in the process measurement y_m after a step with height U in the control variable u, see Figure 40. All blocks in the control except the controller well be identified by the term "process". The step response experiment is executed on the uncontrolled process, so the control loop is open (no feedback) [18].

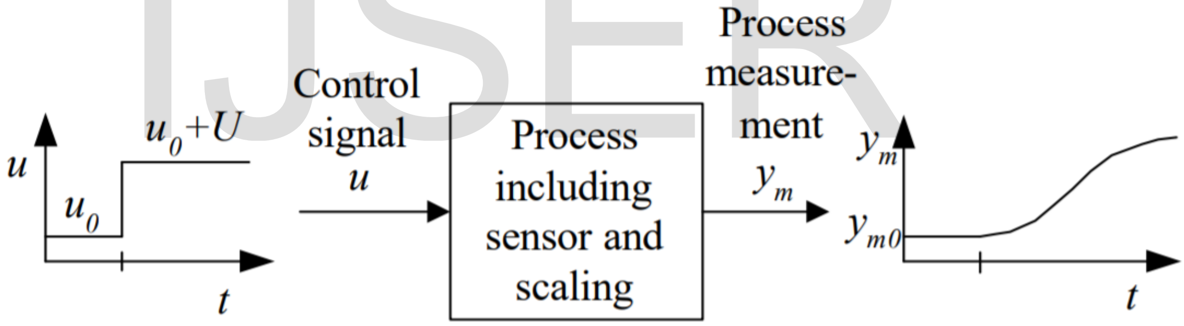


Fig. 40 – The Ziegler-Nichols' open loop method is based on the step response of the uncontrolled process

The method is as follows.

1. If the control loop is closed (i.e. feedback), the loop must be opened. This can be done by setting the controller in manual mode.

2. Bring the process to the operation point by adjusting the control variable manually. This is done by adjusting u0 in Figure 40.

3. Excite the process via a step of amplitude U in the control variable u. The step should be “small” so that the process is not brought too far from the operation point, but of course the step must large enough to give an observable response in process measurement y_m. A step amplitude of U = 10% can be a reasonable value, but the amplitude must be chosen individually in each case. 4. Read off the following characteristic parameters from the step response in y_m:

- Delay time T
- Time constant L

Figure 41 which shows the relevant part of a typical step response. In the figure the time axis starts at the step time. The annotation “0.0” along the y-axis corresponds to ym0 in Figure 2. L is the time from the step time to the point of intersection between the “0.0”-line and the steepest tangent. R is the slope of the steepest tangent.

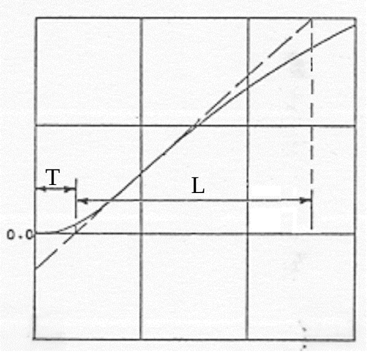


Fig. 41 – Ziegler-Nichols’ open loop method: The equivalent dead-time L and rate R read off from the process step response.

5. Calculate the controller parameters according to Table 1.

6. After the controller parameters have been calculated and entered into the PID controller, the control loop is closed (by setting the controller in automatic mode).

Table 16 – Parameter of PID according to Ziegler-Nichols’

Type of Controller	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

The picture below is shown the simulation of the open loop Matlab Simulink circuit of the PMDC motor chose.

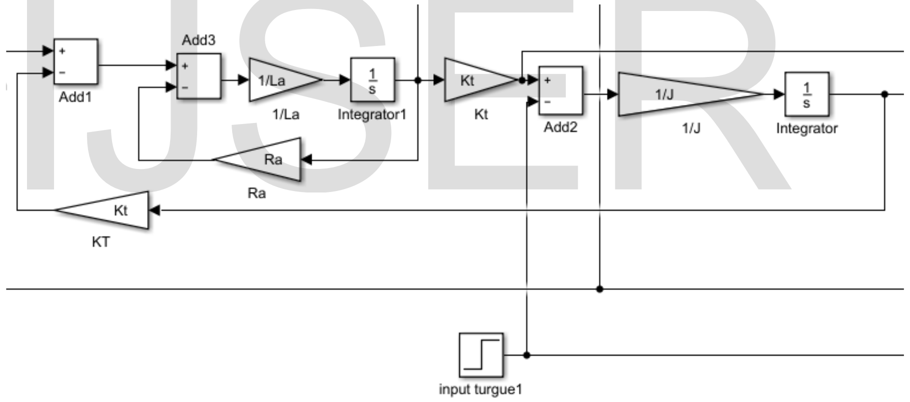


Fig. 40 – Block diagram of the PMDC Open loop transfer function

To get the step response of open loop we will supply 100 VDC as step input to the PMDC Open loop measure the output response and then apply the Ziegler-Nichols method.

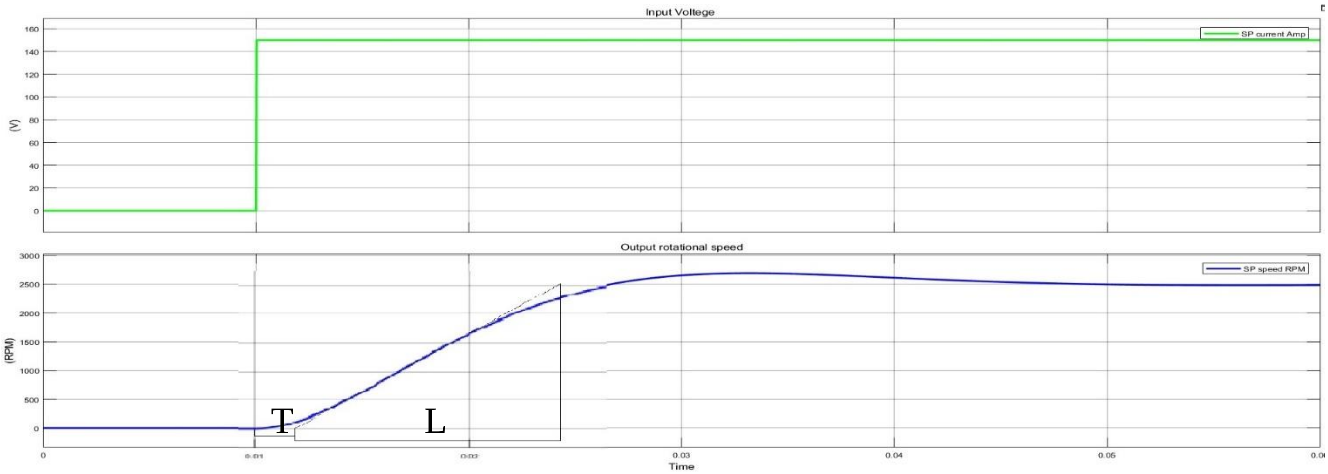


Fig. 40 – PMDC motor’s step response

As shown in figure 40 the step response we get the value of T & L

- T = 0.02 sec
- L = 0.12 sec

Now according to table 16 we can calculate the parameters of the PID

- $K_P = 0.5$
- $K_I = 0.24$
- $K_D = 0.06$

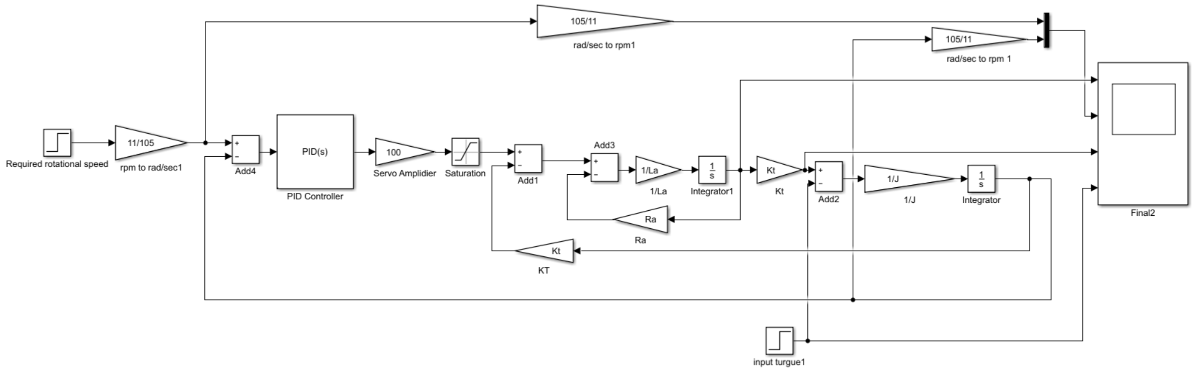


Fig. 41 – Block diagram of the PMDC with the PID in close loop system

After tuning the PID we can observe the final response in (Fig 42) we can see the response has very small error that can be neglected when we start the motor and when we apply the input torque as disturbances.

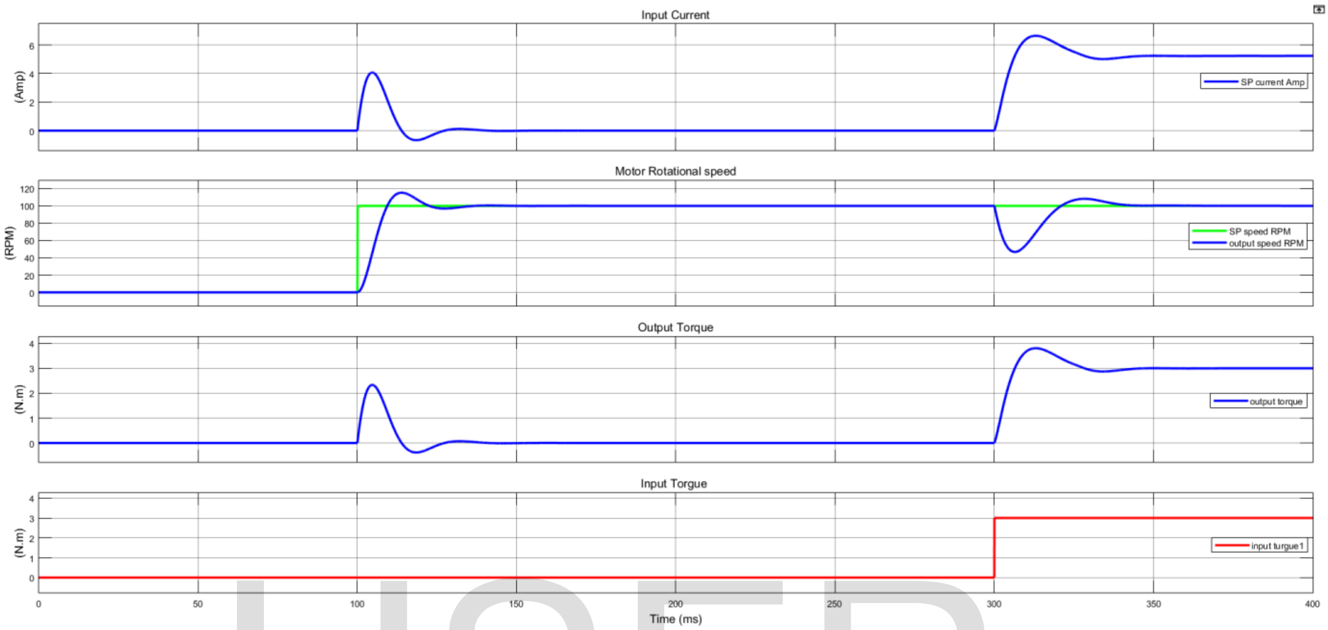


Fig. 42 – PMDC motor final response

4.3 Calculation of Motors speed deference during the Turn

To make the accurate calculation of the speed deference of each one of the three motors inside each module we need to calculate the horizontal and vertical distance from the edge of the weal “that touch the inside wall of the pipe” to the centre of the robot .Three distances shown in (Fig 43) need to be calculated.

$$D_1 = D_P * \cos(30)/2 \qquad (23)$$

$$D_2 = D_P * \sin(30)/2 \qquad (24)$$

$$D_3 = D_P/2 \qquad (25)$$

Where D_P is the diameter of the pipe

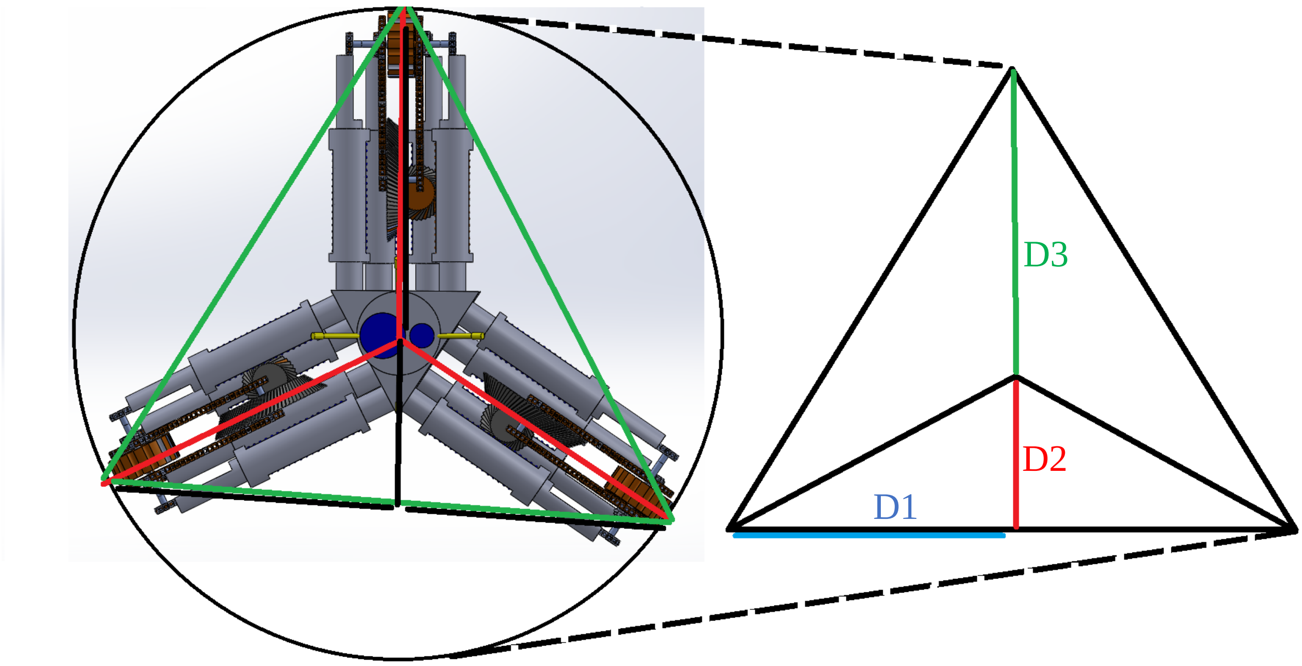


Fig. 43 – Horizontal and vertical distances

The speed should at the centre of the robot will be the same at the straight pipe and during the turn but the speed of the three ends of the leg will be deferent. The deference will be proportional to the diameter of the pipe (D_P) and the diameter of the turn (D_T) and it will also depend on the direction of the turn.

1- Going right

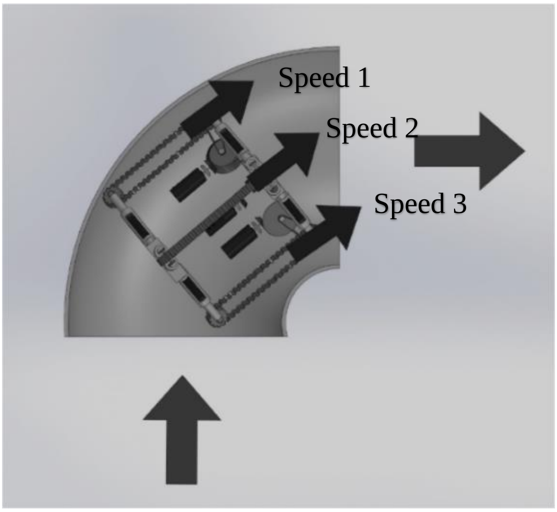


Fig. 43 – Deferent speed during right turn

Speed 1 = Rs * (Rt - cos(30) *Rp)/ Rt (26)

Speed 2 = Rs (27)

Speed 3 = Rs * (Rt + cos(30) *Rp)/ Rt (28)

2- Going left

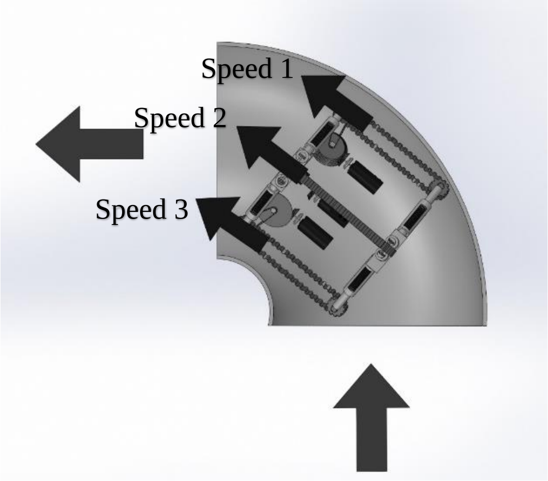


Fig. 43 – Deferent speed during left turn

Speed 1 = Rs * (Rt + cos(30) *Rp)/ Rt (29)

Speed 2 = Rs (30)

Speed 3 = Rs * (Rt - cos(30) *Rp)/ Rt (31)

3- Going up

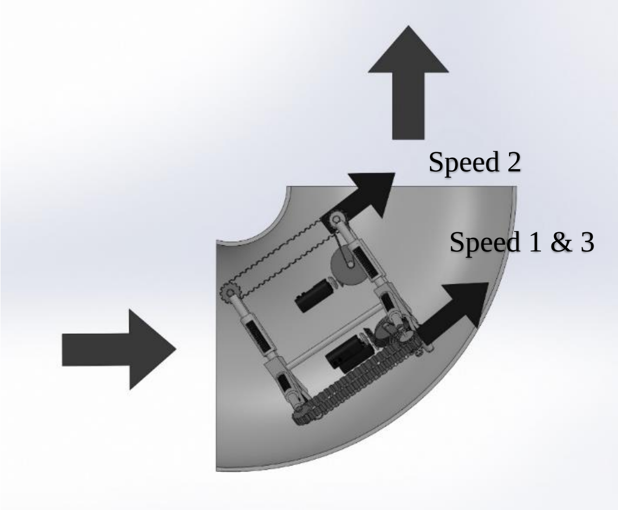


Fig. 44 – Deferent speed during up turn

$$\text{Speed 1} = Rs * (Rt + \sin(30) * Rp) / Rt \tag{32}$$

$$\text{Speed 2} = Rs * (Rt - Rp) / Rt \tag{33}$$

$$\text{Speed 3} = Rs * (Rt + \sin(30) * Rp) / Rt \tag{34}$$

4- Going down

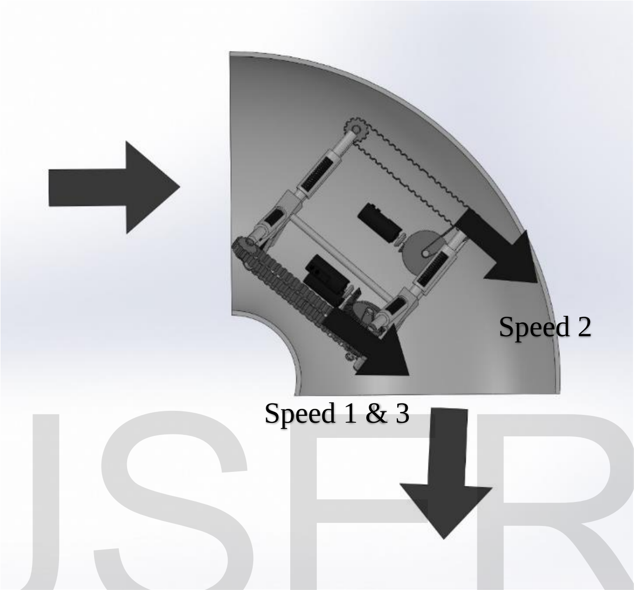


Fig. 45 – Deferent speed during down turn

$$\text{Speed 1} = Rs * (Rt - \sin(30) * Rp) / Rt \tag{35}$$

$$\text{Speed 2} = Rs * (Rt + Rp) / Rt \tag{36}$$

$$\text{Speed 3} = Rs * (Rt - \sin(30) * Rp) / Rt \tag{37}$$

4.4 Information about Sensor and Their Angle of Installation

Even though the robot will be provided with two cameras, (back camera and front camera) the sensors will be need to accurately detect the start of the turn. Each truck model will be provided with nine photoelectric sensors five on the front side of the module and four on the backside of the robot. The front sensor group of the front module will be responsible for detecting of the elbow turn and the T-section during the going forward mode. The back sensor group will be responsible for detecting of the elbow turn during the going backward mode. The front sensors will be organized as shown in (Fig 46).

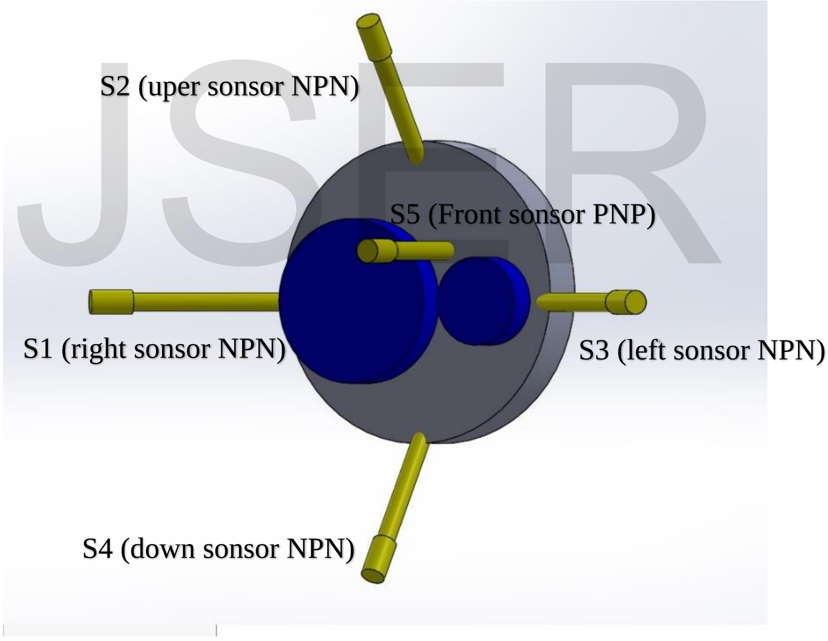


Fig. 46 – Front sensor group

All the sensors S1, S2, S3 and S4 will be NPN photoelectric proximity sensor will be NPN send a signal when loses contact with the inside wall of the pipe. Only the front sensor S5 will be NPN sends its signal whe n contacts with the pipe wall.

When two sensors send their signals that is mean that the robot has reaches a T-section so the robot will stop and wait the instruction from the operator to make the decision of choosing the direction. When only one sensor will send its signal that means that the robot will start the rotation automatically according to the table below.

Table 17 – The Direction related to each sensor

Sensor Num	Turn direction
S1	Right
S2	Up
S3	Down
S4	Left

The angel of installation and the distance of detection of the sensors will be depending on the Radius of the pipe (R_P) and Radius of the turn (R_T). The mathematical description will be shown in the equations below will.

$$\text{Sensor Distance} = \sqrt{(2\,\text{Rt}^2 - \text{Rp}^2)} \qquad (38)$$

$$\text{Sensor Angle} = \tan^{-1}\left(\frac{\text{Rt}-\text{Rp}}{\text{Rt}}\right) \qquad (39)$$

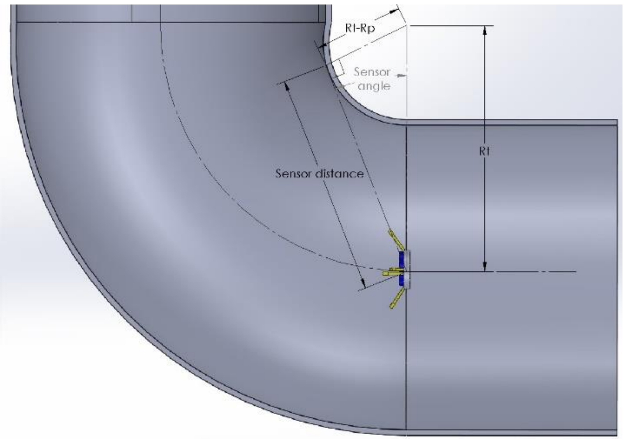


Fig. 47 – Relationship between R_T & R_P to the sensor angel and distance

4.5 Simulating the Moment of Going Up

To simulate the moment of going up we need to simulate the action of the three motors also, we need to simulate the input torque as well as simulating all sensors. The choice has been made for the case of going up because this case the robot will star to claim the vertical pipe and the input torque will go from minimum to maximum.

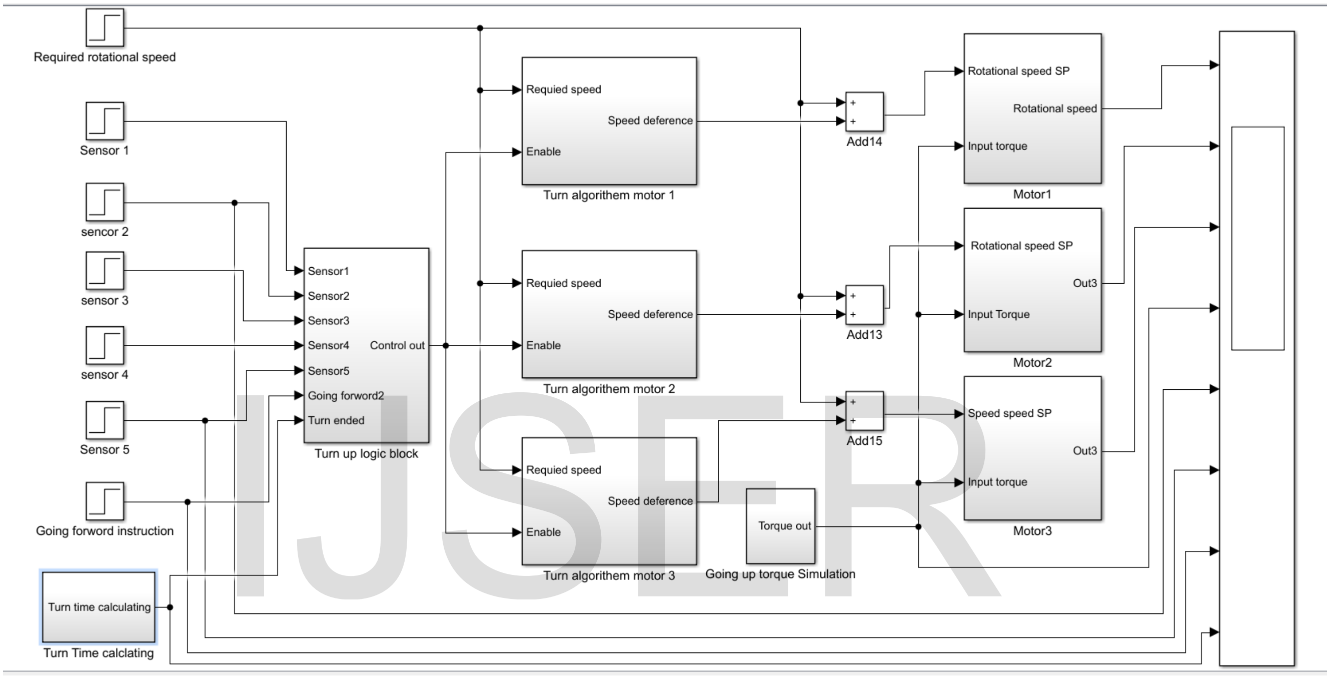


Fig. 48 – Simulating the Circuit of going up moment

The motor blocks will have the motor modules inside as well as the PID .The step input of the required rotational speed well represent the required rotational speed that set by the operator. The turn algorithm blocks will calculate the rotational speed deference according to the equations that explained in 4.3. The turn up logic block will have the five front sensors as inputs and well send the enable signal to the turn algorithm block. The going up torque will simulate the exponential increase of the input torque. The turn time calculating is the simulation of the time required to complete the rotation and back to the normal mode.

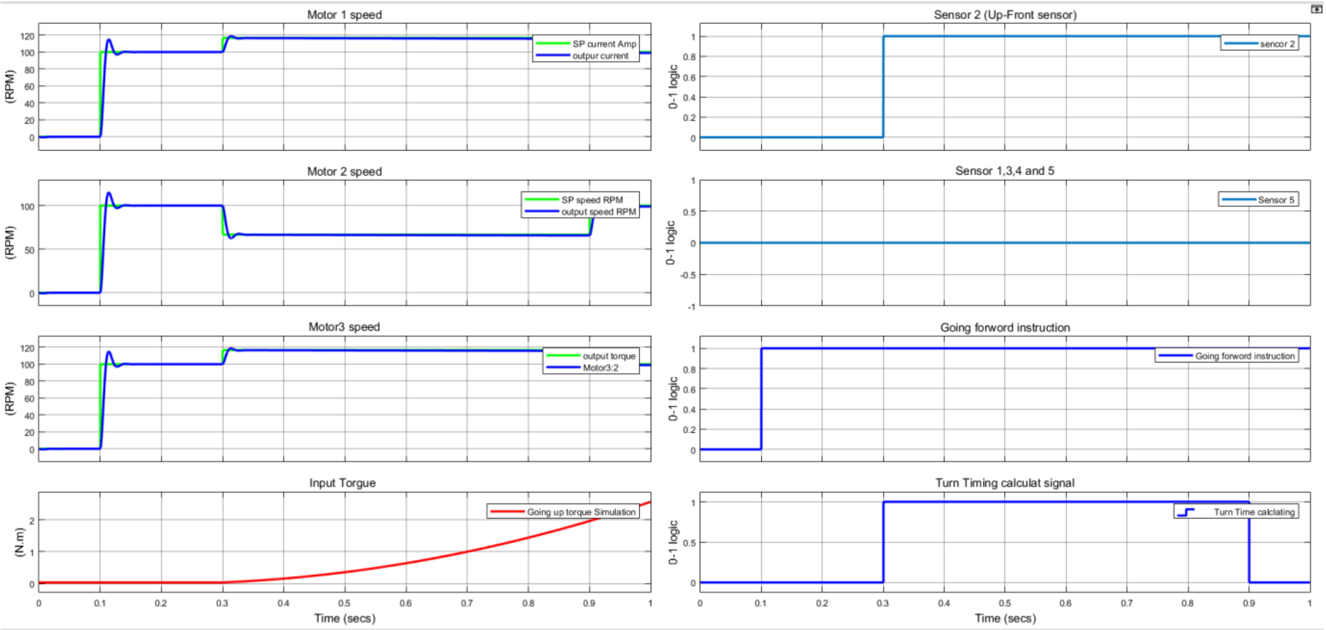


Fig. 49 – Simulation result of going up Circuit

The result of the scope shown in (fig 49). At the zero time the robot is stopped. At 0.1 second, the robot moved forward and the motors starts at speed of 100 RPM. At 0.3 second, the upper sensor S2 will sense the change in the pipe at the up elbow. The motors will change their speed automatically according to the speed deference explained in 4.3. In addition, we can see that the input torque will increase exponentially. At 0.9 second, the rotation will finish and all motors will be back to the required original speed 100 RPM.

The result shows that the exponential change in the input torque will not cause any error during the turn due to the efficient effect of the PIDs connected to the three motors.

The going up considered to be the hardest moment that the robot will face and yet the results shows the successful operation and the motor will operates as should be.

4.6 The Printable of Work Algorithm

The Algorithm shown below in (Fig 50) will explain the algorithm of the operation of the robot. Since the robot provided with equipment that installed inside will provide the motors with the ability to rotate clock wise and counter clock wise so we will get the movement ability to go forward and backward. The operation of the robot will start when the operator starts the robot. Then the operator need to set the robot to go forward or backward. At this moment, the robot will be ready to move .Next step the operator will set the required speed then the robot will start moving. During the robot movement, it might happen to reach an elbow or T-section.

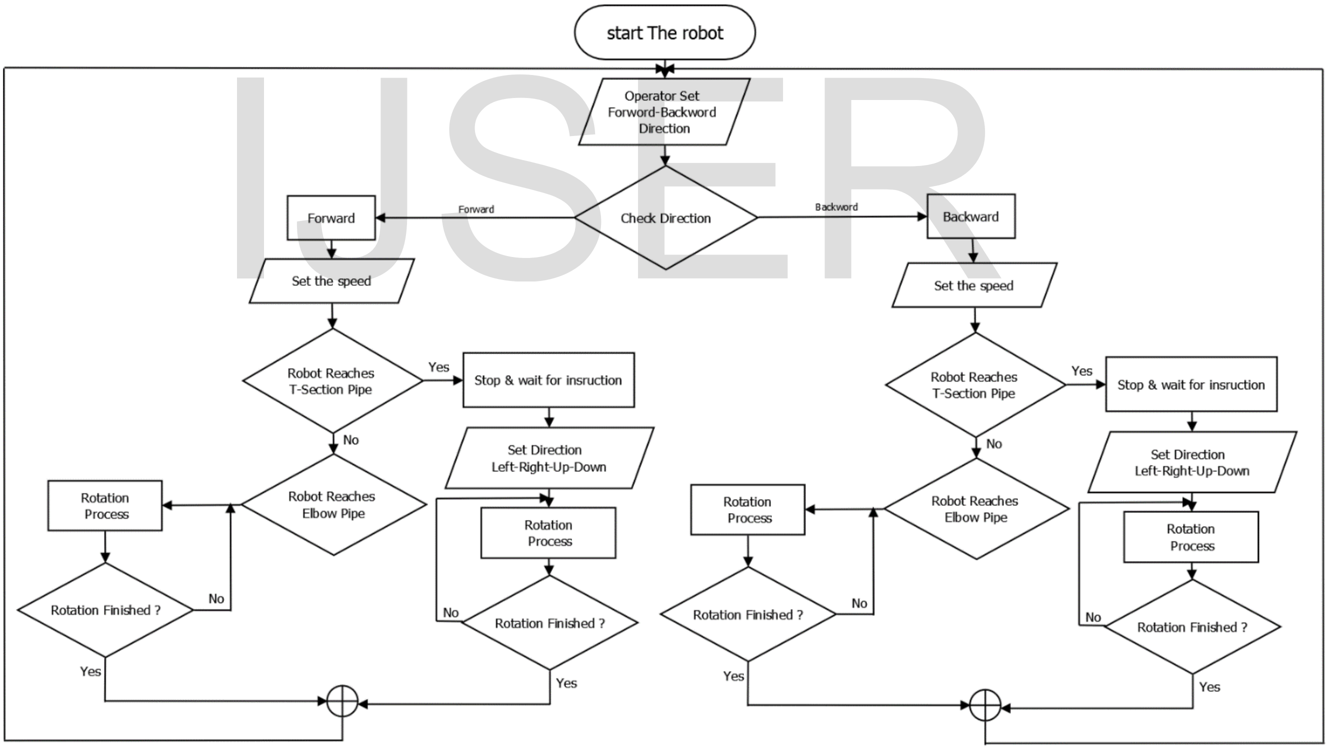


Fig. 50 –Algorithm

When the robot reaches the elbow shaped pipe, the robot will automatically changes the speed of motors according the process explained earlier.

When the robot reaches the T-section shaped pipe, the robot then need will need a decision to be made by the operator. When the operator make the decision, the robot then can perform the turning process. The robot also will have the ability of changing its speed during the operation.

CONCLUSION

Today the oil production is a key industry in many countries worldwide. The transportation of oil through pipelines also plays an important role, because any accident on the pipeline can lead to large economic losses. In order to minimize emergencies, it is necessary to carefully monitor the condition of the pipes and detect damage on time. One of the solutions to this problem is the creation of a mobile robot for pipe inspection, which could quickly scan the status of each section and transmit information to the control station. An approach using modern analysis and data transfer technologies will reduce time and significantly improve the quality of pipe inspection.

With the help of Matlab Simulink and the result we get on the design of the robot, we can get clear image about the final performance and the abilities and limitation.

The designed robot will be able to carry ideational 90 Kg weight during claiming so any pipe inspection sensor will be carried by it easily. The robot can go in a distance of 200 M through pipe network and carry the wire additional weight and still be safe un used space to reach the motors stall tongue.

The Robot will be able to move in a speed of 12 M/min or lower at maximum load during claiming vertical pipes.

Because of the properties of the springs, we chose robot could accept the change of pipe diameter of 5%.

Finally, My deepest thanks to my tutor, Stanislove Voronin, for His valuable guide and help. Also Thanks for all my teachers at SUSU for their effort and to my friends and all who participate with me in this great and useful study experience in Russia.

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