BOURNEMOUTH UNVERSITY

In-Line Inspection Tool

Final Report

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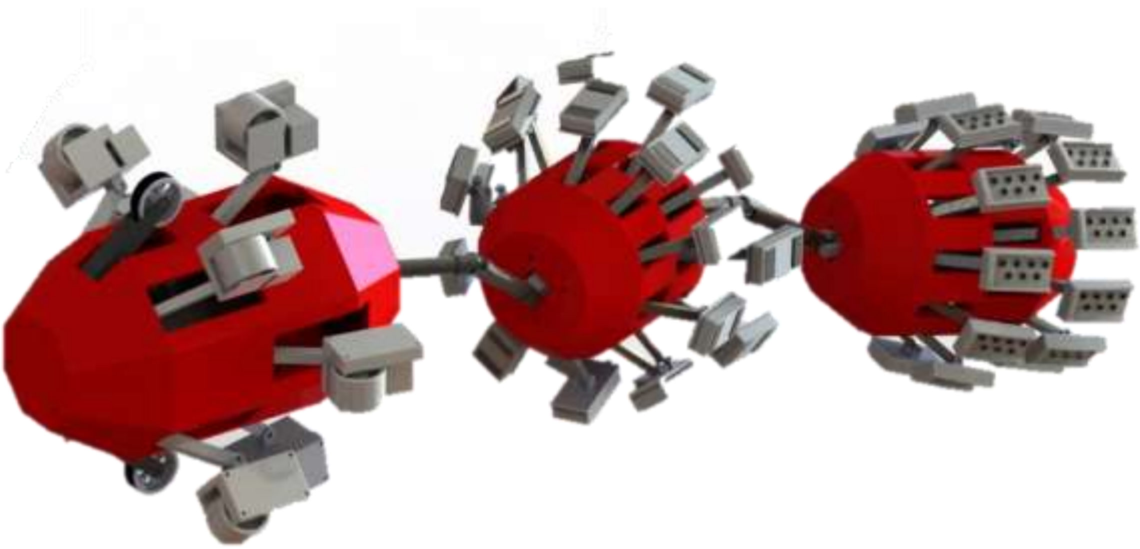

Abstract:

ILIs have been in existence for long time however they are often driven by the pressure difference in a pipeline they are normally built for one size diameter of pipeline. These ILIs are used for oil and gas pipelines where the contents are highly valuable. This project aims to improve on these limitations so that the ILI can scan a range of different diameter pipes and be self-driven. The ILI is designed for steam pipelines as even though their contents are not relatively valuable it does carry large amounts of energy and if pipe ruptures does occur this energy gets released and damages surroundings and in several cases of pipe rupture people have lost their lives. This ILI aims to prevent the pipeline ruptures through detection of faults so that action can be taken and potential lives could be saved.

It is worth noting that not everything could be looked at in detail due to time constrains and a list of further work at the end of the report is given. Particular attention was given to the self-driven and variable diameter aspects of the ILI.

Acknowledgements:

I would like to take this opportunity to thank the lecturers that have taught me over my time here at Bournemouth University. The lecturers here are engaging and they make time to meet with students to discuss their queries. In particular I would like to thank my supervisor, Miahi Dupac, and Xavier Velay for their support with this project.

I would also like to thank my parents who have supported me throughout my time at university.

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1 Introduction

1.1 Outline

Corrosion costs the United Kingdom four per cent of its gross national product every year. In 2011 corrosion cost the UK $97.28 billion (World Bank, 2011).There are many types of corrosion and all types affect the material's properties, they cause the material to become weaker so that the product is no longer fit for purpose and need replacing or it will fail.

Pipelines are used to transport various valuable fluids that industry and the public need. The contents of the pipe are pumped along the pipe at a certain speed this causes friction on the inside wall of the pipe and the contents of the pipe can chemically react with pipe and cause corrosion which gets carried away with the content. This process causes the thickness of the pipe to decrease or for microscopic cracks to appear and this structurally weakens the pipe. Eventually the pipe will fail causing the some or all of the contents to leak out, costing money and damage to the environment.

1.2 Product Background

In the pipeline industry 'Pipeline Inspection Gauges' or PIGs are often used for: separating two liquids in one pipeline, cleaning the pipe, collecting geometric data about the pipe or used to inspect the pipe for corrosion and metal loss. Some individual PIGs can carry out more than one task in one trip such as cleaning the pipe and also separating two products.

For the development of this product focus will be given to the PIGs that inspect the walls of the pipeline for metal loss, cracks or corrosion. These types of PIGs are called 'smart' or 'intelligent' PIGs they can also be called 'Inline Inspection Tools' or ILIs. They use various technologies to detect for corrosion or metal thickness. These technologies will be discussed later in the report. From this point onward the term 'ILI' will be used when talking about 'smart' PIGs.

ILIs are widely used in the oil and gas industry and there are standards and legislations dictating that these pipelines need to be inspected regularly for cracks and corrosion, as it is not only in the interest of the pipeline owners to keep their lines maintained it is also in the interest of the natural environment and gas leaks can be hazardous to the public. However there is a type of pipeline that rarely or never gets smart pigged and these are steam pipelines.

2 Market Analysis

The purpose of this section is to aid in making informed decisions about features and aspects that will go into the product. These features and aspects will be implemented only if there is a need or demand for them. To decide if there is a demand for some of the features of the product, or even the product itself, or research journals will be looked at to understand the scope of the problem and case studies of incidents where pipes have failed.

In this section there will also be analysis of both directly and indirectly competitive products. This is useful to see what features other products have and what features customers are looking for also it influences the pricing of the product by comparing it to what products are selling well on the market. Analysis of other products leads to the ability of being able to see gaps or niches in the market that are not being catered for and they can be exploited with the product, however caution should be taken here as some features could be regarded as undesirable.

After all of the market research is completed then one or more market segment(s) can be targeted and the product can be designed for that, or those, segment(s).

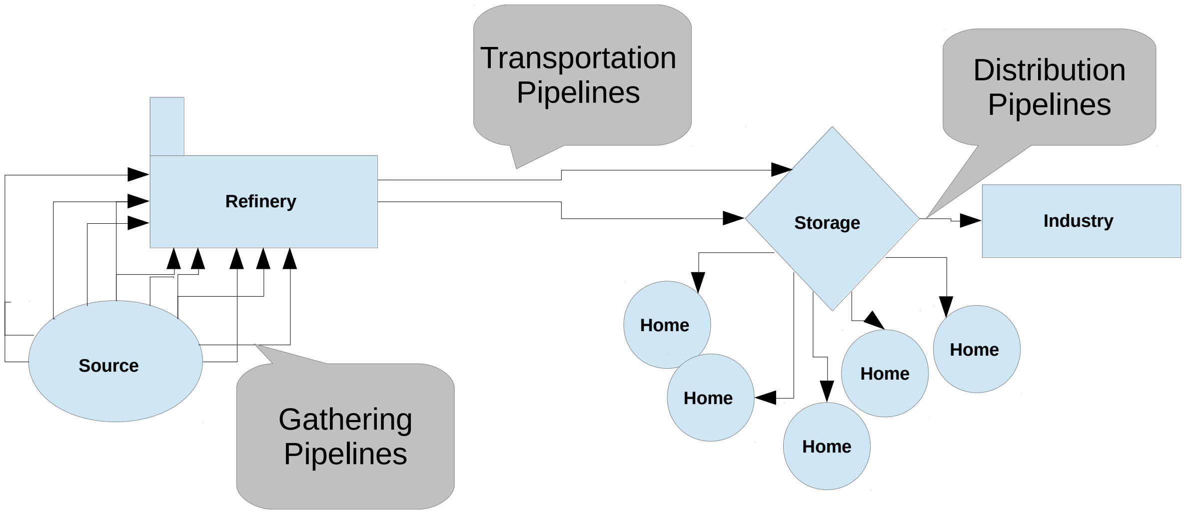


Figure 1- Different Stages of Pipeline Transportation (CEPA, 2012)

2.1 Types of Pipelines

Pipelines can be made of different metals, alloys or polymers. The choice of material and alloy depend on what the pipeline will be carrying. There are a variety of liquids and gases that a pipeline can carry, some pipelines can carry more than one type of liquid or gas. All pipes are used for transportation but there are different stages of transportation. See Figure 1.

The pipeline contents can affect the types of corrosion that occurs in the pipe. The product being transported also determines other aspects that need to be added to the pipeline system, for example in heating pipelines an insulation jacket is applied on the outside of the pipe to reduce the amount of heat loss. These other aspects may cause corrosion or accelerate its effects, taking the heating pipeline again, condensation can form between the insulation and the outside of the pipe and it gets trapped there causing corrosion to the outside of the pipe, which is very difficult to detect. Other pipe features need to be considered in the design of the product, for example there may be a reduction in diameter of the pipeline.

It is worth noting that heating pipes are usually not long distance transportation pipes.

Every pipe is unique in the type of corrosion that it may be susceptible to. Table A1 in **appendicies section A1** shows the main substances that pipelines carry and the type of corrosion that is most likely to affect this type of pipeline.

2.2 Market Size

As shown in Table A1 there are different types of pipelines that are susceptible to corrosion. Now the task is to see where these pipelines are and if it is possible to estimate the amount of pipeline there is. First of all it is necessary to see the applications of these different pipeline types, see Table A2 in **appendices section A2**. (N.B. - domestic pipelines have been omitted as it is not cost feasible to inspect them using an ILI).

Looking at the maps in **appendices section A3**. It can be seen that the majority of oil and gas pipelines in Europe span hundreds of kilometres and heat and steam pipes are more localized to factories and power plants.

Water and steam pipes are all featured in a wide variety of power generation types even more so than oil and gas pipelines. Research into the detection and monitoring of corrosion in oil and gas pipelines will show a very large number of ILI products that are available however researching into steam and water ILIs show very few products, the main reason for this is most likely due to the relatively high value of product in the oil and gas pipelines. It could be argued that the ILI market for oil and gas pipelines is saturated and would be very difficult to penetrate and take market share from established companies. Leaking or burst steam pipes can be very costly to power generation because of the unscheduled down time of the plant needed to fix the pipes. So even though the product itself is not relatively valuable the pipes and their function are. There have been many incidents of steam pipes failing due to corrosion or stress cracking and a few summarised case studies are in **appendices section A4**. *For this reason I believe there is a market niche in this area and I will design the ILI to be used in steam pipes*. Steam pipelines are not normally long distance transportation pipelines they are localized to industrial plants so they are in the gathering pipeline category. This is vital knowledge for the design of the product.

2.3 Competitive Analysis

The main purpose of the product is to detect and assess the amount of corrosion there is in the pipe in a non-destructive approach. Although a steam ILI is unique gas and oil pipeline ILIs are still a great threat as they could easily adapt their designs for this market niche. Methods of measuring corrosion in a non-destructive manner are considered an indirectly competitive product as they the same outcome, of assessing corrosion, as the ILI product does. A full explanation of these products and methods can be found in **appendices section A5**.

2.3.1 Directly Competitive Products

1) Other ILIs
2) External Pipe Inspection Robots
3) Visual Inspection
4) Handheld XRF

2.3.2 Indirectly Competitive Products

1) Coatings. There are many different types of coatings that can be applied to pipelines:
    a) Metallic coatings
    b) Inorganic coatings
    c) Paint coatings
2) Well-Designed Pipelines and Material Selections
3) Cathodic Protection
4) Scanning Electron Microscopy
5) Corrosion Coupons
6) Patrolling the Pipeline

7) Measuring Product Flow

8) Measuring Pressure

Figure 2 – GE's ILI. (GE, 2013)

2.4 Competitive Companies

Although there are very few products in industry that are like the one being developed in this report there are several other ILIs types outlined in that could easily be adapted by adding a module on to their existing design. There are several large multinational companies that could easily enter the targeted market niche and try to take market share away as they already have distribution channels set up and could make changes that could out pace this company. It is important to see what the competition is doing so that this company can outpace and adept faster than them to retain a large market segment. For this reason a pie chart of the most threatening companies has been outlined in Figure 3, the larger the section of the circle the greater the threat the company poses. Another market niche that has been realised is that the majority of companies do not sell variable diameter ILIs, this will be another unique selling point of the product.

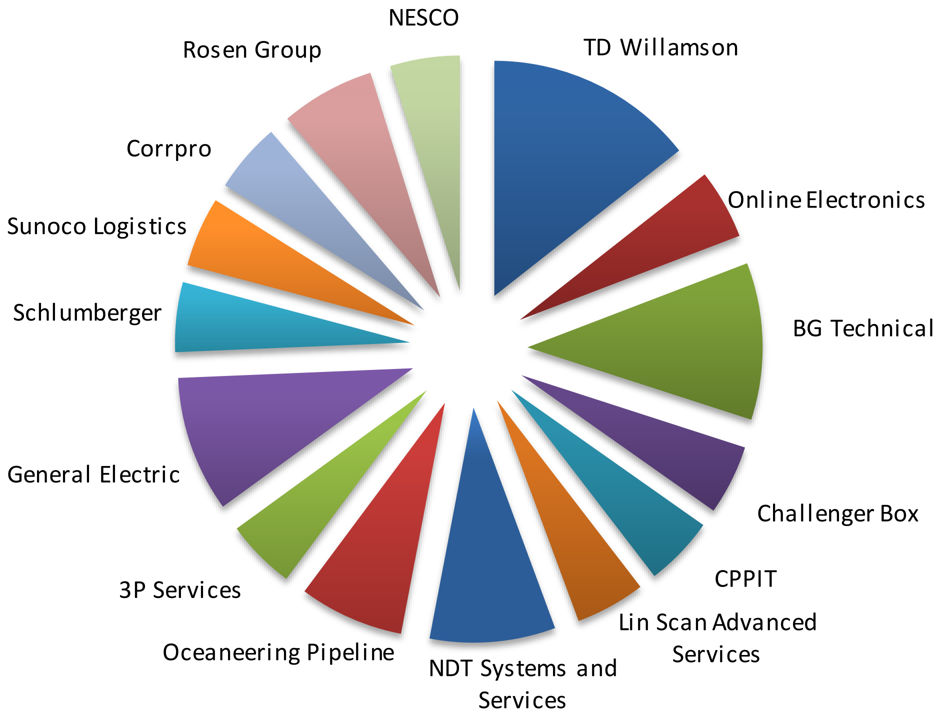


Figure 3 - Competitive Companies Pie Chart

2.5 Initial Pricing

For the ILI the product needs to be priced competitively. In this case either the individual product could be priced however most manufacturers of ILIs do not sell their products they provide the service of having the pipeline inspected. Different types of ILIs have different service costs and are usually priced on the distance they cover. **Appendices section A6** goes into greater detail on pricing.

2.6 Distribution

Most competitive companies either lease their equipment or they provide the service of inspecting the pipe and this may or may not include analysis of the data. Pipeline inspection is normally an outsourced operation, the outsourced company usually uses its own workforce and the equipment is sent to the site where needed from the storage site. For this company there could be many storage sites across Europe with the product so that the transportation time is reduced or could have one storage site and fly the equipment and the workforce out although there could be language barriers although there are methods that could overcome this. The storage spots will need to be near to both motorways and airports. Details about sales and services can be found in **appendices section A7.**

2.7 Market Analysis Conclusions

The results of the market research show that there is a niche in the market for an ILI in steam pipelines. It is possible that the ILI market for oil and gas pipelines has been saturated due to a large number of well established companies with very similar products to each other. The steam pipes can be regarded as gathering pipelines as they are dominantly used locally in industrial plants. Every pipeline is unique and different forms of corrosion or defects affect every pipeline and even sections of pipelines.

From the competitive analysis there is a wide variety of competitive products however ILIs give a complete view of the condition of the pipeline. The biggest competition is from large established companies in the pipeline industry that could easily adapt their designs to enable them to impinge on this new found market niche.

The pricing of the product is very difficult at this stage as it is very unique product and other ILIs in the oil and gas industry normally price by the job. The oil and gas inspection industry is also not relatable to the steam pipeline sector.

Competitive companies do not sell the ILI to the pipe operator as they provide a service. The price will have to be figured out in the final design. The product is going to be aimed at the European market however it could be marketed to other countries that have the same or lower standards.

3 Product Design Specifications

A full PDS can be found under **appendices section A8.** The main features and characteristics of the product have also been added under this section.

3.1 Product Overview

The product is a smart PIG or ILI for steam pipes with the capabilities of detecting metal wall thickness and scanning for cracks and defects. The product will be self-driven and be able to handle a wide variety of pipe diameters.

3.2 Product Background

There have been numerous incidents of steam pipelines rupturing and causing destruction to surroundings and also harm or death to people. There are several supporting case studies in the appendices under **appendices section A4**. Steam pipes are commonly used in the production of electricity and in other industries such as paper fabrication. There are also networks of steam pipes under many urban areas that provide district heating.

3.3 Main Features and Characteristics

- Scan a range of diameter pipelines between 400 mm to 600 mm.
- Ability to scan the pipeline at a maximum speed of 0.25 m/s.
- Have six-degrees of freedom and manoeuvre around bends of 90˚ whilst scanning.
- Ability to record the distance travelled and orientation so location of faults can be pinpointed.
- Be able to work in a dirty environment as corrosion products may fall onto ILI and could cause seizure of mechanical parts.
- Easy to maintain and take parts off to inspect or replace. Using as few tools as possible.
- ILI must not cause damage to pipeline that it is inspecting.
- ILI must not weigh above 30 kg.
- ILI must be environmentally sustainable and utilize as many recyclable materials as possible.

4 Concepts

There are several functions that the ILI needs to accomplish and these functions effectiveness depends on the design of the components. It is necessary to explore many different designs and evaluate and compare them as to ensure that you have an optimal design. To find out all the different functions a task breakdown is needed for the ILI. This is shown below in Figure 4. The selected concepts have been brought to the main report and are shown below. The other concepts and concept selection are under **appendices section A9 and A10,** respectively.

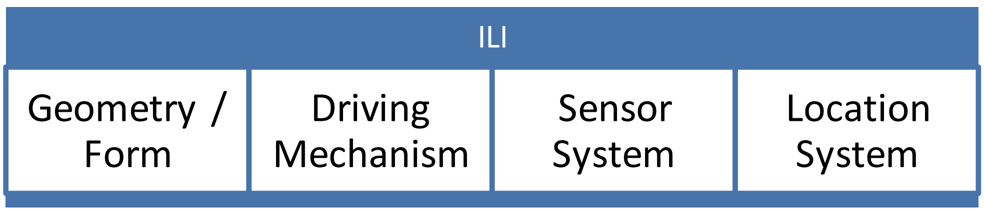


Figure 4 – Task Breakdown

4.1 Concept Generation

4.1.1 Geometry / Form

The geometry of the product is important as it must move inside pipelines and when going around bends the main body of the ILI must not make contact with either itself or the pipeline as this can cause damage to either or both bodies.

Hybrid Design:

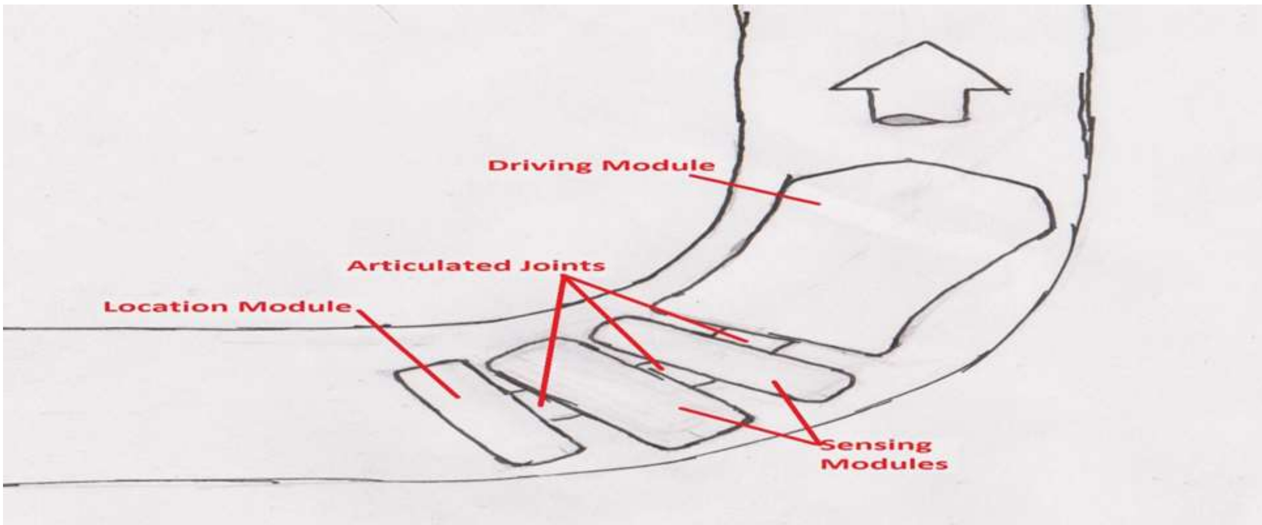


Figure 5 – Hybrid Design Concept

This combines the 'Flexible Snake' and the 'Towing Modules' design. This is design is the most practical allowing for correctly sized modules for their functions whilst retaining the flexibilty to go around bends.

4.1.2 Driving Mechanism

It is neccesary to explore different driving mechanisms that will allow for sufficient traction at different diameters.

Individually Powered Wheels:

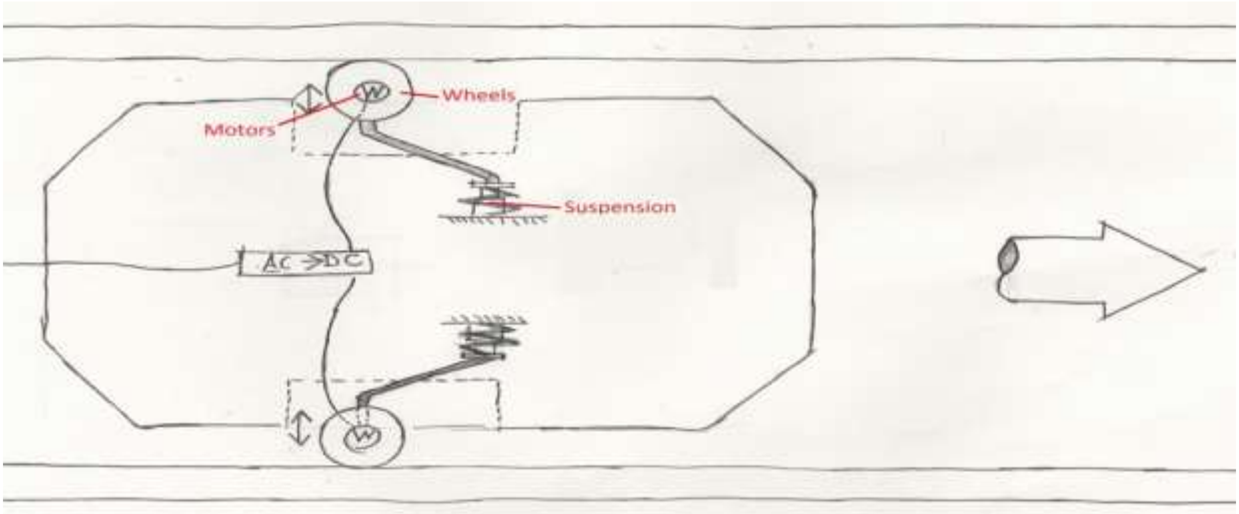


Figure 6 – Individually Powered Wheels Concept

The wheels are powered directly by electric DC motors attached to them. The suspension allows for variable diameters whilst also providing the neccesary normal force for friction on the wheel and pipe wall.

4.1.3 Sensor System

In MFL and ultrasonic systems the sensors need to be in contact or very close to the surface being analysed. The design of the sensor system also has to accommodate for variable diameter pipes.

Pantograph:

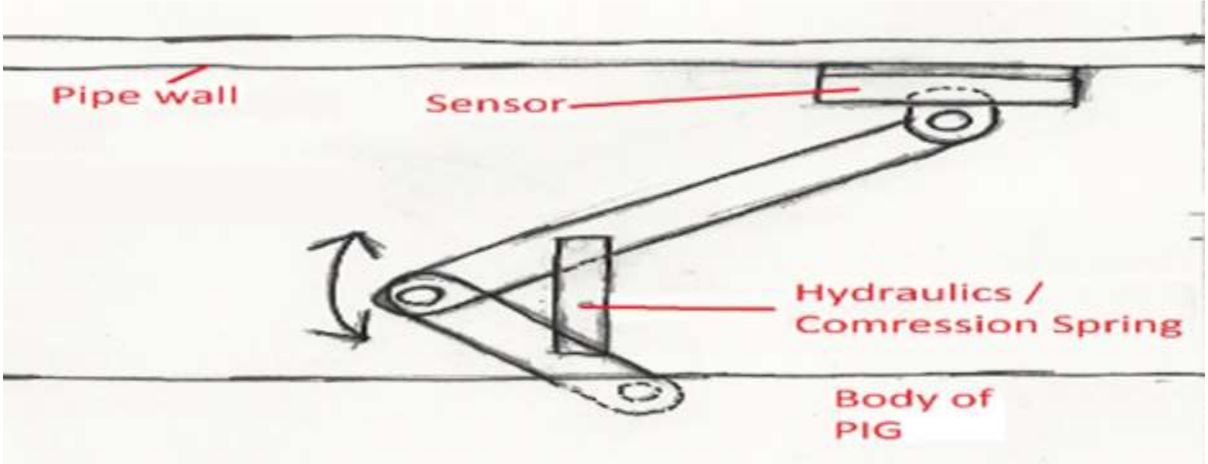


Figure 7 - Pantograph Concept

The two rods are pinned together and are separated by either hydraulics or compression springs to ensure that the sensor is in contact with the pipe wall. This set up allows for a wide range of diameters depending on the distance of the hydraulics/ spring from the pin connection. A tapered roller bearing or a CV joint could be used at the pinned joint to allow for stresses when the ILI rotates inside the pipe.

4.1.4 Location System

It is very important to know where the locations of the faults are or where the wall thickness is low so that the correct method of repairs or replacement can be decided.

Odometer:

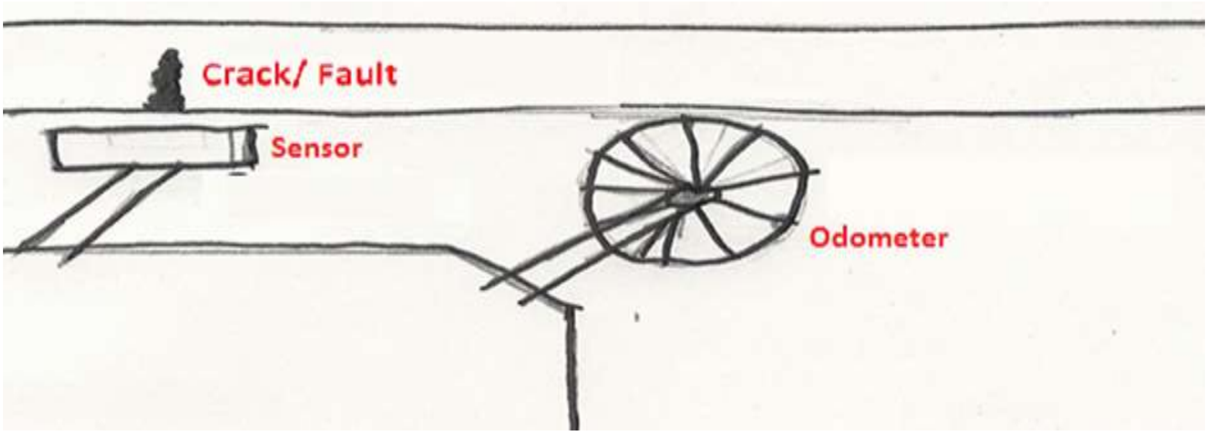


Figure 8 – Odometer Concept

The odometer is a wheel that is in contact with the pipe wall and electronically records the number and fractions of rotations. Using this data the distance travelled can be calculated. The odometer is widely used in other competitive ILIs. A similar system to the driving mechanism or sensor system will be used to allow the odometer measure at different diameters.

4.2 Initial Full Design

Using the concepts selected a full design of the ILI can be shown. This is likely to change during the technical analysis as ideas and research will be on going throughout this section and concepts may not be feasible or economical.

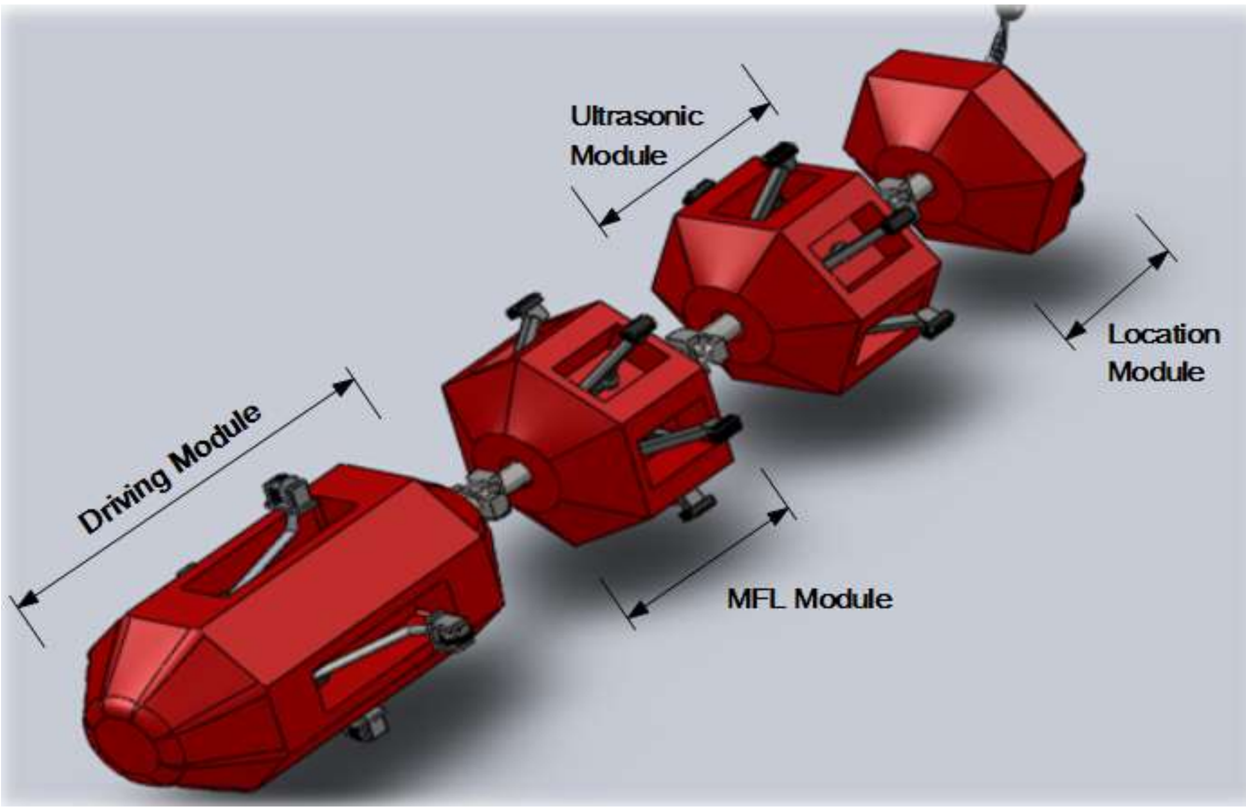


Figure 9 – Initial Full Design

5 Technical Analysis

A technical analysis needs to be done for detailed design and so that components can be specified and explained why they were chosen. The technical analysis will consist of mechanics and electronics and proves the design through calculations. As many aspects of the ILI's design have been covered however some areas have been omitted due to time constraints. As mentioned before the design is likely to change. Sections 5.4 to 5.15 are mechanics and 5.16 to 5.22 are electronics.

5.1 Functional Decomposition

A functional decomposition is useful to show the key areas and components that need to be covered in the technical analysis.

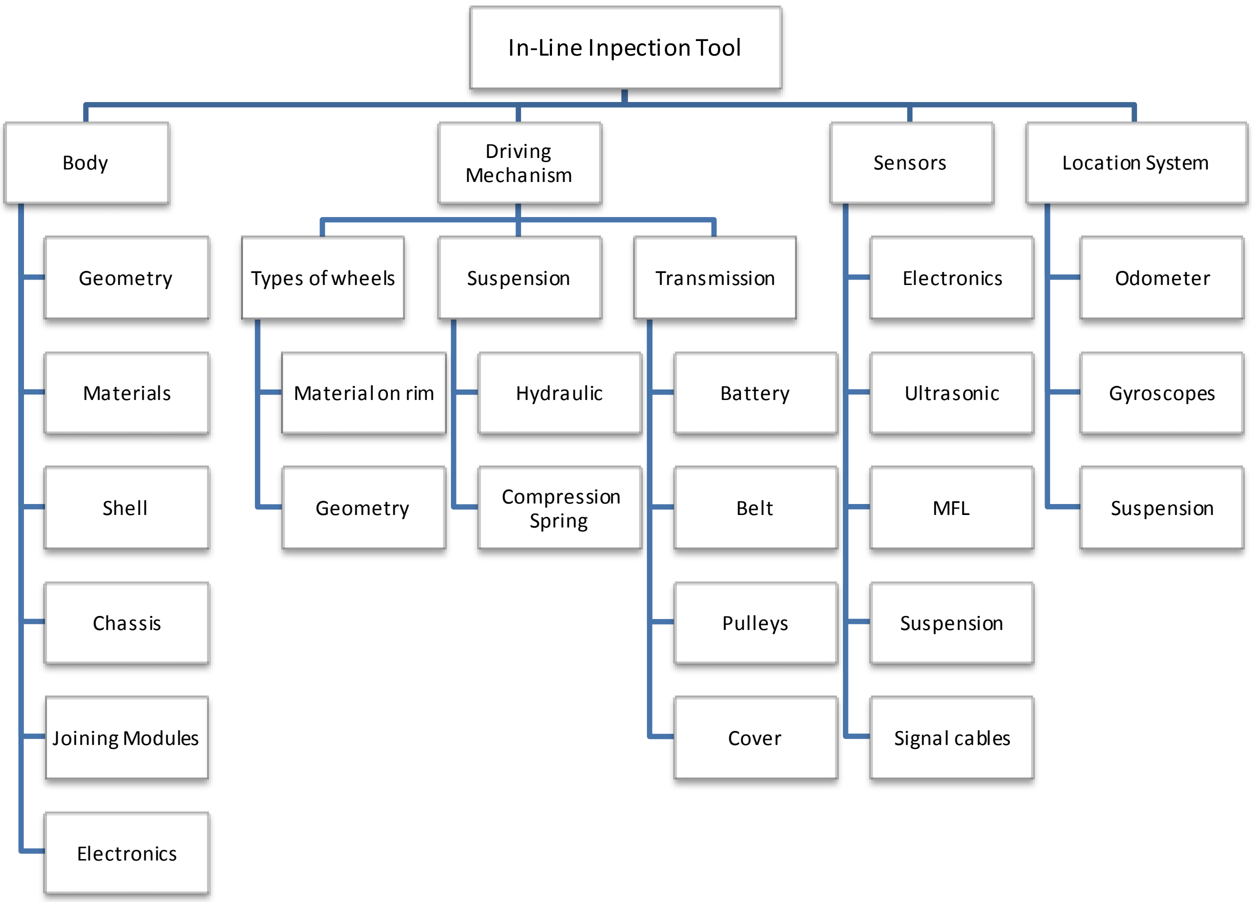


Figure 10 – Functional Decomposition

5.2 Pipeline Fixings and Features

There are various fixtures and fittings in steam pipelines that are used to control the steam and its quality a full list and explanation of these are in **appendices B under section B1.** There are some features and fixings that the ILI will not be able to manoeuvre around so they will have to be taken out and replaced with a section of pipeline. See **section B1** for more details.

5.3 Geometry

The geometry and dimensions of the ILI needs to be considered so that it does not make contact with the pipeline. The most likely situation where there is going to be contact is in the 90˚ bends in pipelines which have a diameter of 400 mm, the lower limit in the range of possible diameters the ILI can inspect and the upper limit is 600 mm, see **appendices B section B2** for reason why these diameters were chosen. The longest module will be the driving module so this module will be considered.

The finding the geometry and dimensions of the driving module was an iterative process and the solution to it is shown below in figure 11.

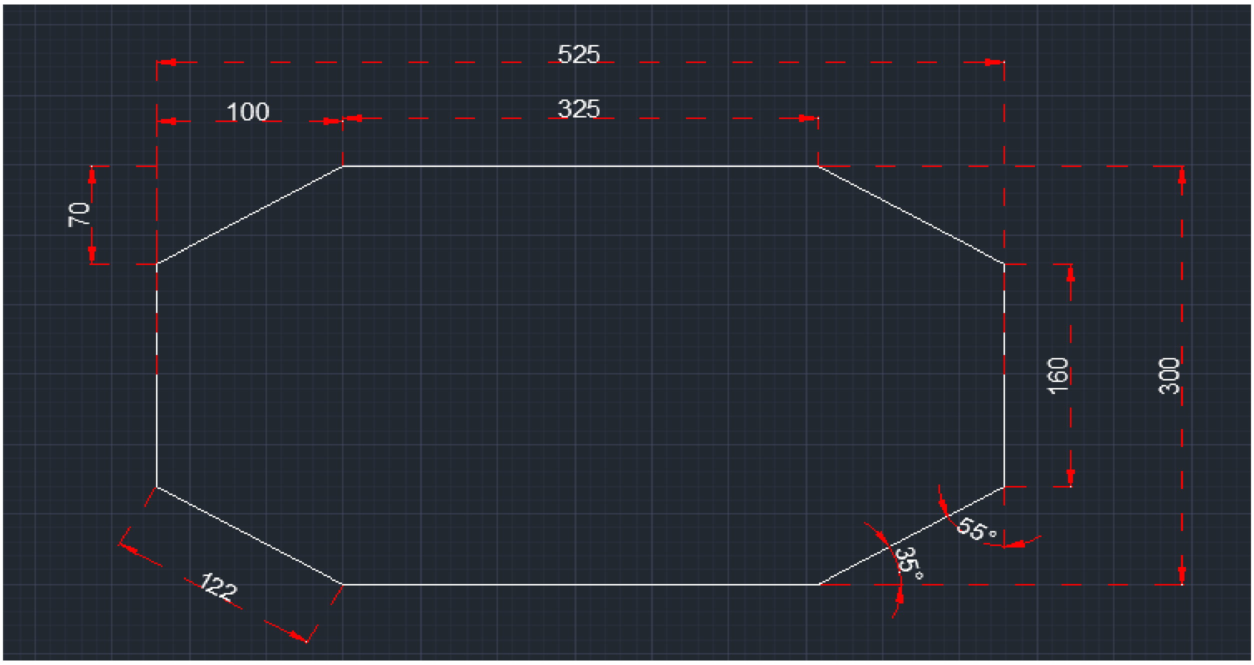


Figure 11 – Driving Module Geometry and Dimensions

Figure 12 shows that the geometry defined above does not cause contact with the pipeline at any stage in cornering.

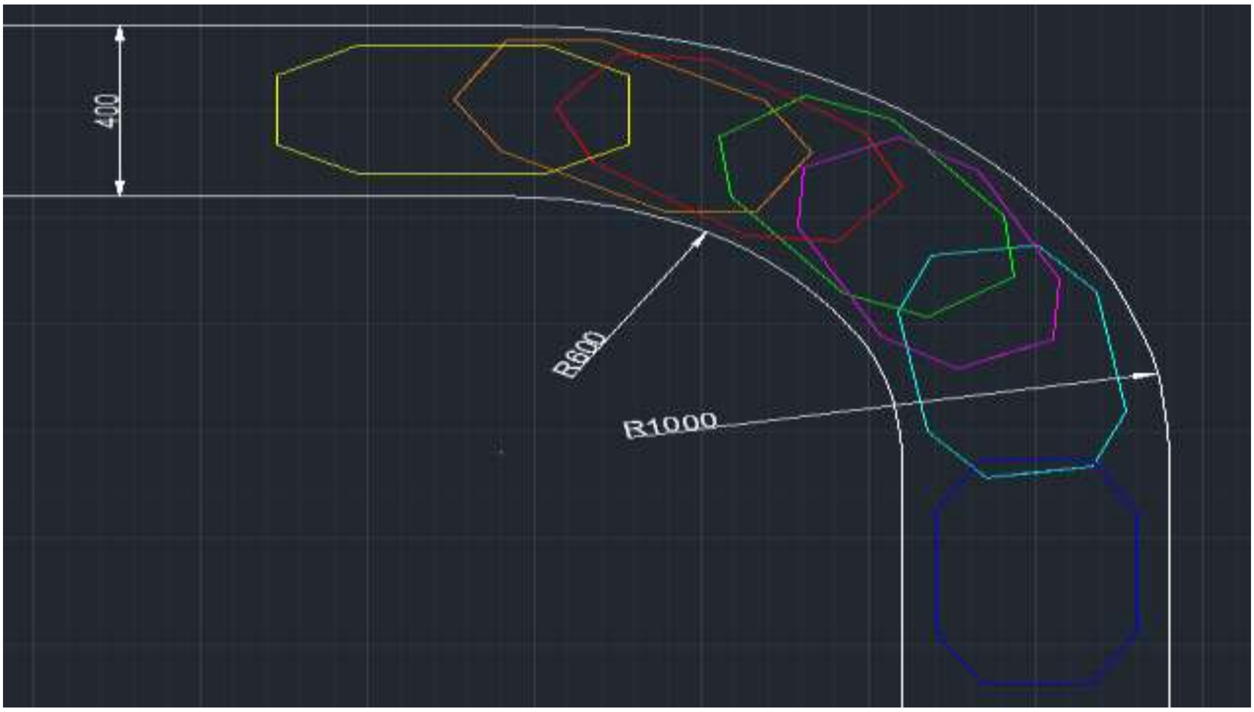


Figure 12 – Driving Module Geometry and Pipeline Bend

Mechanics

5.4 Angular Velocity and Centripetal Force

Angular velocity (ω) in the bends needs to be known as using this the value of the centripetal force can be calculated to check if these forces affect the ILI significantly. The ILI will experience a different centripetal force as the bend radius is different for different points on the ILI. Three points across the width of the pipe have been taken; the inside, middle and the outside, these cause the radius in the equation to vary. The linear velocity of the ILI is specified as 0.25m/s as this is its maximum speed.

The angular velocity values and centripetal force calculations are shown in the **appendices section B3**.

Table 1 below has been compiled to show the different centripetal force values for the ILI in the maximum and minimum sized pipelines and at the three different points across the pipelines.

-	400 mm Pipeline	600 mm Pipeline
Inside:	F = 3.13 N	F = 2.09 N
Middle:	F = 2.35 N	F = 1.56 N
Outside:	F = 1.88 N	F = 1.25 N
Maximum	F = 3.13 N	
Minimum	F = 1.25 N	

Table 1 – Centripetal Forces on the ILI

The maximum centripetal force of 3.13N is comparatively very small to other forces the ILI is under so it can be regarded as negligible.

5.5 Sensing Technology

Knowledge and understanding of the sensing technology is necessary as they provide the data that is needed to assess the state of pipelines. If the ILI is designed incorrectly then the sensors will only have a limited use and they will not be able to give an accurate view of the pipeline and clients would look to competition to provide a comprehensive inspection of their pipelines.

5.5.1 Magnetic Flux Leakage (MFL)

The orientation of the magnetic field to the crack is very important, in ILIs there are two orientations that the magnetic fields can be established, longitudinally and circumferentially. A longitudinal magnetic field can be induced to a pipeline by using the longitudinal field that occurs in solenoids or using permanent or electro magnets. A circumferential magnetic field can be set up by passing a current around the inside wall of the pipe. Sensing in both of these orientations gives the best likelihood of the crack being detected because if the crack is parallel to the flux lines then it will go undetected, Figure 14 shows this as the greater amount of flux leakage, or stray flux, the greater the chance of detection. An orientation of 45 to 90 degrees of the flux lines to the crack is needed for it to be detected. (NDT, 2013)

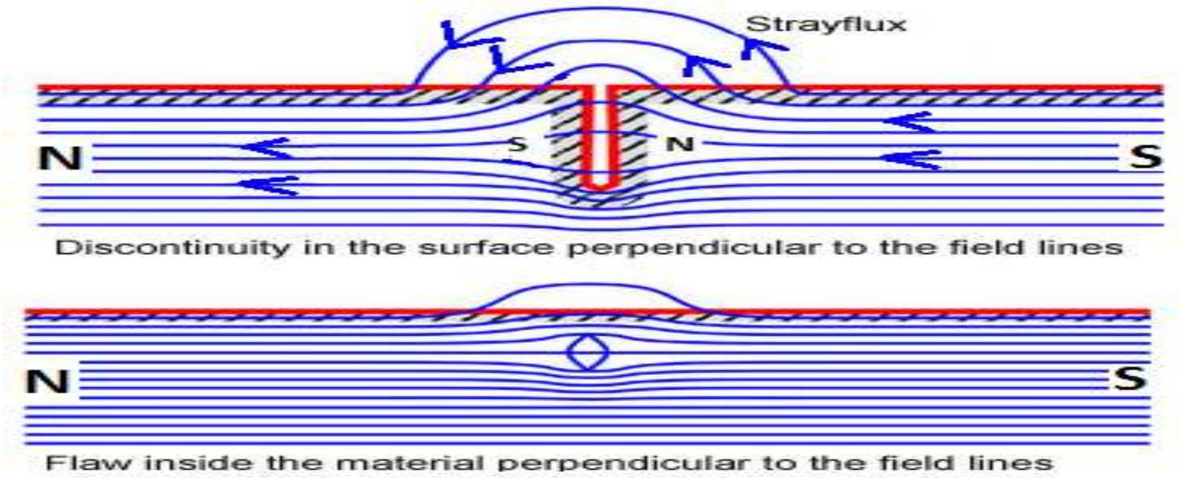


Figure 13 – Polarization of Crack and Flux Leakage (QNET, 2011)

In MFL ILIs horseshoe magnet permanent magnets are used. These magnets are attached to steel brushes that make contact with the pipeline. The sensor is either an induction coil or Hall probe and it sits between the two poles of the permanent magnet. There is a circular array of these sensors on the ILI to inspect the whole of the pipeline and with stronger magnets used a greater wall thickness can be assessed.

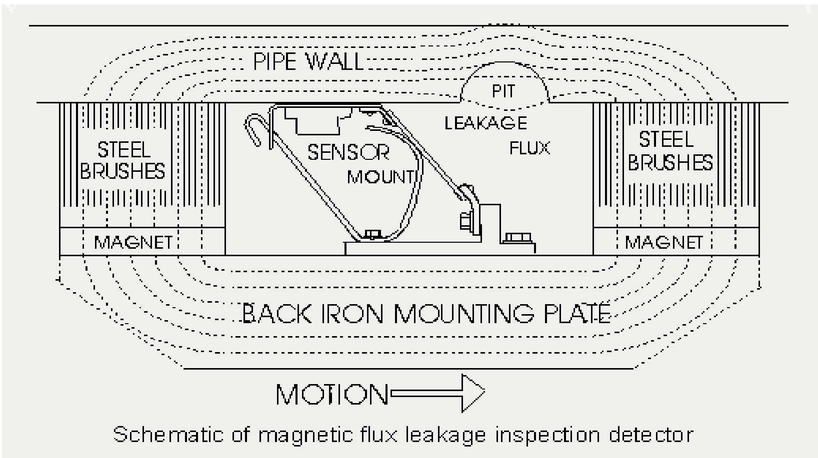


Figure 14 – ILI MFL Sensor Diagram (Queen's University, 2006)

For more detail on MFL see **appendices section B4**.

5.5.2 Ultrasonic Testing

High frequency sound waves are used to measure wall thickness and internal structure of the pipeline. A transducer is used to produce the sound waves and they act as both a transmitter and a receiver as they operate in an impulse echo mode. To measure wall thickness the transducers need to be at right angles to the pipeline wall as shown in Figure 15 on the left. If cracks are needed to be detected then the sensors will have to be angled to that the incident wave gets refracted at less than 45˚ as they propagate into the pipe wall, see figure 15 on the right. (Beller, 2007)

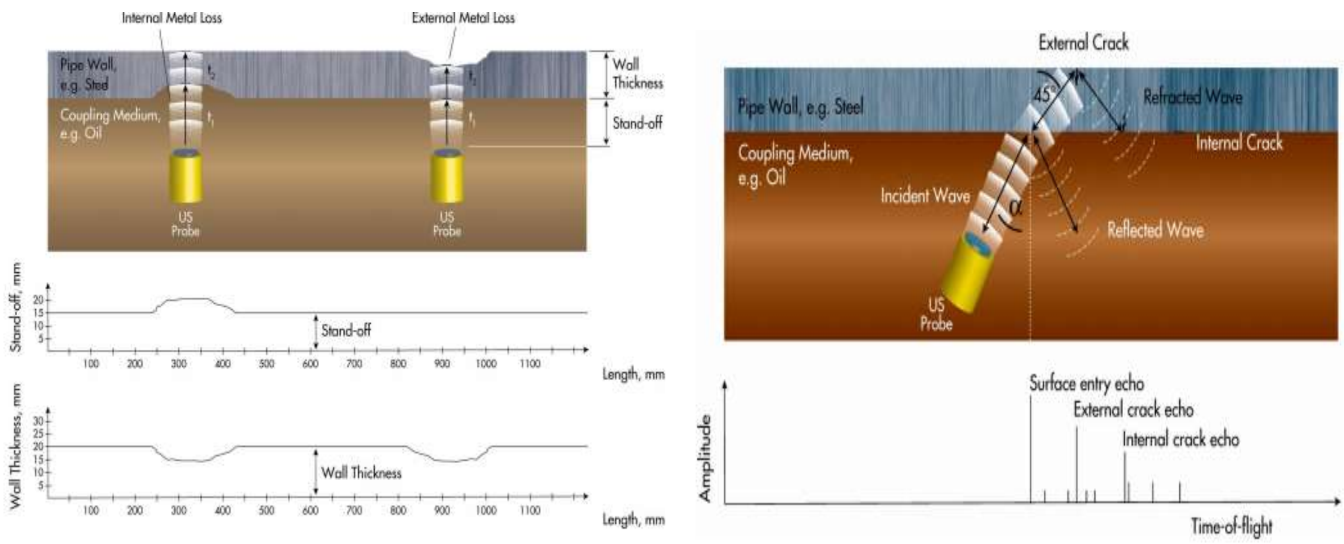


Figure 15 – Diagrams of Wall Thickness Detection, left, and Crack Detection, right. (Beller, 2007)

An advantage of ultrasound is that it provides very accurate and reliable quantitative data on wall thickness and defects; the latest technologies have a resolution of 0.06 mm. The issue with UT testing in the application of this ILI is that it requires a liquid coupling medium. However there is development being done on a UT transducer that does not require a medium which will be available in the near future.

The UT transducers are arranged in patterns on a plate the greater the number of transducers on a given area of a plate the greater the resolution. (Beller, 2007)

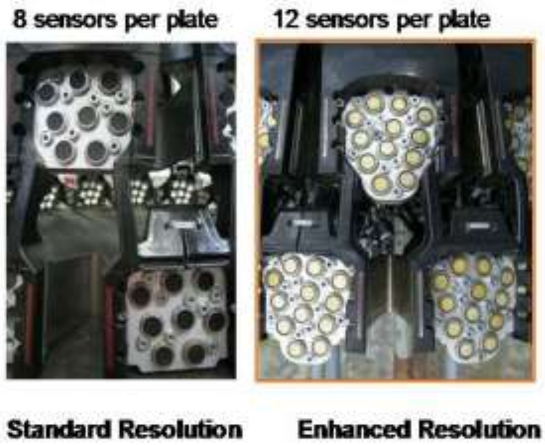


Figure 16 –ILI UT Transducers (Beller, 2007)

5.6 Sensor Width

It has been decided that 20 sensors will be used to scan the circumference of the pipeline. It is aimed that the 100% of the circumference in a 600 mm diameter pipeline will be scanned. For this to be possible the sensors need to have a width (or arc length) of 600π/20 = 95 mm. This also means that the sensors will overlap the covered area in a smaller diameter pipeline however software can be utilised to take this into account in the results. To ensure that the sensors do not make contact with each other they have been staggered across the length of the chassis. Figure 17 shows the MFL module.

The sensors will need to be curved for the pipeline the arc angle in a 400 mm pipeline is 18.1 ˚. See **appendices section B5** for the calculation.

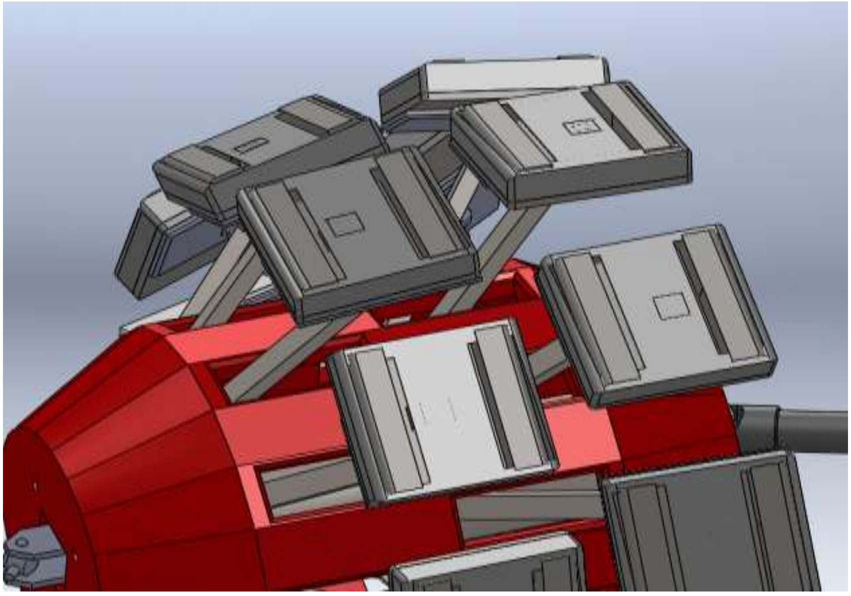


Figure 17 –MFL Module Showing Staggered Sensors

5.7 Reaction Force with Wall

It is useful to know the value of the static friction so that the reaction force between the wheel and the pipeline can be calculated. Wet friction will be looked as there can be a thin film of water on the pipeline's wall which would cause slipping if the calculations were done with dry friction.

The aim is to calculate the value for the reaction force (F_R or R) (see Figure 18) so that if the ILI fails then the ILI can be held stationary vertically in the pipeline. So that it does not fall and cause damage to itself or the pipeline.

$$R = 183.9\,N$$

See **appendices section B6** for the full equation and methodology.

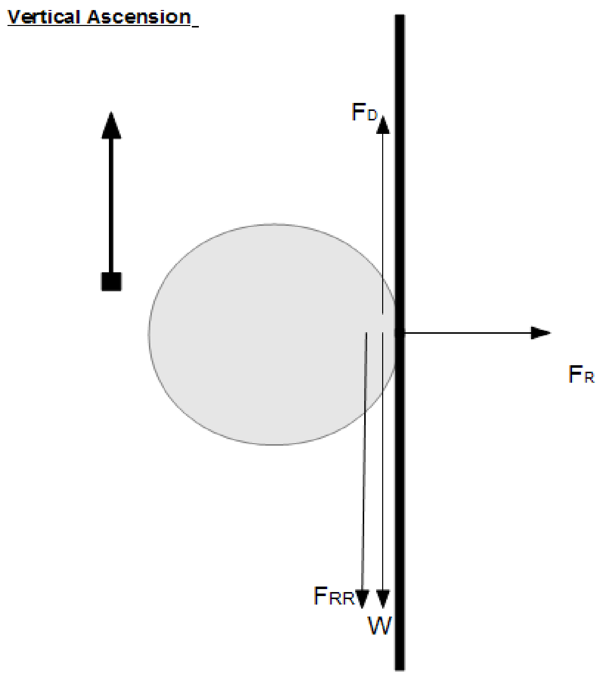


Figure 18 – Force Diagram Ascension

5.8 Rolling Resistance

Rolling resistance or rolling friction is a retarding force on the wheel or rotating object. Energy is dissipated due to the friction at the contact point, the elastic properties of the materials and due to the roughness of the rolling surface. It is very important not to get rolling resistance confused with sliding friction as sliding friction gives a higher frictional force meaning that a larger pushing/driving force is needed, this is the main advantage of a wheel. (Lippet and Specktor, 2012)

The horizontal and vertical rolling resistance will need to be found so that the amount of power the motor needs to supply can be calculated.

Horizontal rolling resistance is 2.90 N.

Vertical rolling resistance is 5.44 N.

By resolving the forces the **driving force** (F_D) is 42.23 N

See **appendices section B7** for the full equation.

5.9 Torque on the Wheel

The driving force is known and the diameter of the driving wheel is 75 mm so the torque on the driving wheel at the point of contact is 1.58 Nm.

Using this value the shear stress on the drive shaft for the wheel can be calculated**,** see **appendices section B8**. The shear stress comes to 8.05 MPa and the shear yield point of steel, the material the shaft will be made from, is 203 MPa (CES, 2013) this proves that the shaft can take the shear stress and also that the shaft could be made thinner or from a different material.

5.10 Motor Power

Knowing the torque and the speed the power that the motor needs to supply to the motor can be calculated.

The angular velocity of the 75 mm diameter wheel travelling at 0.25m/s is 6.67 rads/s.

This gives a minimum power of 10.53 W that the motor must supply.

A 15 watt compound motor has been chosen as it also has a planetary gear box incorporated into it. This helps in the speed reduction needed. The planetary gear box has a reduction ratio of 20:1 so the output shaft rotates at 125 RPM down from 2500 RPM from the motor input; the wheel needs to rotate at 63.6 RPM to be at 0.25 m/s. The main reason why a planetary gear box has been chosen is because of its compactness and also the input and output shafts are aligned. Other advantages are the high reduction ratios offered, the compactness also means that they are relatively lightweight, they can also transmit high amounts of torque and they are highly efficient. (Gayatri Exim, 2008)

A worm wheel was initially desired as they offer high gear reduction ratios as well however the input and output shafts are perpendicular and this could not be incorporated into a compact lightweight transmission system. The worm wheel would have been a safety feature as they are self-locking, the driven gear cannot drive the worm wheel, this means that if there was a sudden drop in torque or power on all wheels the ILI would not fall under the action of gravity as the wheels could not rotate due to the locked transmission. This safety feature will now have to be realised electronically using back EMF to the motors and a mechanical brake.

The motor's specifications can be seen of in **appendices section B9**. Research on motors can be seen in **appendices section B10**.

5.11 Belt Drive

An open belt drive is used to transmit the power from the output of the planetary gearbox to the drive shaft of the wheel. The main reason why a belt drive was chosen is because it can transmit power to two parallel shafts that are a relatively large distance apart.

The belt will be a synchronous (or variable speed) belt as these are used for lower speed applications with relatively high torque, as opposed to the friction belt type. Synchronous belts transmit power through mechanical linkages between the teeth in the belt and grooves in the pulley. (Engineering Toolbox, 2010).

Figure 19 – Synchronous Belt (Gates Corporation, 2004)

The pulleys that will be used will be made of aluminium; nylon 66 was considered to keep the cost low it also has good wear resistance a desirable characteristic for the grooves in the pulley. However polyamides are moisture sensitive and they have poor durability in alkaline conditions. The feed water in the boiler has chemicals added to make it alkaline to inhibit corrosion and these chemicals condense on the pipeline walls.

There will be a transmission casing attached so that it covers the belt drive from corrosion products that may fall off the inside of the pipe. The gearbox casing will also be able to mount the two bearings needed for the driven and driver shafts for good alignment and to reduce bending on the shafts.

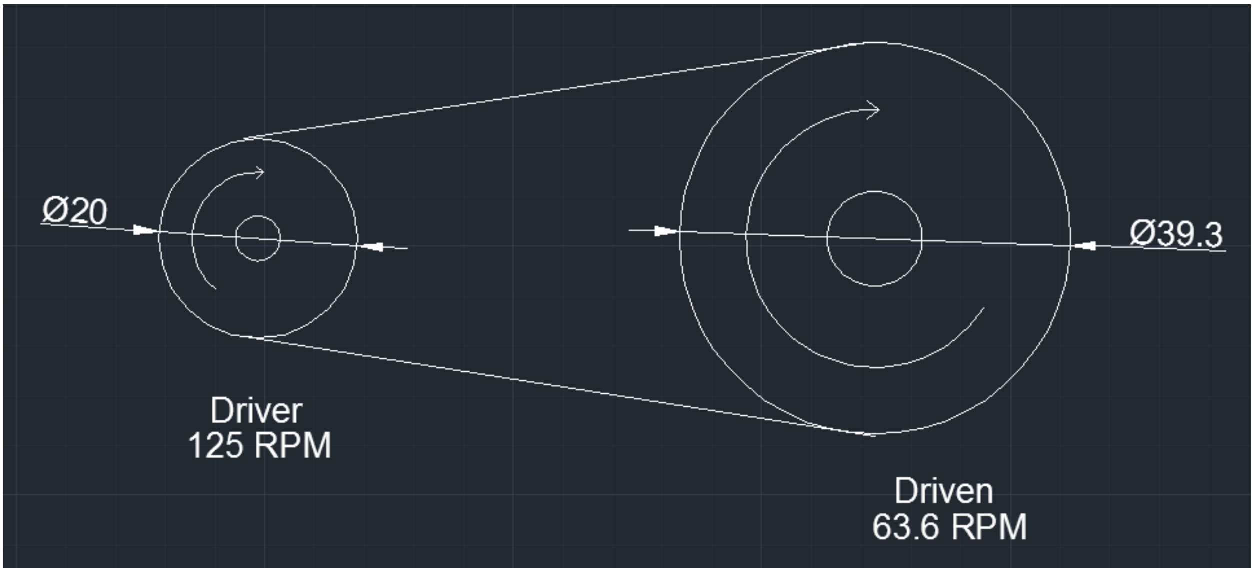


Figure 20 – Diameter and RPM of Pulleys

Torsion springs will be placed at the pin joint between the base plate and the arm bar this is to ensure that the tangent to the drive wheel at the point of contact with the wall is parallel to the pipeline direction and so that the system does not over or under rotate and cause damage.

A diameter of 20 mm has been chosen for the driving pulley and with a velocity ratio of 1.965 the diameter of the driven pulley is 39.3 mm.

Figure 21 is a diagram of the drive system this figure excludes the transmission system apart from the 10 mm drive shaft for the caster wheel. There is a table below the figure to show the different components.

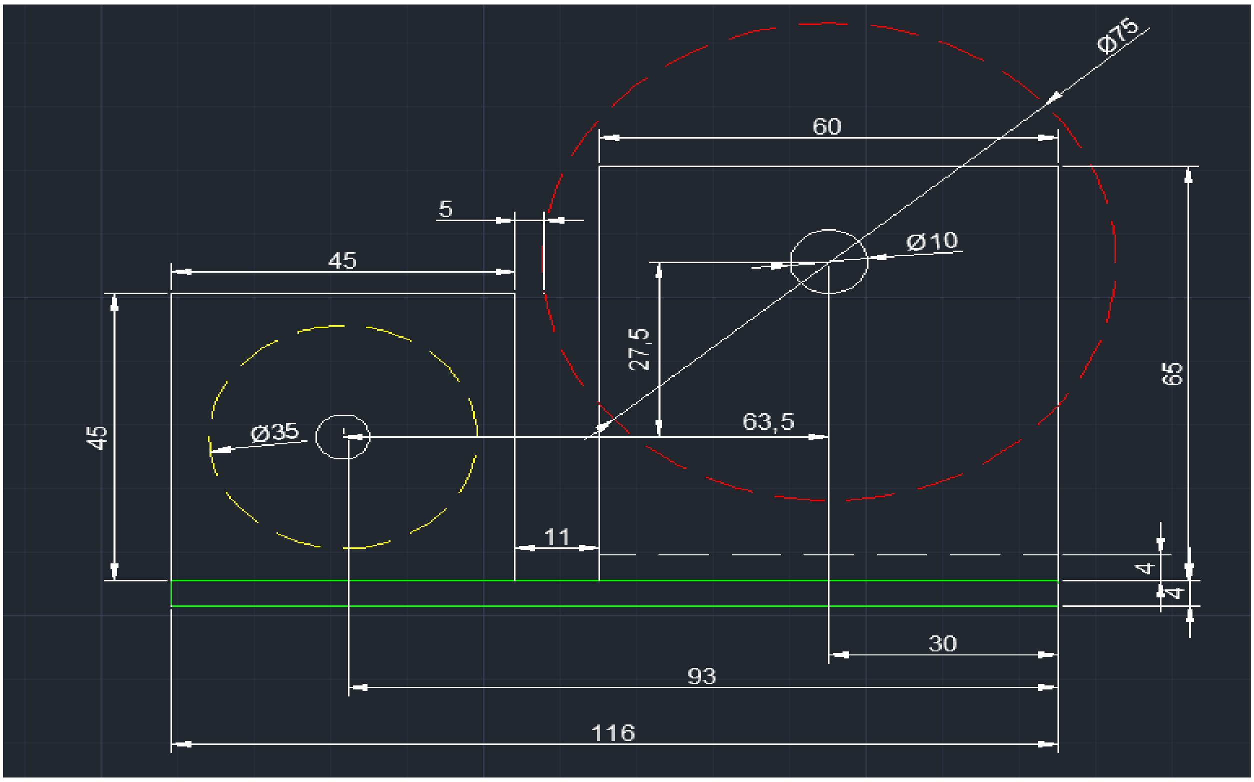


Figure 21 – Dimensions of Drive and Transmission System

(green solid line)	Base Plate
(yellow dashed line)	Motor
(red dashed line)	Caster Wheel
45 x 45	Motor Housing
65 x 60	Wheel Case

Table 2 – Key for Figure 21

Using Figure 21 and Table 22 the length of the belt drive can be calculated as the distance between the two shafts can be found. It is calculated to be 69.2 mm using this and other known information the belt length is 232.7 mm. See **appendices section B11**.

The belt's size can be calculated and it is 4 mm wide and has thickness of 2 mm this size can also take the stresses induced on it. See **appendices section B12** for full explanation and equations.

Chain vs. Belt

Table 3 below shows the advantages and disadvantages of chain and belt drives. Highlighted points in red are important reasons/factors why a belt drive was chosen. (Grainger 2007)

Chain Drive	Belt Drive
Alignment is more critical than belt drives	Wear is easy to notice
Higher wear on sprocket/wheel	Higher frictional losses
Heavier	Lighter
Higher vibrations	Quieter and lower vibrations
Lubrication needed (not needed on belt)	Smoother transfer of power
Expensive	Less frequent maintenance procedures
Chains can be repaired belts cannot	Smooth transfer of power even under shock loading

Table 3 – Chain vs. Belt Drive

5.12 Arm Bars and Mass-Spring Dampers (MSD)

Size of Holes in Shell

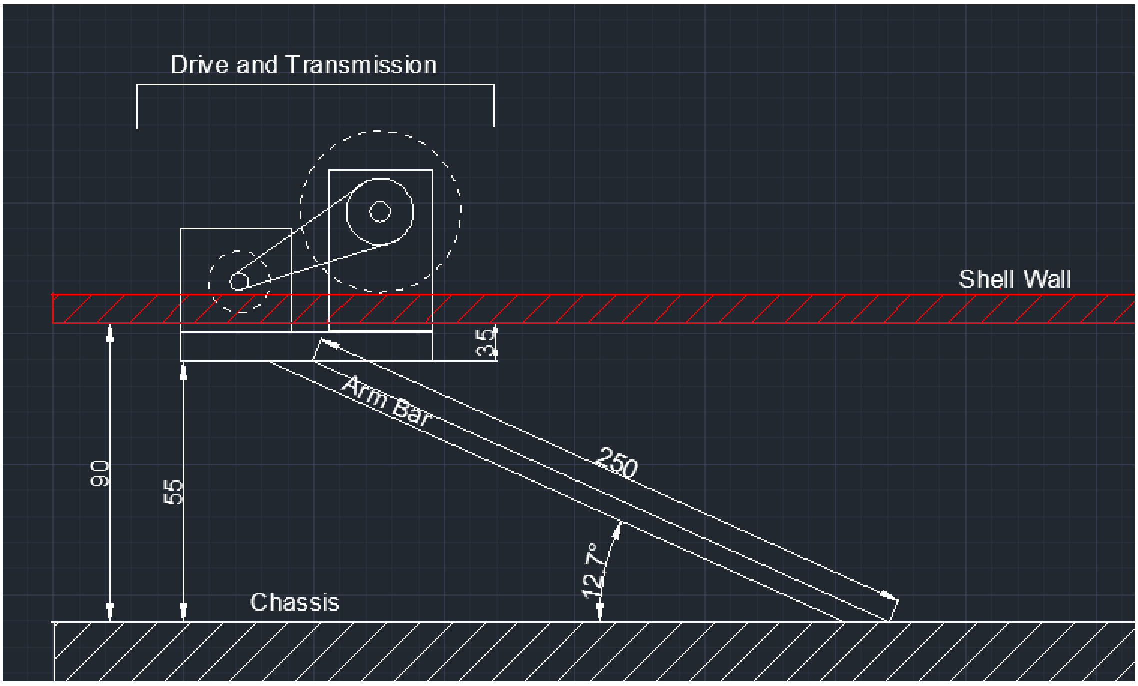


Figure 22 – Diagram of Arm Bar and Measurements

The arc length that the arm bar travels during and extension and compression needs to be known as the hole sizes in the shell need to be known. The arc length is 111.7 mm this means that the change in horizontal distance is 47.7 mm and as the drive and transmission come below the shell wall the width of this must be added so the hole must be 150 mm long and the width is the same as the drive and transmission system plus extra for safety, this comes to 65 mm. The full equation and workings can be seen in **appendices section B13**.

Location and Extension of MSD

The MSD will be pinned to the chassis at one end and pinned to the arm bar at the other. The bar needs to move though and angle of 25.6 degrees to accomplish a change of 100 mm of vertically. The MSD will be placed at an angle to the chassis, there are two variables here; the angle between the MSD and the chassis and the distance between the pinned joint of the arm bar to the chassis and the pinned joint of the MSD to the chassis. See **appendices section B14** for calculations and the method used to achieve the result as well as a full description. Table 4 below shows the final decided values these need to be looked at in conjunction with Figure 23, these values were decided after doing iterations by varying the angle between the chassis and the distance between X and Z the spread sheet was used to determine the variables. At different extension there will be different forces acting on the arm bar these forces need to be known for fatigue and to calculate if the bar can take the amount of stress, this is solved in **appendices section B15**.

Angle (η)	75 degrees
Location point Z	(-125, 0)
Point A	(-117.9, 26.6)
Length (l)	120.8 mm
Length of MSD (Z to A)	86.3mm
Extension (E or A to B)	60.0mm

Table 4 - Final Values for MSD

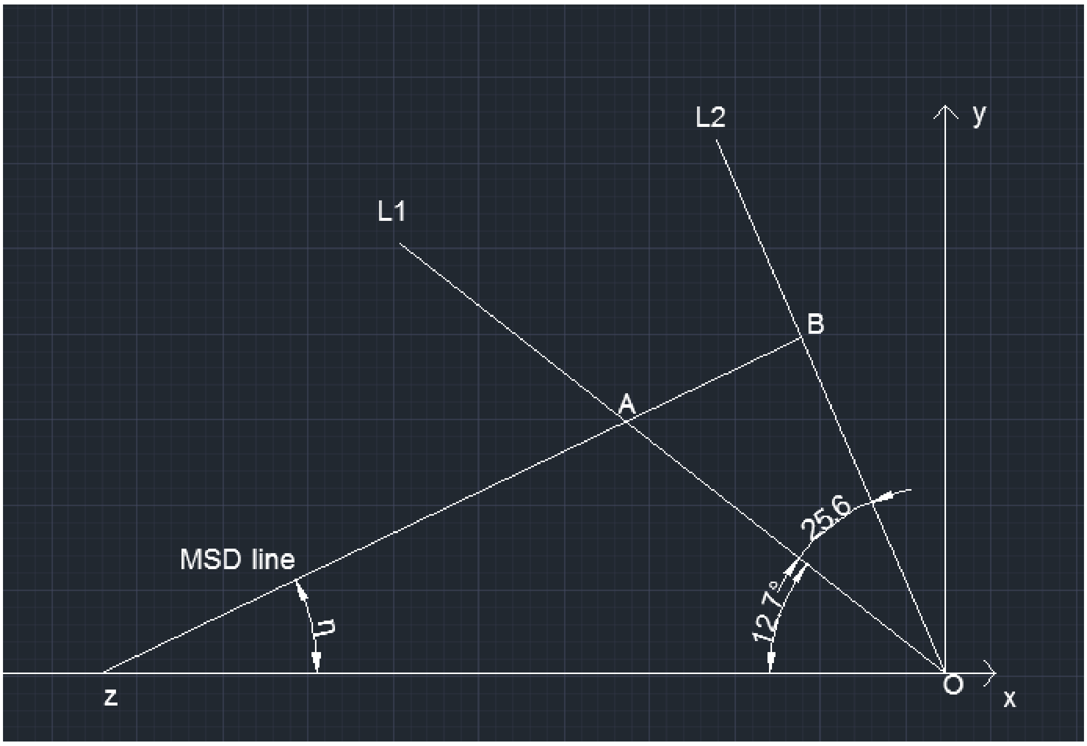


Figure 23 - Line Diagram showing nomenclature and positioning for MSD

For the UT and MFL modules a polymer spring will be used to keep the sensors against the pipe wall whilst offering the ability for them to extend and compress for variable pipe diameters. The polymer spring will be a conical compression spring. The smallest diameter end of the spring will be compressed against a flange coming from the chassis; it will have a squared and ground end. The larger diameter end will be attached to the arm bars for the sensors and it will need to have a closed and not ground end so that it can be threaded through the arm bars for the sensors. A polymer spring is going to be utilised as it is a cheaper alternative to 40 MSDs and it reduces the weight it was also chosen because the sensors do not need a large reaction force with the pipeline wall like the driving wheels need. There will be two conical polymer compression springs in each module as the 20 sensors are staggered across the chassis. It is also worth noting that the odometer have been moved to the driving module because of this staggering reducing the need for an extra module.

Design of the MSD

It has been calculated that the compression spring on the MSD will have a spring rate of 990 N/m. The spring wire diameter will be 6 mm and the coil diameter will be 40 mm. The number of turns the spring will have is 20.45. See **appendices section B16** for full calculations and methodology.

The viscous damper will have a diameter of 25 mm and it will provide critical damping, so no oscillations which would cause hammering between the wheel and the pipe wall. The damping coefficient is 81.3 and the damping force it provides is 3.25 N. Calculations and methodology can be seen in section B16.

MSD to Arm Bar Joint

A pin knuckle joint will be used and the diameter of the pin is 10 mm. The bending and shear stress need to be calculated. This is calculated in **appendices section B17** and the results tell that the pin will not fail.

FEA on Arm Bar

Below are figures for the FEA on the arm bar it shows that the maximum stress is far below the yield stress of the steel that is used for the arm bar. The highest stress occurs in the gap for the joint between the MSD and arm bar, see Figure 24. It also shows that there is very little deflection of the bar, see Figure 25.

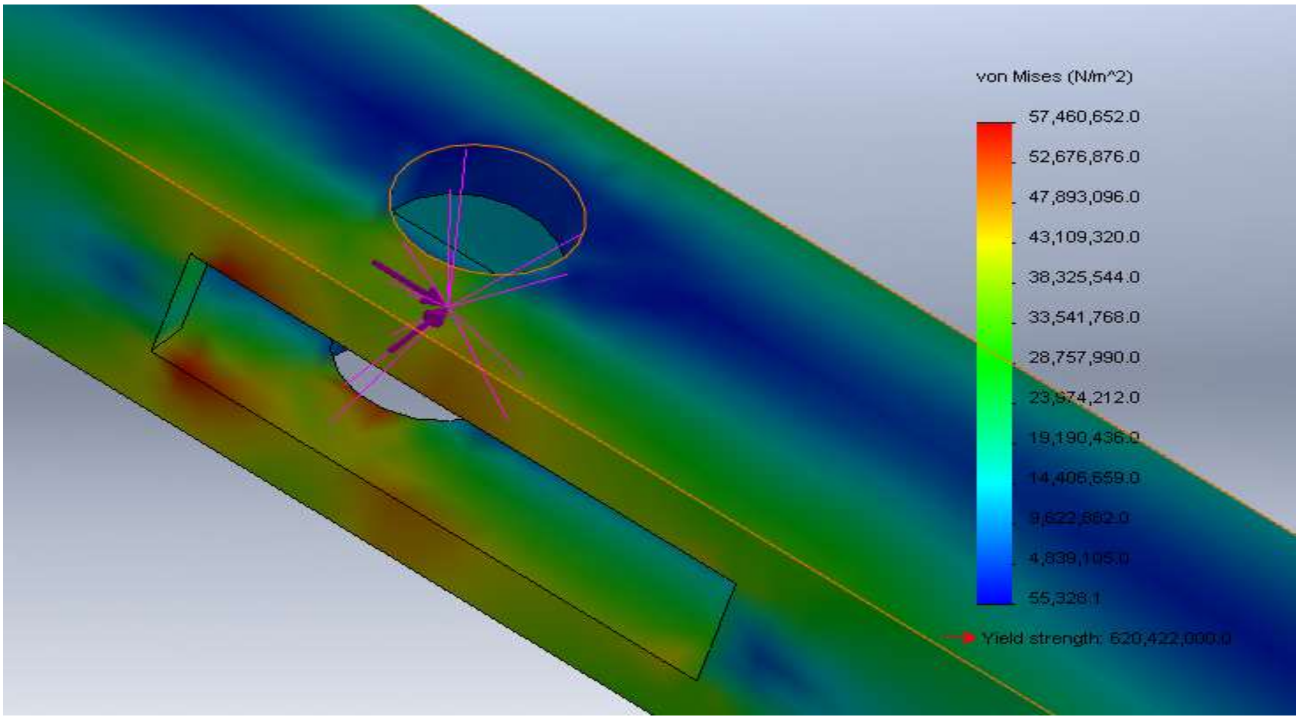


Figure 25- Stress FEA Arm Bar, MSD to Arm Bar Joint

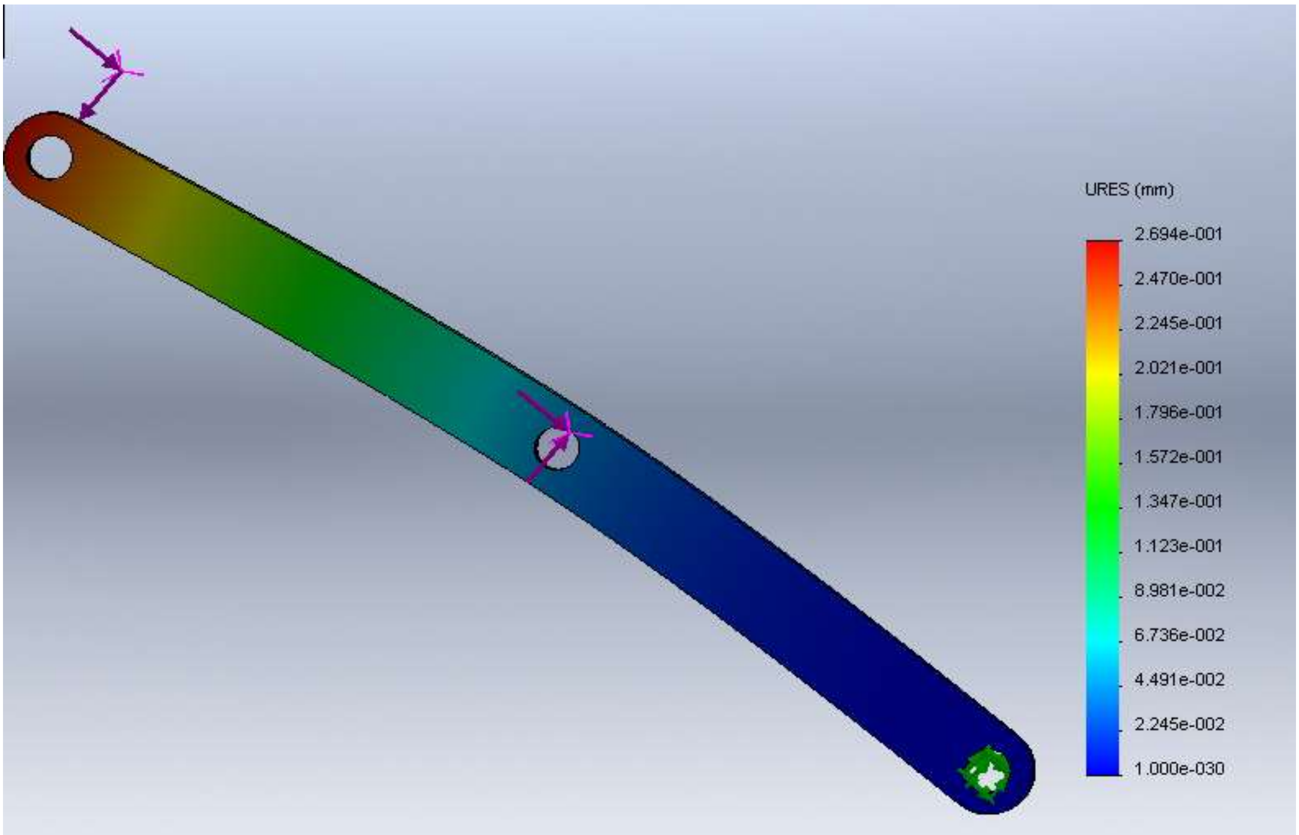


Figure 24 – Deflection of Arm Bar under Maximum Loading

5.13 Centre of Mass

Driving Module

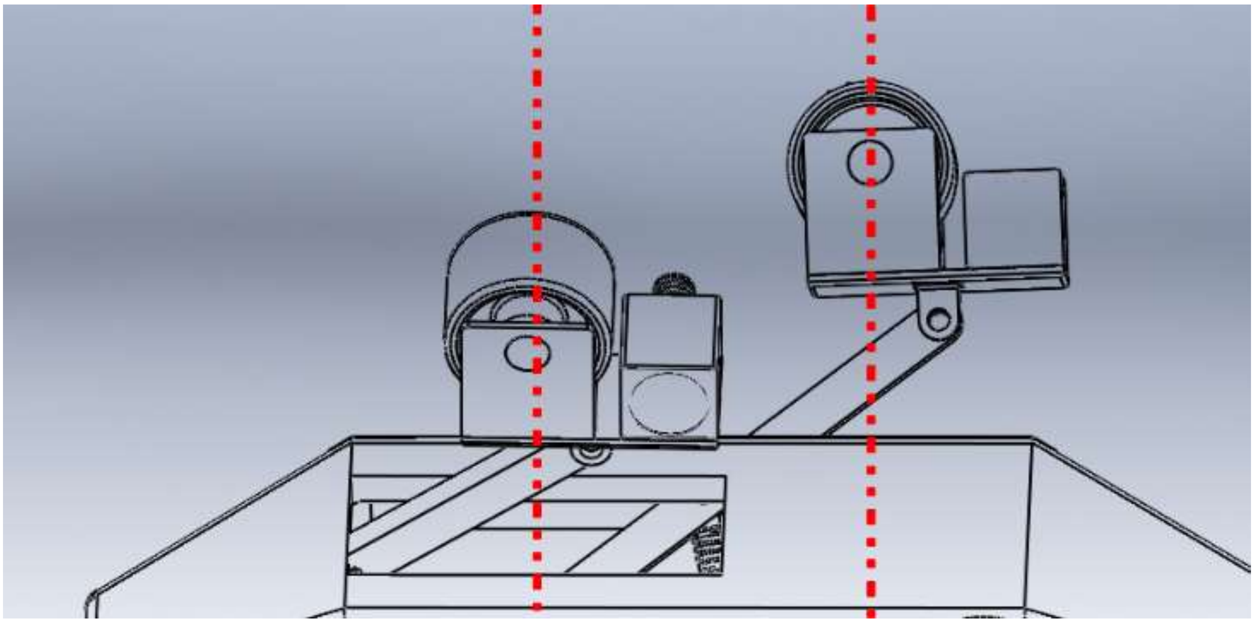


Figure 26 – Centre of Mass of Driving Module

It is aimed that the centre of mass (COM), in the y-direction, relative to Figure 26, for the driving module is between the two dotted red lines to avoid the driving module tipping over. In the x-direction the centre of mass is aimed to act along the centroid of the octagon cross section of the chassis. The electronics that are housed within the chassis need to be attached in carefully considered locations as the without the electronics the COM will act along the centroid due to a high level of symmetry in the design. The electronics will also have a large influence in the location of the COM in the y-direction as they could be used to tip the line of action back within the region to balance the driving module.

Drive and transmission system

Finding the centre of mass for the drive and transmission system is important because the location of the pinned joint needs to be above this. All the components masses have been taken into account in Figure 27 is fairly obvious that the centre of mass will be around 86 mm because of the much larger 18.74 kg mass that comes from the reaction with the pipeline wall.

Mass, m (kg)	0.469	0.170	0.639	18.74	Σm = 20.02 kg
x (mm)	22.5	58	86	86	ẋ = ----
mx	10.55	9.86	54.95	1611.16	Σmx= 1686.5

Table 5 – Centre of mass of components

$$\dot{x}\sum m = \sum(mx)$$

$$\dot{x}(20.02) = 1686.5$$

$$\dot{x} = 84.2\, mm$$

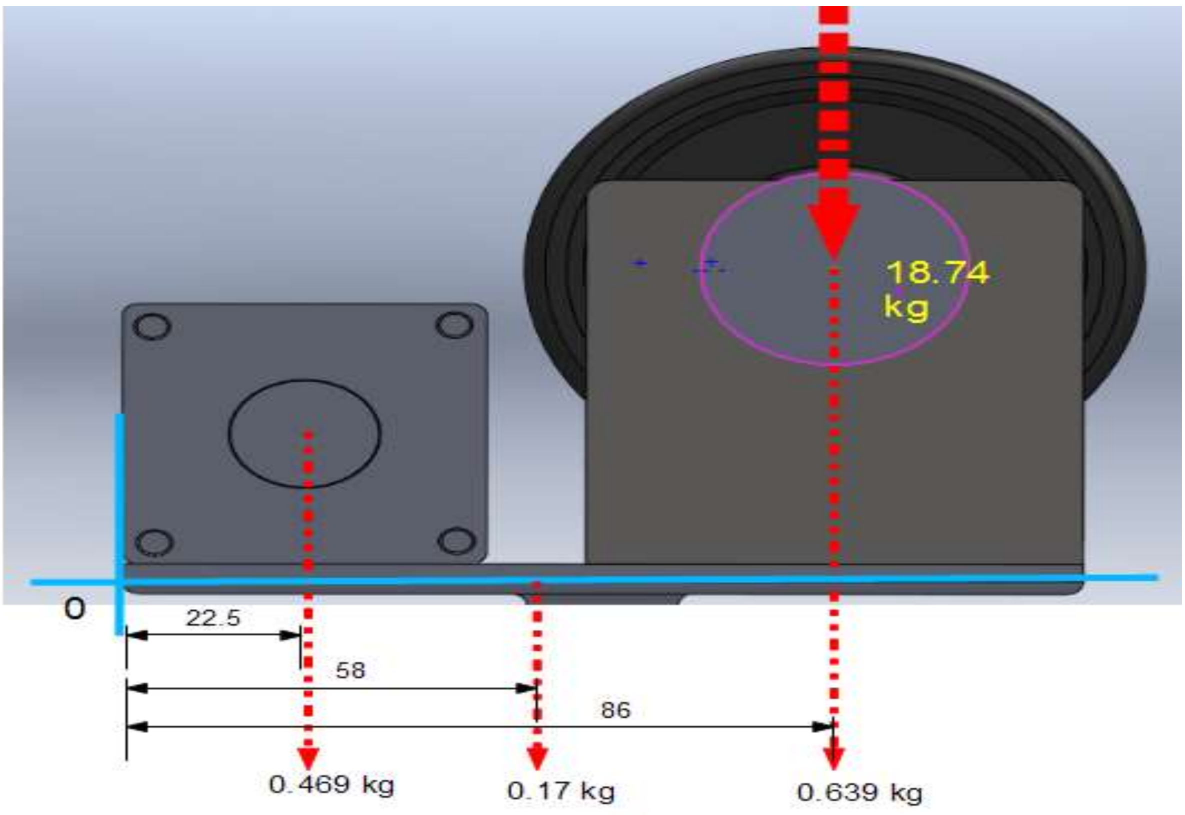


Figure 27 – Drive and Transmission Centre of Mass

So 84.2 mm from 0 in Figure 27 is where the centre of mass for this drive and transmission system is. The pin joint will be connected at this location and torsion springs will prevent the system from rotating excessively. Components for the drive and transmission system can be seen in **appendices section B18.**

5.14 Chassis

An FEA was applied to the chassis of the driving module and forces were applied to the eyes of the knuckle joints for the arm bar to chassis and to the fork eyes in the MSD to chassis joints. The thickness of the chassis is 5 mm and the eyes will be T-welded to the chassis. Figures 28 and 29 show that the stresses are around 121 MPa, which is 5 times below the yield stress of the steel. The displacement FEA shows that there is a maximum displacement of 0.02 mm. The chassis was planned to be made of steel however the FEA simulations show that aluminium would be better as the yield stress of aluminium is still less than any stress shown in the FEA. The displacement was very small with a maximum displacement of 0.02 mm. FEA on the eye for the module linkage joint can be found in **appendices section B19** of the appendices.

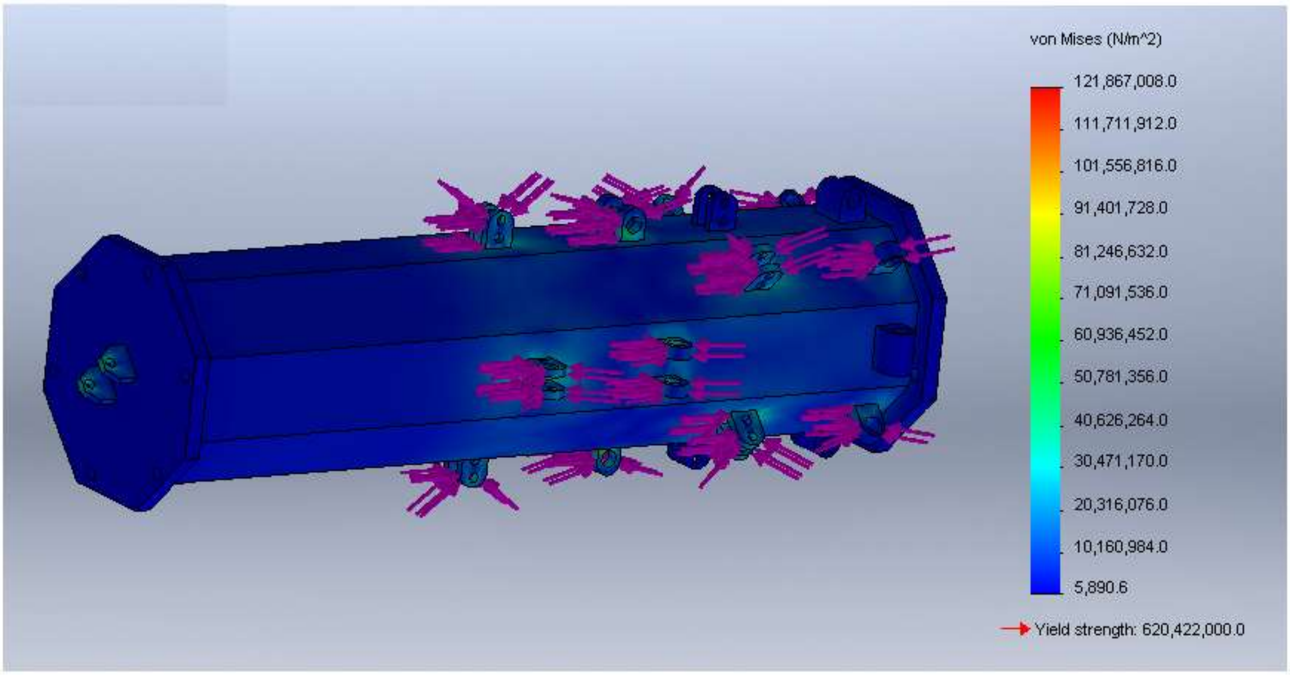


Figure 28 – FEA on Chassis

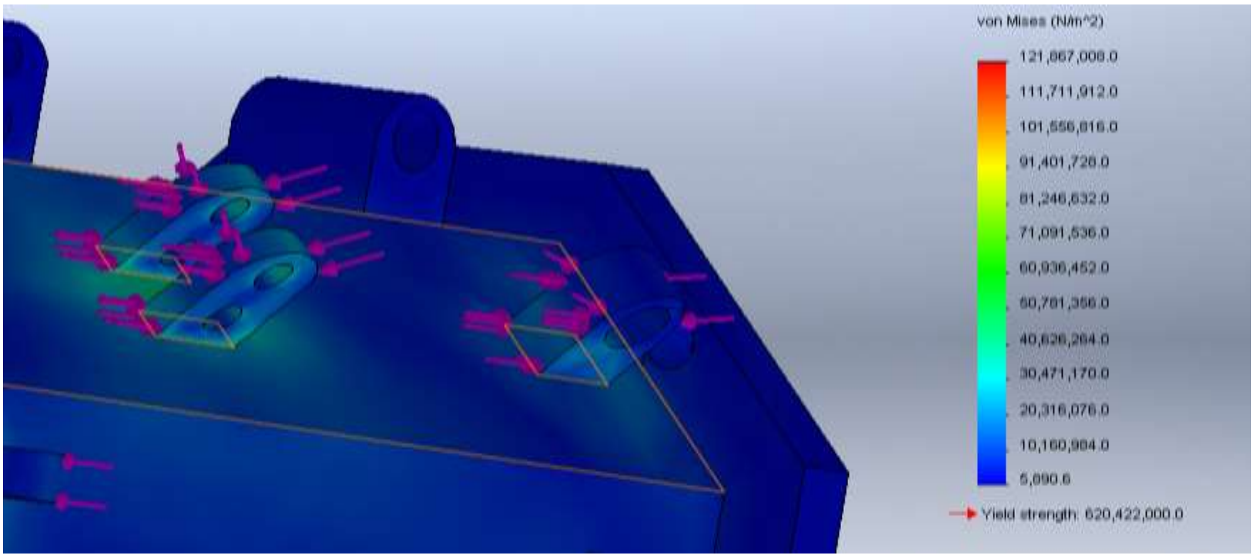


Figure 29- FEA on Knuckle Joints for MSD and Arm Bars

5.15 Module Linkages

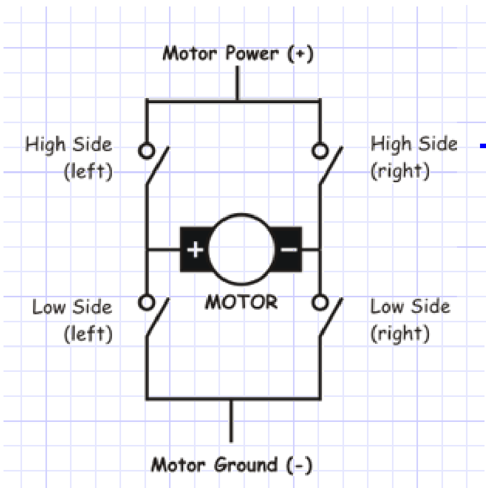
Initially it was thought that the modules should be linked together using a universal joint (UJ) however they are more expensive than other solutions. They would also require maintenance and they could get seized by corrosion products that will fall onto the joint. The wiring going through the universal joint was another challenge that can avoided by a different solution. The alternative chosen is to have a flexible elastomer joint between the joints however the main disadvantage to elastomers compared to a steel UJ is that elastomers are likely to rupture. The flexural strength of the a linkage which is 30 mm in diameter with a 10 mm bore and is 400 mm long is 7.68 MPa, which is much lower than the 17MPa modulus of rupture for 50% carbon black filled butyl rubber (CES,2013). The equation can be seen in **appendices section B20.**

5.16 Motor Control

The motor will need to be able to move in reverse, it will need to be able to vary its speed and torque to adjust for different driving conditions and angles of elevation in the pipe. The motor must be able to provide braking using back EMF. These are the four features need to accomplished electronically.

Reverse

An H-bridge will be used to control the motor these are also solid state devices that can be digitally controlled and they are more commercially available than SSRs. They are overall more compact and in terms of their functions they are the cheapest option. They can also be used to brake the motor and PWM (see braking section below) can be easily integrated into the circuit. SSRs are another option research on these can be seen in **appendices section B21**.



High Side Left	High Side Right	Lower Left	Lower Right	Quadrant Description
On	Off	Off	On	Motor goes Clockwise
Off	On	On	Off	Motor goes Counter-clockwise
On	On	Off	Off	Motor "brakes" and decelerates
Off	Off	On	On	Motor "brakes" and decelerates

Figure 30 – H-bridge control circuit (McManis, 2006)

Variable Speed and Torque

The control of the speed, acceleration, torque and direction of the motor will be done by a DC motor drive as they can have programmable logic implemented into them which is desirable for the ILIs digital system. The motor drive is made out of solid state components so vibration and impact loading is not an issue to the components. Figure 31 shows a typical DC motor drive circuit however in my design the input will be a DC voltage and an inverter will have to be used to supply the AC input to the field windings.

The voltage across the armature, that will be used to control the speed of the motor, will be varied by using pulse-width-modulation (PWM). PWM will also mean that the motors power output can vary as not all the motors will be running at their maximum power all the time.

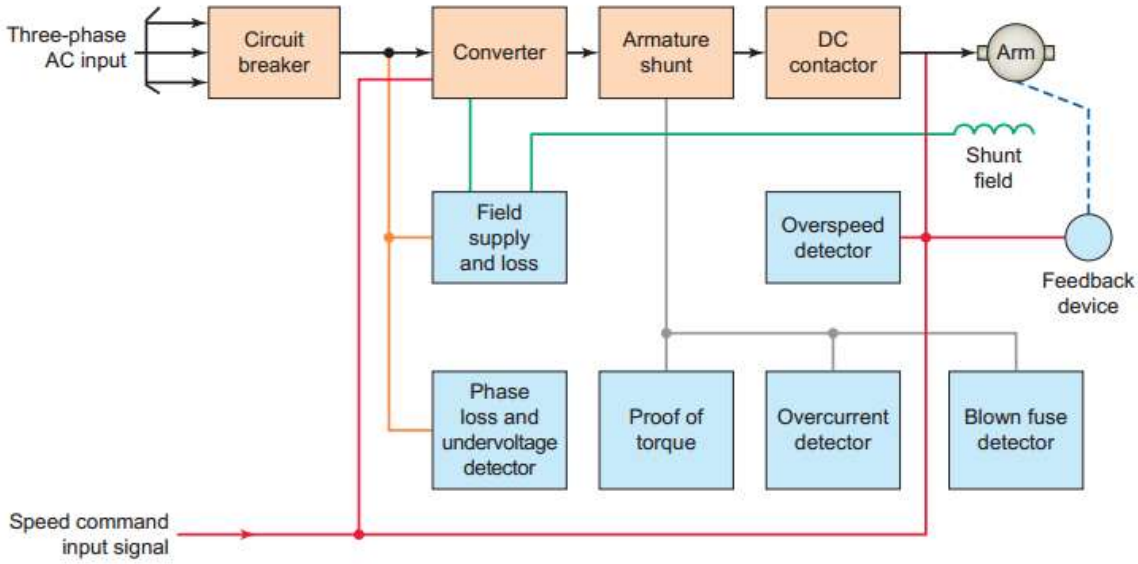


Figure 31 – DC Motor Drive Circuit (Acroname Robotics, 2006)

Braking

Another advantage of utilising PWM is that is can be used to control back EMF. As stated in the reverse section the H-bridge control circuit can use PWM the connection is shown in Figure32.

Using PWM, giving back EMF, in combination with the braking from the H-bridge means that variable braking can be applied and the braking can be controlled to the same degree as the velocity of the motor this gives a very good control over the motion of the motor and thus the wheels.

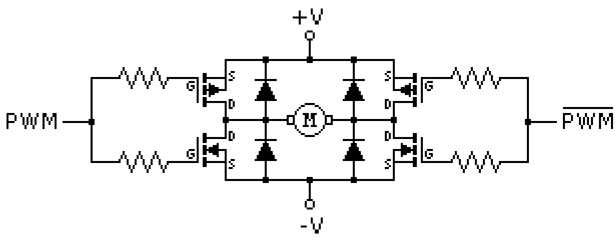


Figure 32 –PWM to H-bridge (Allaboutcircuits, 2012)

Initially it was thought that the back EMF and the braking from the motors would be sufficient to provide enough braking force to keep the ILI vertically stationary in the pipeline however the braking methods described are more used to keep the ILI from excessively accelerating whilst falling under its own weight and there if there is an issue with the electronics then there is no back up so it has been decided that a mechanical brake is needed on each motor.

A permanent magnet electromagnetic brake will be used, in these when the power is suddenly lost these brakes engage. A calibrated accelerometer will be in series to this as it will provide the acceleration limit at which the brake will engage.

A flow diagram for the coding has been created and can be seen in **appendices section B22**.

5.17 Proximity Sensors

The ILI may need to stop abruptly if it encounters the end of the steam main. Sensors will be needed to check that there is pipeline for it to move along these sensors will also be able to detect an obstruction such as a closed valve so that the ILI does not collide into the obstruction. If an obstruction is presented the coding will allow 15 minutes for the obstruction to be removed, such as opening the valve, otherwise the ILI will shift into reverse and return back to the point of insertion.

These sensors will also be used to detect an upcoming gradient change that the so that the ILI may need to change power to different motors to cope with the bend or change in the shape of the pipeline.

Research into different types of proximity sensors can be found in **appendices section B23**. However microwave radar array was chosen. Microwaves have a smaller wavelength this means that they can detect greater detail than larger wavelength radio waves. It is possible for radar to detect corner radii as it can measure the angle between different beams shown by the angle beta in Figure 33. If software were used to look for specific returning wavelengths then an accurate picture of the pipeline can be determined. This is the main reason why radar will be used in the ILI.

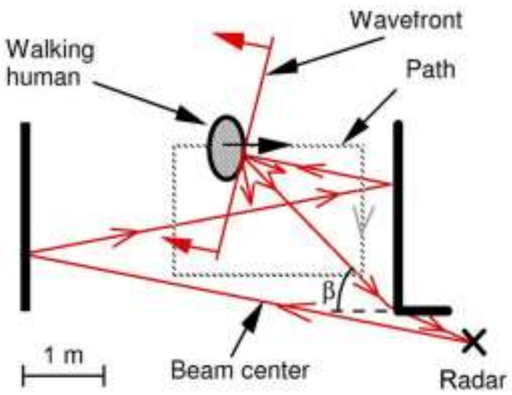


Figure 33 –Radar detecting corners (Sume and Gustafsson, ,2011)

5.18 Battery

A Li-ion battery has been chosen because it has the greatest power : weight ratio when compared to other battery chemistries. However the power it can hold, the capacity of the battery, and the duration it can power the motors, sensors and the computer needs to be calculated. This can be seen in **appendices section B24**.

A 265 watt-hour battery has been selected. It has a weight of 4.31 kg and costs £794 (JEGS, 2013). This battery can supply enough power to inspect a 2 kilometre long pipeline. A smaller battery could be used for smaller inspections as this would decrease the weight.

5.19 Computer

For the ILI it has been decided that a Raspberry Pi will be used as an SBC it also has a great processing power when compared to its power consumption and price. Another advantage of the Raspberry Pi is the fact that it is easily programmable. Figure 34 shows the relative size of the Raspberry Pi (Raspberry Pi, 2013). For more information on SBCs see **appendices section B25**

Figure 34 – Size of Raspberry Pi (Yates, 2012)

5.20 Data Storage

Data coming from the sensors can be stored in a variety of ways depending on the quantity and acquisition speed of the data. Common methods of storing data in ILIs are by using hard disks drives (HDD), solid state drives (SSD), flash drives and data loggers. An SSD is resistant to shock and vibrations, which will occur in the ILI, as there are no moving parts and they consume around half as much power as a HDD and they deliver consistent fast read and write speeds (Rose, 2013). The downside to SSDs is the price when compared to the alternatives however they are decreasing in cost and the in the case of the ILI the reliability of the SSD to record the data is worth the extra cost.

5.21 Data Acquisition

Data acquisition has also been looked at as noise affects the signals from the sensors. A differential amplifier will be used to reduce the noise of the signals. More information can be seen in **appendices section B26**.

5.22 Power On and Off

Two push buttons at either ends of the ILI are needed to turn the ILI on and off. The two buttons need to be switched on simultaneously as if there was just one button this may get switched by a feature when travelling within the pipeline which would mean that the ILI has to be recovered manually. It is possible to turn the ILI on and off from both the front and back as sometimes it is not necessary for the ILI to reverse back to the point of insertion if a collection point at the end of the inspection is possible.

Figure 35 – Push Button with LED

6 Materials and Manufacturing

6.1 Drive Module Chassis

It has been decided that the chassis will be made from an aluminium alloy and the aluminium will be extruded. In the FEA in section 5.14 it shows that the maximum stress in the chassis is 121.9 MPa so the yield strength of the aluminium alloy must be above this strength, a safety factor of 1.3 for different loads has been decided upon this gives a maximum stress of 158.5 MPa. The aluminium alloy will be cold extruded to increase the yield strength due to work hardening. Another advantage of cold extrusion is the good control of dimensional tolerances so no machining is likely to be needed, which reduces the cost and time to manufacture the ILI. The downside to extrusion is that surface and internal cracks can develop. The tendency for cracking depends on the die angles, the material impurities and the speed of the extrusion, as the faster the extrusion the greater the amount of heat generated (Gupta and Mittal, 2009) The cross section of the chassis would look similar to the hollow hexagon shaded in blue in Figure 36.

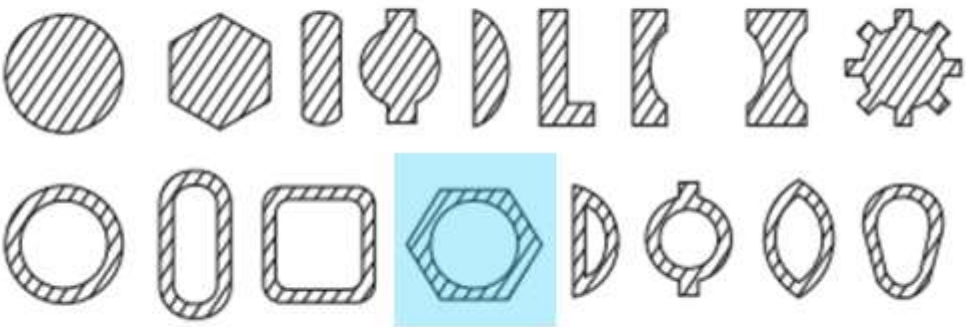


Figure 36 – Possible Extruded Shapes (Gupta and Mittal, 2009)

The aluminium alloy chosen is 5052, H34, see Figure 37 for comparisons. So its main alloys are magnesium and chromium it is cold worked and then tempered by a low temperature heat so that it has half of its maximum hardness. This grade of aluminium also has excellent corrosion resistance, has high fatigue strength and excellent workability. (Aluminium City Limited, 1999)

Only the driving module chassis has been considered however the chassis for the other two modules would be similar except they would have lower thicknesses. The transmission pulleys will be bought in however the transmission casing will be of the same aluminium as the chassis.

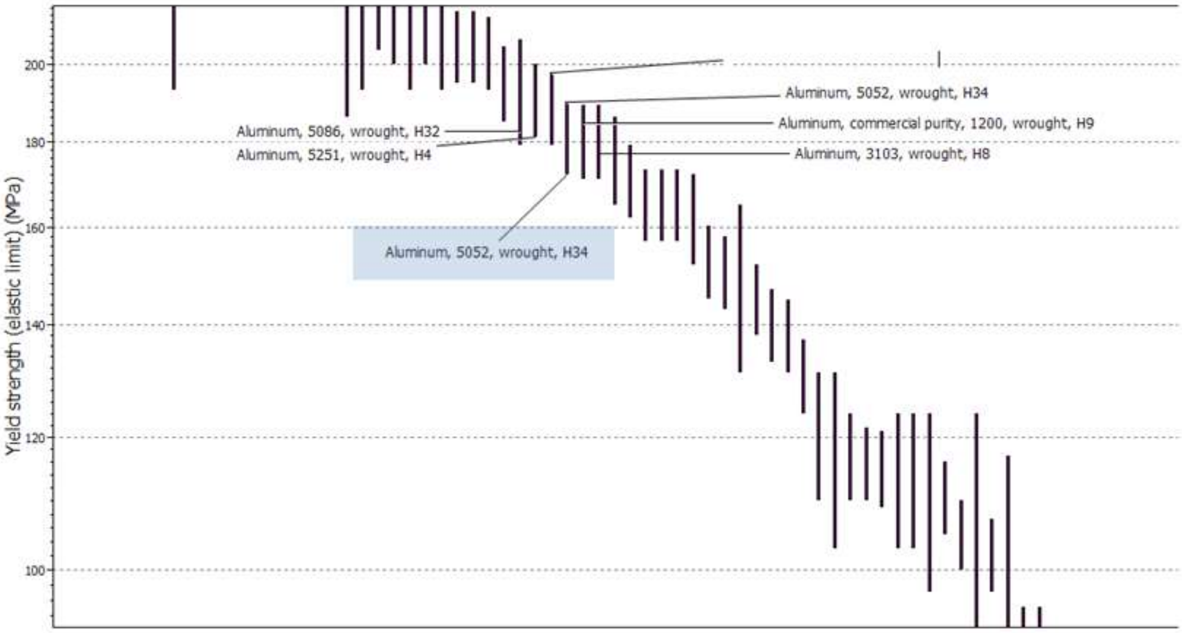


Figure 37 – Different Alloys of Aluminium with Yield Strength (CES, 2013)

6.2 Arm Bar and Base Plate

The arm bar and base plate will be made out of steel. The steel will come from an extruded process then the holes and radii will be machined. This method has been chosen as it is the cheapest and most economical method of making the arm bars. The extruded bars will be bought and the machining could be done in house. The steel has to have a high fatigue limit as there are varying stresses on the arm bar as shown in the FEA in section 5.12 the yield stress of the material must be over 57.5 MPa. Even though aluminium alloys are capable of a yield stress above 57.5 MPa they have a much lower shear modulus and shear stress is likely to occur if the ILI rotates in the pipeline. A safety factor of 2 should be added to the yield stress of the steel because of variable loading and fatigue, so a yield stress of 115 MPa is required.

It is desirable that the steel is corrosion resistant so chromium must be an alloying element; good machinability is also desired so a small amount of sulphur must be added. Manganese should also be added to the steel as it improves the strength and toughness of the steel. It is also desirable that the steel is as lightweight as possible. A stainless steel is the ideal material according to the CES Edupack selector. In Figure 38 it shows that Stainless Steel AISI 430 has the highest yield strength to weight ratio and also it has the ideal alloying elements as shown in **appendices section B27**. (Chase Alloys, 2011)

The knuckle joint eyes on the chassis, the motor and wheel case will be made of the same material as they require similar mechanical properties.

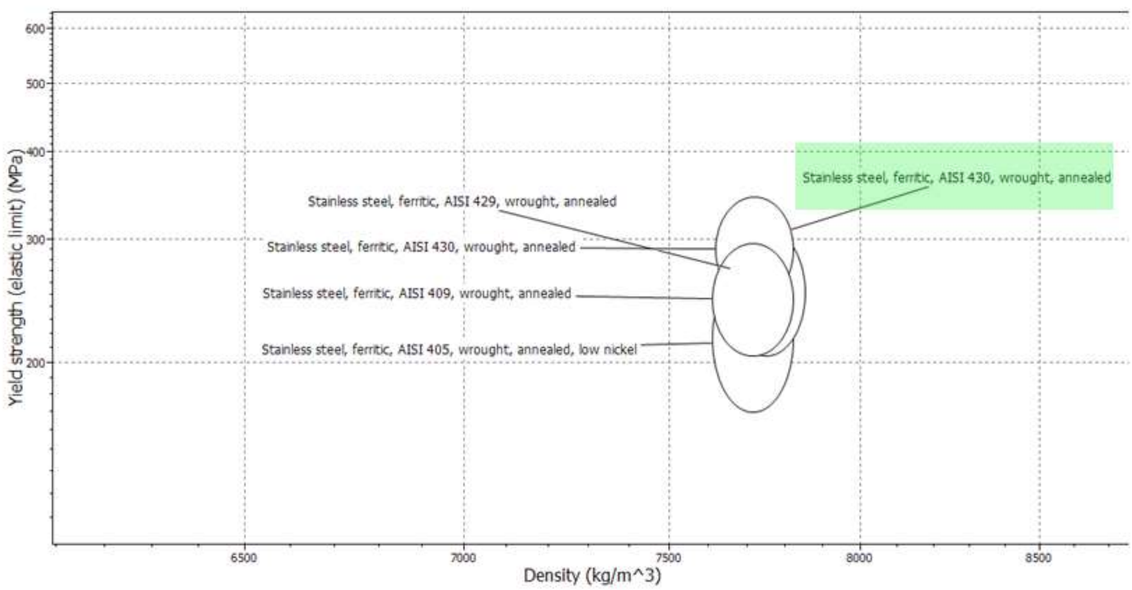


Figure 38 – Steel Selection Process Results (CES, 2013)

6.3 Shell

The shell of the ILI will be made from a plastic. The chosen plastic will need to have good ductility and fatigue strength due to vibrations that that will be transmitted through the chassis. Initially it was a choice between ABS and Polypropylene (PP) as they both have the desired characteristics. However PP was selected as it has higher fracture toughness, so the shell is less likely to develop large cracks. PP is also has a lower density than ABS so it would make the overall ILI lighter it also has a greater higher strain value indicating that it is more ductile than ABS. PP is also cheaper and recyclable another two key issues that need to be taken into consideration when designing a product.

Talc will need to be added to the PP to slightly increase the stiffness of the PP and calcium carbonate is going to be used as filler in the resin as it improves the impact strength of the PP. (Plastic Materials Inc., 2012)

Rotational moulding was considered as a manufacturing method of making the shell so that it could be made out of one part however the need to have holes in the sides for the arm bars to protrude though makes this method unfeasible. Compression moulding was also considered however this is more commonly used from thermosets and PP is a thermoplastic. So the shell will be made in two halves using injection moulding and then attached together using lip and grove and countersunk bolts so that they are flush to the outside surface of the shell. Snap fits are avoided as they can break and are tricky to remove for maintenance issues.

Figure 39 shows the split line for the shell.

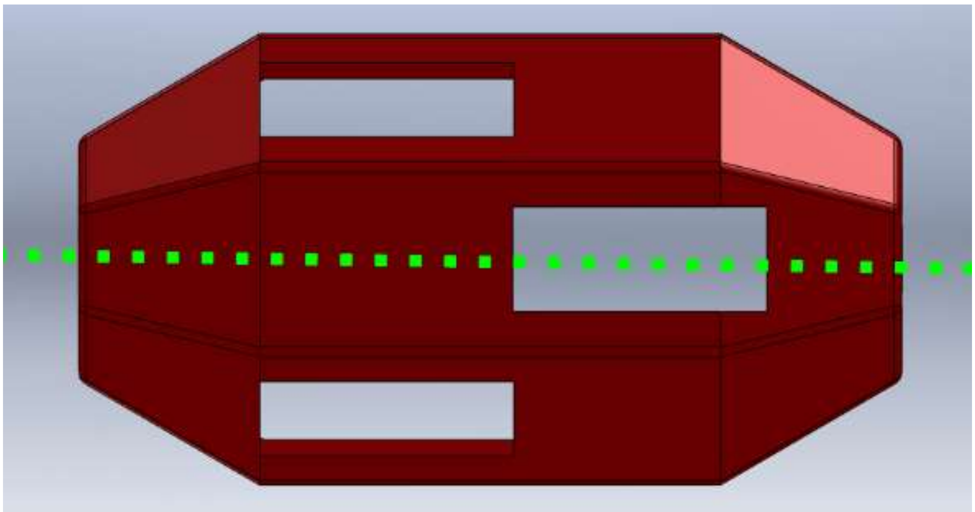


Figure 39 – Split Line for Shell

6.4 Module Link

In the module linkages section 5.15 it was shown that 50 % carbon black filled butyl rubber will be used because of its rupture modulus. The easiest way to form a hollow tube is to extrude it the carbon black can be added to the butyl rubber compound before extrusion. However if there is a change in the design later that requires an orientated reinforcement such as steel rods or glass fibres then the more expensive resin transfer moulding will need to be used to manufacture the module links.

The steel eyes for the knuckle joint will pressed onto the rubber by a flange the wiring will come out of the side of the rubber shaft before this point and will be surrounded by a protective cover whilst they are exposed between this point and the point that they enter the chassis.

7 Design for Assembly

This section details the method of how the ILI is put together in order. The ILI will be put together manually so these instructions need to be as clear as possible to be understood. These instructions are presented in a series of steps here to be followed. This is a low-volume product so the need for careful precise manufacture is more important than speed. Part reduction was considered throughout the design however this is an area that could be improved on because the mechanics of combined part is more complicated than the two separate parts. The components have been designed so that an average sized man can put them all together, such as the holes in the shell have also been sized so that a hand and arm can fit comfortable through them. There will be marks on the components to tell which the front and back of the ILI and other marks that help with the build of the ILI. The reason for the main use of screws and bolts for the product is because it is designed to be easily maintainable and parts are supposed to be easily accessible, this is not an issue as it is not a consumer product. The use of screws and non-permanent fixings also mean that parts can easily be recycled at the end of their lifetime so the product has also been designed for disassembly. Full step by step instructions for assembly of the driving and sensor modules and the linkages are available in the **appendices section B28**.

8 Price

A full product cost breakdown can be found in **appendices section B29**.

The total cost for the whole ILI comes to £ 2,808. This value does not have the manual labour time and cost needed in making the product factored in to it nor does it have the machining time or the time for assembly or does it reflect the amount needed for maintenance and testing of the product. In addition overheads also need to be added to this. It is estimated that all of these other factors increase the true cost of making and maintaining the ILI to be a 6 fold increase. So the true cost of the ILI is £ 16,848. This is under budget when compared to the estimated £ 20,000 in the PDS. However there may be other overhead costs that have been overlooked.

9 Weight

The estimated mass of the ILI was 30 kg however the actual figure is 53.18 kg. However some of the components masses were estimated due to time constraints. The weight could have been brought down if the design of the ILI was changed or the use of composite materials we implemented into the design. The mass of the ILI is estimated to be around 31.9 kg and the sensor modules were estimated have a mass of roughly the same and each sensor module is estimated to have a mass of 10.6 kg, which is over double the estimated mass for the sensor modules. A full breakdown of the weights of individual components is shown in **appendices section B30.**

10 Aesthetics and Ergonomics

The product is considered not to have any need for aesthetics as it is a purely functional product it is not going to be seen by many as during the time when it is in operation it will be in a pipeline. The product will be coloured red so that it may be seen, by workers when it is travelling towards or away from them, against a black or grey pipeline interior.

The product will be mostly transported in a case so that ergonomics are dependent on the case for transport however during set up the ILI can be handled by holding the ILI joint eyes which are connected to the chassis the best effort has been made to make the eyes not sharp. At no point must the ILI be grabbed by the holes that the arms protrude through and lifted.

11 Safety

The product has been designed with safety to both humans and the existing pipeline in consideration. The UK government has set no specific requirements such as weight limits (HSE, 2013) however it is recommended when handling the individual modules at least two people should help with lifting as limit the risk of causing damage and harm to either themselves or the ILI if the connected ILI needs to be lifted then a team of at least 4 is advised. The best efforts have been made so that components on the ILI are not so sharp that they would cause an incision on skin. The battery is the highest risk component to human safety and research has been completed on the correct operating conditions that the battery should be under, and the ILI has been designed to meet those conditions. An ILI launching device will also need to be manufactured so that the ILI can cleanly be fed and extracted from the pipeline.

Effort has been made to reduce the amount of vibration, which can cause damage to pipeline, by the use of various forms of suspension. Loading on the pipeline has been tried to keep to a minimum this is another reason why eight driving wheels were implemented instead of four as a greater contact area was given. The sensor module has also been designed so that there is minimal friction and contact which could cause damage to the pipeline.

12 Sustainability

There are several environmental aspects in the design of the ILI. Screws and bolts have been used throughout the assembly so there are no permanent fixings this means that it is easy to access individual components so they can be recycled. There is no use of composite materials, which are often difficult or impossible to recycle. The three most common materials used in the ILI are steel, aluminium and PP all of which are highly recyclable, this will give the ILI a better cradle to cradle standpoint, see Figure 40 for cradle to cradle diagram. More information on the sustainability of the product can be found in **appendices section B31.**

Figure 40 – Cradle to Cradle (Faces of Design, 2013)

13 Final Product

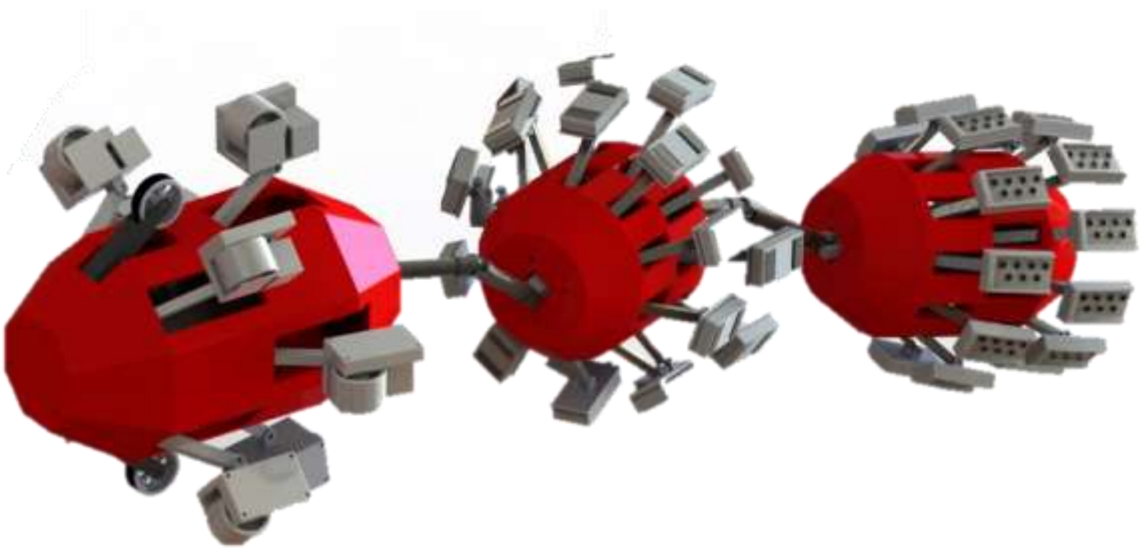


Figure 41- Complete View of ILI

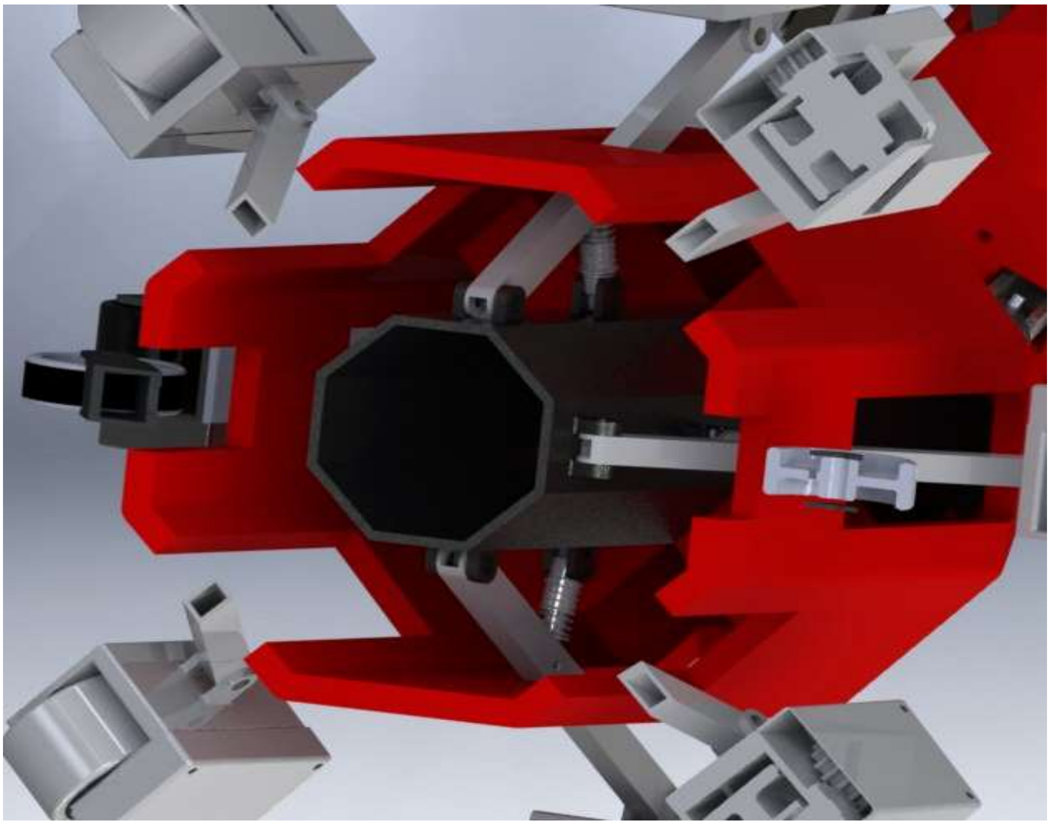


Figure 42 – Inside the Driving Module

Figure 43 – Driving System

14 Conclusion

It is clear that steam pipelines carry high amounts of energy and when rupture occurs this energy becomes very destructive to the surroundings, which unfortunately can result in the loss of human life. Currently research is being done on how to predict failures in steam pipelines and the corrosion mechanisms that occur in the pipes is being better understood. Currently in the EU there are no regulations governing the inspection and testing of steam pipelines. Owners of steam pipelines often employ point tests to survey the condition of their pipeline however this only gives a limited view of the true state of the pipeline and its integrity. Often sections of steam pipeline are difficult to access so frequently areas along the pipeline are omitted in testing.

The ILI product is a solution to this issue as it gives a comprehensive view of the condition of the pipeline so that it can be assessed and measures can be taken to correct any locations that could be deemed unacceptable. The ILI is designed to be as adaptable as possible with variable diameter inspection and the ability to move in all six degrees of freedom. This means that individual sized ILIs do not need to be manufactured and that the ILI manufactured is frequently in operation thus recovering its costs and making the company highly profitable.

The main issue with the design is the weight; it is significantly larger than estimated. The chassis and the shells are the heaviest components to the product. If the product was to be redesigned then the chassis' weight could be reduced by using a rib and skin design, similar to the fuselage of aircraft. The weight of the shell could also be greatly reduced by the use of composite materials, fibre glass or carbon fibre would suit this application well.

If the product were to be redesigned again a different drive and transmission system would be chosen because the eight arm bar system could be considered resource hungry and a potential lighter more efficient system could be used. It is though that a train bogie design as seen in Figure 41 could be adapted for the purpose. The materials and design of some of the components would change to be more unconventional and innovative however this would require a greater level of technical analysis.

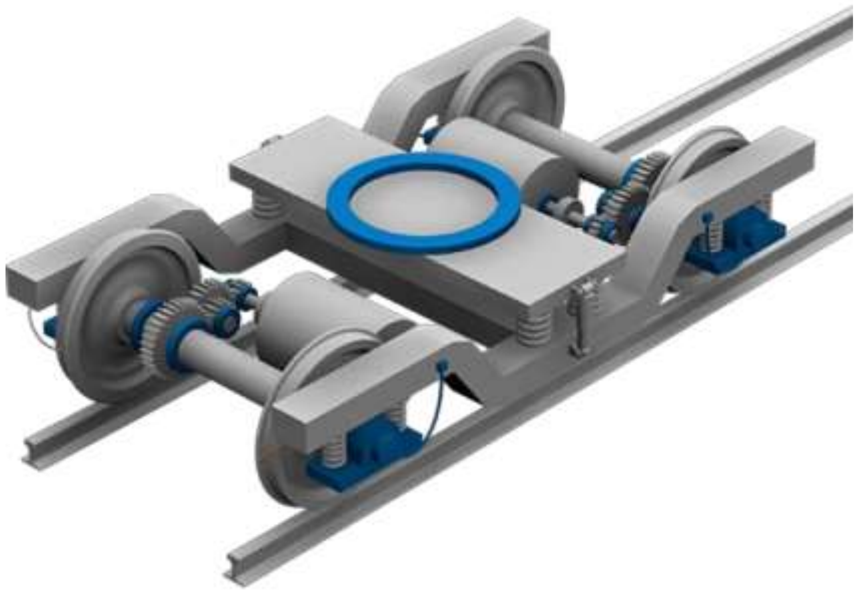


Figure 44 – Train Bogie (SKF, 2013)

15 Recommendations

In the future if this project was extended or if was passed onto another engineer then there are still several aspects that could be researched further in depth or other calculations and design needed for the ILI which could not be met through this report because of time constraints are:

1) Reduction of weight using different design and the use of composite materials.
2) Investigation into the feasibility of using a train bogie style drive and transmission system.
3) Software design for the ILI and greater in depth electronics with a full schematic design, manufacture and testing of an electronic circuit could be done
4) Research into ergonomics and the best way to handle the product
5) Design of an ILI launcher for different angles the launcher can also be a receiver or a separate receiver could be designed.

6) Research into the acquisition and the processing of the signals from the MFL and UT sensors and how to read the data.
7) Designing the ILI so that modules are combined into a smaller flexible unit.
8) Further research and development of how the location and position system will work and how to implement it into the electronic circuit.
9) Calculations for the MSD on the odometers and the variable helix polymer spring for the sensor arms.
10) Calculations for the MSD on the odometers and the variable helix polymer spring for the sensor arms.
11) Calculations, further FEA and simulation on all of the components on the ILI and simulation for vibration and fatigue loadings.
12) Calculations of thermal expansion and contraction and how they may affect the ILI and its life span. As there can be a very large differences of temperature inside the pipelines between summer and winter and between different locations in Europe.

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Appendices A

Final Report

By Peter Dobson

Table of Contents – Appendices A

A 1 Pipeline Contents and Corrosion

Oil and gas	I.	Hydrogen Sulphide (cause sulphide stress cracking, SSC)
	II.	CO_2
	III.	Chloride (cause hydrogen induced cracking ,HIC)_
	IV.	Sulphur Corrosion
Water	I.	Microbial
	II.	Erosion
Heating	I.	High Temperature
Slurry (Solid mineral particles in a liquid medium)	I.	Erosion

Table A1 – Pipeline Contents and Corrosion (Menon, 2011)

A 2 Pipeline Contents and Applications

Oil and gas	I.	Long distance transportation
	II.	Fossil fuel power stations
	III.	Extraction and refining
Water	I.	Transportation of water for drinking or irrigation
	II.	Water treatment plants
	III.	Power plants (fossil fuel, nuclear, geothermal, indirect solar, hydrodynamic)
	IV.	Drainage
	V.	Sewerage
	VI.	Industrial plants (cleaning cooling)
Heating / Steam	I.	Power plants (fossil fuel, nuclear, geothermal, indirect solar)
	II.	District heating
	III.	Manufacturing plants (e.g. paper)
	IV.	Means to transport thermal or kinetic energy
Slurry	I.	Short distance coal transportation
	II.	Used to transport material from extraction site to consumption or refinery

Table A2 – Pipeline Contents and Applications

A 3 Maps

A 3.1 Oil and Gas Pipelines in Europe

Figure A1 - Oil and Gas Pipelines in Europe (Nationmaster, 2012)

A 3.2 Steam Pipelines in Europe

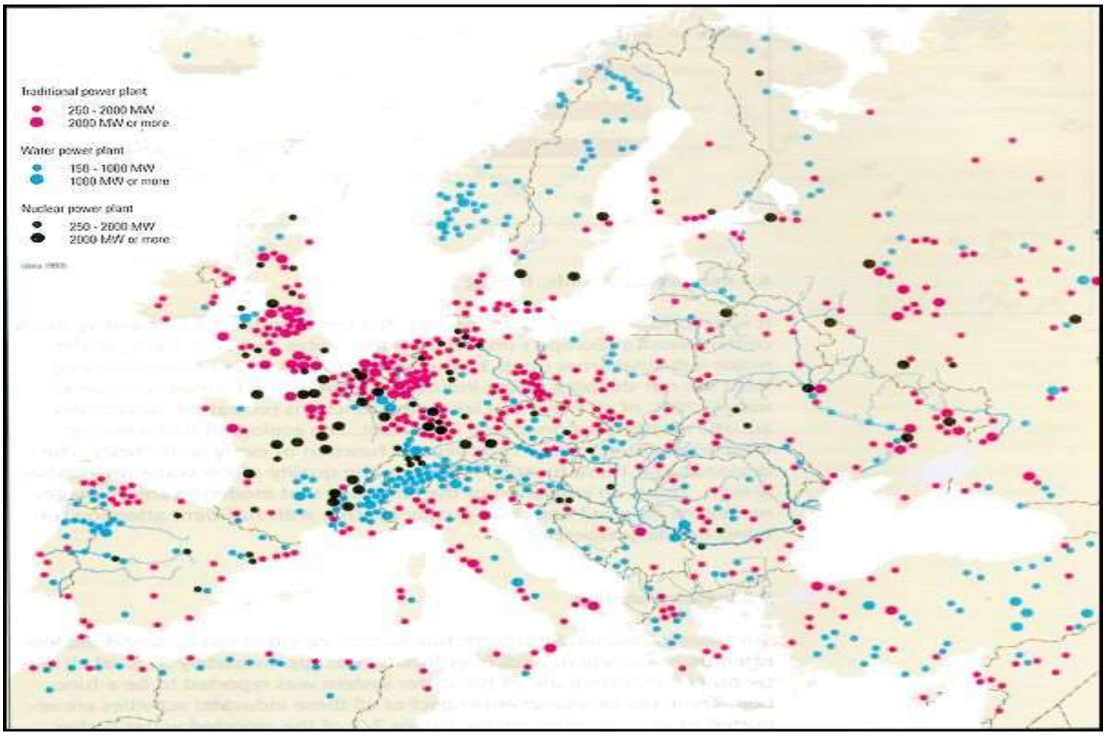

Figure A2 – Locations of Steam Pipelines in Europe (Nationmaster, 2012)

A 4 Case Studies

Location	Mihama, Japan, Nuclear Power Plant
Date	9th August 2004, at 3:28 p.m.
Cause	Flow accelerated corrosion (FAC) and/or cavitation-erosion
Summary of event	A piping rupture occurred, due to corrosion in the condensate system, killing five men and injuring seven. The pipe was scheduled for an ultrasonic inspection 5 days later, on the 14th of August and had not been inspected since 1976, when the plant first opened. The rupture was 560mm in size and the wall thickness of the pipe was 1.5mm down from 10mm when first installed. This incident prompted ultrasonic testing of nearly half of the country's 52 nuclear power plants steam pipes. It was found that in recent years, prior to 2004, 16 plants have replaced their steam pipes due to corrosion.

Table A3 – Case Study 1 (NACE International, 2005)

Location	41st Street and Lexington Avenue, New York City, Manhattan
Date	18th July 2007, approx. 6p.m.
Cause	Steam hammer, condensate drainage blocked
Summary of event	Steam pipe exploded underground causing a rectangular crater of about 11 by 13 meters and a plume of steam as high as nearby skyscrapers. One person died and 30 were hurt. The 24 inch (610mm) pipe that was installed in 1924 and is maintained by a company called 'Con Edison.' The company said that the pipe was thought to have ruptured because of cold rain water that penetrated the ground and cause water hammer on the hot pipe. This explosion caused other knock on effects on the bus and subway services and businesses in 15 to 20 surrounding buildings were without power due to damage to electric cable damage. Asbestos was at first assumed to be in the steam so people were evacuated. 250 fire-fighters and 300 police officers were sent to the area. This event made worldwide news and there have been more than a dozen steam pipe explosions in the past 20 years.

Table A4 – Case Study 2 (Barron, 2007)

Location	565 MW coal-fired power station
Date	[unknown]
Cause	High temperature creep
Summary of event	The rupture was a 12-foot tear along the longitudinal seam weld of the main steam pipe. The pipe has a diameter of 18 inches (475mm) and a wall thickness of 2.5 inches (64mm). The cause was thought to be high temperature metallurgical creep, creep is an issue in steam pipes that are constantly subjected to high temperatures and flow rates. The pressure in the pipes was 16.7MPa and the rupture caused displacement to auxiliary piping, bent I-beams, moved pipe supports and blew off roofing and siding.

Table A5 – Case Study 3 (Intertek, 2011)

A 5 Competitive Products

A 5.1 Directly Competitive Products

A 5.1.1 Other ILIs

There are many different types of ILIs on the market that use different detecting methods or a combination of methods to detect wall thicknesses and some can see cracks as well as other defects. All these sensors have advantages and disadvantages with respect to the type of defect that needs to be detected. Below is a list of the different types of sensor technologies that are currently in use in ILIs.

Magnetic Flux Leakage (MFL)

Eddy current Testing (ET)

Ultrasonic Testing (UT)

Electromagnetic Acoustic Transducer (EMAT)

Acoustic Emission (AE)

Geometry Testing or Calliper PIGs

It is worth noting that in MFL there are is a subdivision of high and low resolution which is basically the accuracy level of the sensor and the higher the accuracy the higher the cost. ILIs can be even more specific in their application; some of them are only for use in certain types of pipelines and are only for an industry set size diameter of pipe, they can have different methods of detecting their location and thus the location of the defect and they have different methods of moving within the pipe. (T.D Williamson, 2011)

A 5.1.2 External Inspection Robots

These are robots that travel along the outside of the pipe and inspect the pipeline wall thickness for signs of corrosion. They are usually in un-piggable pipelines and they can have a mechanism to get around obstacles such as supports or some are moved around the object by a person. Usually a worker walks along the length of the pipeline and pushes the robot however there are robots that are remote controlled. These are also regarded as In-Line Inspection Tools as they are not free roaming and they can use any of the sensing technologies however high resolution MFL techniques are commonly used. (NDT, 2012)

A 5.1.3 Visual Inspection

All of these techniques use cameras to visually inspect the inside of the pipe, they are different ways to convey the camera through the pipeline.

Visual inspection robots usually have wheels or caterpillar tracks and the camera has a servo motor to control its position and it is controlled wirelessly via radio by the workers who watch the video and assess the degree of corrosion. These are also known as ‘Remote Operated Vehicles, (ROVs)’ or ‘crawlers’.

The **push camera** is a camera on the end of a long flexible tether, with the wires inside the tether. The tether gets fed through the pipe at the entrance of the pipe by a worker. Their main advantage is that they can look inside pipes with a diameter as small as one inch and also see into areas that a robot would get stuck in, such as inside tanks or pipes that are semi-blocked.

Bore scopes can either have a camera or can be used with the human eye. There are rigid and flexible bore scopes, with rigid ones a better image quality attained but with the flexible type you can see around corners and tight gaps. These non-electronic bore scopes have a short range though. Video bore scopes are very similar to push cameras except push cameras have a much greater range.

A 5.1.4 Handheld XRF

These are handheld 'gun' shaped devices that record the metal thickness at the point where the detector touches the outside of the pipe these devices use similar technologies that are used in other ILIs (see section A 5.1.1), however ultrasound seems to be the most widely used.

There are other methods such as the handheld X-Ray Fluorescence (XRF) device which tells the elemental composition and percentage of the scanned location. From this information the amount of corrosion can be calculated and the certain types of corrosion can be identified.

A 5.2 Indirectly Competitive Products

A 5.2.1 Coatings

There are various different types of coatings that can be applied to inside and outside of pipes to reduce corrosion.

Metallic Coatings

Metallic Coatings can be divided into two groups; cathodic and anodic. The cathodic coating metals are ones that are more noble than the substrate (pipe material), so the coating is less reactive than the substrate, this means that it acts as a barrier between the substrate and the pipe product. However if there is a defect in the cathodic coating exposing the substrate which is effectively now an anode in a solution galvanic corrosion occurs. In anodic coatings the coating works as a barrier like cathodic coatings however if there is a defect in the anodic coating a cathodic reaction will occur on the substrate so it is protected cathodically. (E.Bardel, 2003)

Inorganic Coatings

Inorganic Coatings prevent corrosion by creating a barrier between the substrate and the environment. In terms of pipelines this normally means coating the pipe with mortar internally or externally. *Ceramic* coatings can be applied by thermal spraying. Ceramic coatings can be used to provide thermal barriers and are used in high-temperature corrosion and wear applications. *Ceramic-metallic* coatings are very hard are have applications where there is a high rate of wear or erosion.

Nitriding can be performed on steels that contain alloying elements that can form nitrides (such as molybdenum, aluminium, chromium and vanadium). They produce a very hard surface that has excellent wear and fatigue properties. The process is exposing the clean surface of the metal to anhydrous ammonia at elevated temperatures.

Another form of inorganic coatings are *conversion coatings* this is normally a treatment that is applied to the metal to change the properties near to the surface into an oxide or apply a film. For steel anodizing is not appropriate as the oxide has poor cohesion with the substrate. A process called ‘phosphatizing’ can be applied to steels. It can be painted on, sprayed on or the steel can be immersed in a phosphoric acid with iron, zinc or manganese. The process gives the steel a strong bonded thick porous layer of fine phosphate crystals. The coating does not provide a significant amount of corrosion resistance but acts as a very good base for oil or paint coatings. (Corrosion Doctors, 2012)

Paint Coatings

Paint Coatings are the most common way of corrosion protection. The paint can protect from corrosion in several ways. Metallic powders added act as cathodic protection and can protect the binder from UV degradation if the concentration of the powder is high enough they can cause the paint to have a colour so they are regarded as ‘pigment’ sometimes. The binder can be bitumen, organic materials (e.g. linseed oil), synthetic organic materials (e.g. chlorinated rubber or polyurethane) or inorganic (e.g. silicate). The binder usually acts as a barrier for the substrate by resisting the transportation of water, ions and oxygen. The paint can be applied by (electrostatic) spraying, by brush or by dipping. Before the paint is applied the surface has to be clean and have roughness so that the paint adheres well to the substrate. Cleaning can be done by: using organic solvents such as white spirits, alkaline cleaning agents or a combination, high pressure steam with small amounts of cleaning agent. (Bardel,2003)

A 5.2.2 Well-Designed Pipelines

Geometry affects most forms of corrosion and there are general rules that can be followed to increase the lifetime of the pipeline;

1) Design with sufficient corrosion allowances. In pipes the wall thickness is twice the estimated corrosion depth at the end of the products life.
2) Design the system so that components that are likely to suffer from corrosion are easy to replace, such as sacrificial anodes.
3) For structures exposed to the atmosphere design for effective drainage and ventilation or the opposite, where no air or water can be present.
4) Allow for cleaning and inspection and to use joints that don’t cause corrosion problems, so that stagnant water doesn’t accumulate in small crevices.
5) Avoid cold and hot spots and try to keep the surface temperature as even as possible to avoid thermo-galvanic corrosion where hot surfaces form an anodic surface and cold

surfaces a cathodic surface. Cold spots can also form condensation where corrosion can occur. This is highly applicable to steam pipes.

6) Take the surroundings into account and if other systems are present such as electrical systems that could be short circuited. Think what may be affected if there was a leak in suspected corrosion areas.
7) Avoid high corrosion risk areas on load-bearing parts by designing so that the high risk areas are in less crucial areas. (Bardel, 2003)

A 5.2.3 Cathodic Protection (CP)

In CP the aim is to make the steel pipe or object you want to protect from corrosion the cathode and to do this you have to create an external current through the environment. This can be done in two ways;

a) By using a less noble (more reactive) material, this material is called the 'sacrificial' anode as it loses material and needs to be replaced eventually. The anode is attached to the structure that needs to be protected via a metallic conductor. The current will flow from the anode to the structure, so the oxidising reaction will be transferred to the anode. (see figure A3 a)
b) By using an external current source (usually a rectifier that converts AC to DC current.)

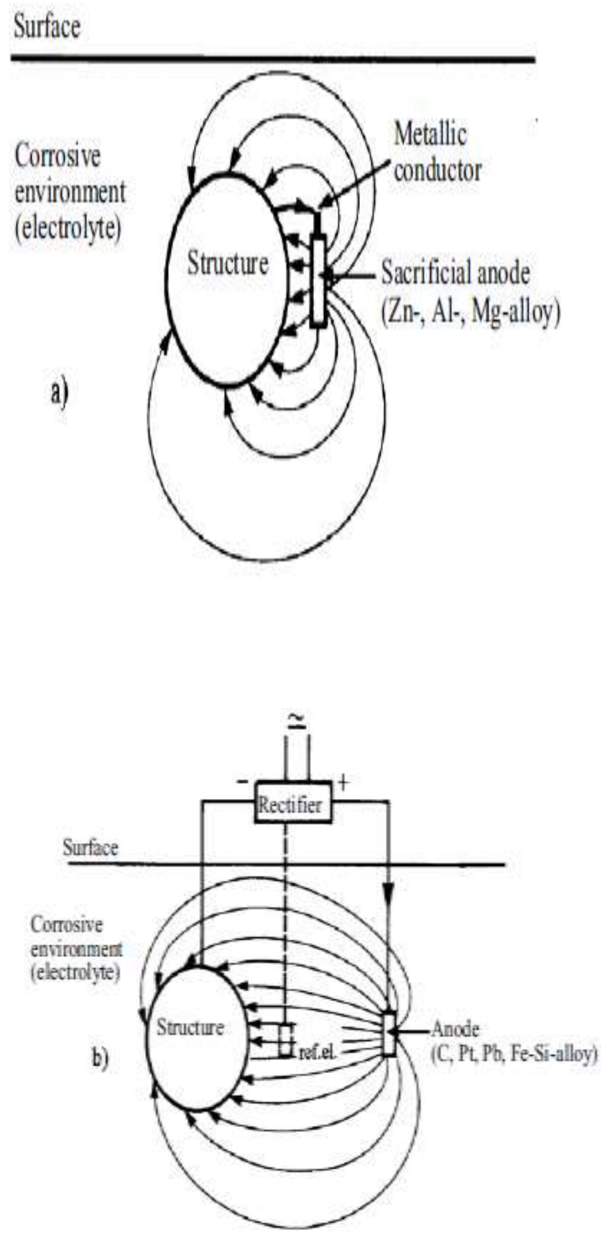

Figure A 3- Galvanic Corrosion (Bardel, 2003)

This is very similar to electrolysis. (see figure A3 b)

(E.Bardel, 2003)

A 5.2.4 Scanning Electron Microscopy

In SEM a focused beam of electrons scans the surface of the specimen. SEM can give topological data and can penetrate the surface of the sample. The main disadvantages of SEM are that it takes a lot of time to analyse the data and it is a form of destructive testing. In SEM, like in XRF, the elemental composition of the area being studied can be obtained. A big advantage of SEM is that you can see microscopic cracks and defects in the surface and underneath the surface and pictures of these can be obtained. (Carleton College, 2012)

A 5.2.5 Corrosion Coupons

The weight loss technique is very simple technique where a specimen or 'coupon' of the same alloy that the pipe is made of is attached to the inside of the pipe and exposed to the operating conditions for a period of time then they are removed and analysed in the laboratory. The coupons can have features such as weld lines that may be present in locations in the pipeline.

There is an electric form of the coupons they are called 'Electrical Resistance' (ER) probes this is a more direct way of collecting the data as it can be read at any time and does not require removal. There is a loop of the same alloy as the pipeline steel that is attached inside the pipe and subjected to operational conditions. As the corrosion in the loop increases so does its electrical resistance which gets displayed outside the pipe. (Alabama Speciality Products, 2012)

A 5.2.6 Patrolling the Pipeline

Patrolling the pipeline by foot, helicopter or light aircraft is used to look for leaks of the product; they can be in the form of a liquid which will show on the ground as a damp patch or discolouration of the ground or gases that may give off a distinct odour. High pitched noises may be heard as the product is leaking out under pressure.(Menon,2011)

A 5.2.7 Measuring Product Flow

Measuring the product flow as it enters the pipe and again as it leaves the pipe if there is a variation in volume over a given time period or a lack of expected volume this may indicate a leak. Usually when measuring the volumes the pressure and temperature variations are considered, changes in density or product concentration may also be accounted for. (Menon, 2011)

A 5.2.8 Measuring Pressure

Often in pipelines there is a system that can measure the pressure in the pipeline at certain points along the line. If there is an unexpected or unexplained drop in pressure at a point this can indicate that there is a leak somewhere between where the pressure drop has been sensed and the previous sensor where the pressure is indicated as normal. This narrows the range of pipeline that needs to be inspected for a leak.

Hydrostatic testing can be applied if there are valves that can block the flow of the product are in the system. Some pipelines such as gas lines need to be pumped full of water to do this type of testing as water is incompressible, other lines may be able to use the product that is in them such as crude oil. (Menon, 2011)

A 6 Initial Pricing

According to Penspen Integrity (2004) the 1991 prices for ILIs in the US for gas and oil pipelines were:

High Resolution MFL = $3 000 to $5 000 per mile

Low Resolution MFL = $450 to $1 350 per mile

Geometry ILI = $100 to $200 per mile

There will obviously be other charges as this is the price only for inspection some companies charge for the preparation of the ILI, calibrating the ILI and analysing the data.

Using the 'Consumer Price Index, (CPI)' which tells the change of prices for consumers every year, the price of these services can be roughly estimated for the present. The formula is as follows:

$$Present\ Cost = \frac{Present\ CPI}{Past\ CPI}\ x\ Old\ cost \qquad \text{(A1)}$$

From official tables the present CPI (taking the average value of 2011) was 224.93 and the past CPI (average CPI in 1991) was 136.2. The current day costs of these services are:

High Resolution MFL = $4 954 to $8 257 per mile

Low Resolution MFL = $743 to $2 230 per mile

(Source: US Department of Labor, 2012)

These prices cannot be extrapolated for the use of the product in this report it only shows the high prices of these ILIs in the industry. There is also higher competition in this industry compared with in 1991 also better technologies which may have reduced the price of inspections and many large pipeline owners and operators have their own ILIs. These prices shown are for oil and gas pipelines, not steam pipelines and they are not relatable costs.

As many manufacturers of ILIs do not sell their products but provide services it is difficult currently to estimate the price of the product. Quotes from competitors were enquired however all were ignored most likely due to the email address domain not being from a company. The total price of the product can be determined when the final design is completed.

A 7 Sales and Services

There are rules and regulations in countries to how often a pipeline needs to be inspected, this depends on the contents of the pipe and other factors however operators may choose to have their pipeline inspected at any time as long as it is more frequent than the regulations dictate however companies do not release details of how regularly they have their pipelines inspected or to what degree of accuracy.

If the product is sold to a company then maintenance and a warranty will need to be given as it will have a very high retail value. The product will need to be designed so that it does not damage the owner's pipelines. The product will be sold in the EU due to harmonized standards across the EU and a large market area. The high standards in the EU may mean that the product could be sold to other countries with the same or lower standards.

A 8 Product Design Specifications

A 8.1 Performance

A 8.1.1 - The product will be able to scan a 1 meter length of horizontal pipe in a minimum of 4 seconds.

A 8.1.2 - Size of crack or corrosion defect need to detect depends on legislation and standards. In European standards if the wall thickness is less than 85% original value then it is deemed unacceptable.

A 8.1.3 - The product will be able to detect metal wall thickness to an accuracy of ± 5%. The product will work in non-ferromagnetic stainless steel pipes using a different type of sensor other than MFL, ultrasonic works in stainless steel pipes.

A 8.1.4 - Must be able to ascend or descend a pipe at any gradient. The product must also be able to move around bends of 90º (internal angle) with a bend radius of 1.5 times the pipeline diameter whilst scanning for corrosion.

A 8.1.5 - The range of the product will depend on the pipeline geometry and the battery capacity.

A 8.1.6 - Product must be deployed and received at the end of a session easily. It must take less than 30 minutes from beginning assembly to starting detection.

A 8.1.7 - Product must know its own location and hence where the corrosion or fault is when it is inside the pipe.

A 8.2 Environment

A 8.2.1 - The product will be able to scan a 1 meter length of horizontal pipe in a minimum of 4 seconds.

A 8.2.2 - Size of crack or corrosion defect need to detect depends on legislation and standards. In European standards if the wall thickness is less than 85% original value then it is deemed unacceptable.

A 8.2.3 The product will be able to detect metal wall thickness to an accuracy of ± 5%. The product will work in non-ferromagnetic stainless steel pipes using a different type of sensor other than MFL, ultrasonic works in stainless steel pipes.

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A 8.2.7 - Product must know its own location and hence where the corrosion or fault is when it is inside the pipe.

A 8.3 Life in Service

A 8.3.1 - A three year guarantee will be provided with the product provided that product has not been extensively mistreated.

A 8.3.2 - An aim of 100 hours of service before inspection or maintenance is advised.

A 8.3.3 - Instead of supplying the product to customers the product may be used to provide a service in which case maintenance can be done by in-house professionals

A 8.4 Maintenance

A 8.4.1 - May require light maintenance between inspections but users are most likely mechanically minded and skilled with tools so can easily fix small issues and could potentially assess the cause of problem.

A 8.4.2 - Product must be easy to take apart for maintenance using common tools.

A 8.4.3 - Must be easy to clean the product and cleaning products must not detriment the product through chemical reactions or remains of cleaning tools (e.g. steel wool strands blocking mechanisms). As product will need to be cleaned after every use.

A 8.4.4 - Product can be returned under guarantee or aftercare policy to supplier for servicing and inspection.

A 8.5 Quality and Reliability

A 8.5.1 - High quality will be met by compliance with all the standards and legislations.

A 8.5.2 - Reliability will be met through rigorous testing of product and components. Some undemanding maintenance may be needed by users between inspections.

A 8.5.3 - The product will use the highest standard of materials and manufacturing methods that are allowed when related to the price of the product

A 8.6 Target Product Cost

A 8.6.1 - Aim to have competitive pricing however since the product has unique features the price will be justifiably higher than competition.

A 8.6.2 - The product has an estimated manufacturing and materials cost of £20,000

A 8.6.3 - The product will have an estimated maximum purchasing cost of £50,000. Hire purchase and lease transaction are other options for the product either direct through manufacturing company or a 3rd party an estimated hire rate of £1,000 per hour will be aimed for

A 8.7 Ergonomics

A 8.7.1 - Product must not be difficult to handle. Two or a maximum of 4 people may be needed to handle the product. A separate jig may be designed to mount the product and align it with the pipe before insertion.

A 8.7.2 - Modules can be carried in a case by persons aged between 18 to 55 provided they have no health issues.

A 8.8 Size

A 8.8.1 - The product will be able to serve a variety of pipeline diameters due to its design. The range of sizes of pipeline will be between 400 mm to 600 mm

A 8.9 Weight

A 8.9.1 - If a modular product is needed then the weight of any module cannot exceed 30kg for handling purposes.

A 8.9.2 - The total weight of the product must not cause inelastic bending or deformation of the pipe.

A 8.10 Noise and Vibration

A 8.10.1 - Noise at pipe opening at either end must not exceed 85dB as to not damage the hearing of the user. Ear protection could be used to allow for a higher decibel value.

A 8.10.1 - Vibration caused by the product's motion in the pipe must not cause weakening of the pipeline in the steel pipe or at joints and welding. It must also not cause resonance in either the pipeline or itself.

A 8.11 Materials

A 8.11.1 - Materials chosen will provide the structure with its strength, rigidity and physical properties needed to withstand the factors that may affect the product that are outlined in this PDS. They will also influence the functions and the life of the product.

A 8.11.2 - No new materials will be developed but use of modern materials and composites will be considered and studied for feasibility.

A 8.11.3 - Materials used will be easy to manufacture process and treat to keep the cost of the product down.

A 8.11.4 - Materials will need to be resistant to corrosion and the effects of the environment inside and outside the pipeline.

A 8.11.5 - The effects of wear will influence the choice of material of components that in moving contact with the pipeline. The components of the product will be more sacrificial relative to the inside of the pipe.

A 8.12 Processes

A 8.12.1 - Processes chosen will be used to increase life or strength of product and will be available at an acceptable cost from either in-house manufacturing or higher cost set up processes may be contracted out.

A 8.13 Assembly

A 8.13.1 - Assembly of product will be done by hand due to the very high initial cost of automated machinery. If after 3 or 4 years of trading there is significant demand and retained profits allow, machinery will be considered.

A 8.14 Quantity

A 8.14.1- Depends on market and demand for the product

A 8.14.2 - An aim of selling 50 in the first year of trading and trying to breakeven within 6 years of trading. Alternatively aiming for 500 hours of time in service per year between all manufactured ILIs.

A 8.14.4 - If the product is used as a service then a lower quantity will be needed however the maintenance demand will be higher.

A 8.15 Shipping and Transportation

A 8.15.1- Product will be packaged in modules for simple transportation and handling by courier but all modules will aim to arrive at the same time.

A 8.15.2 - Product will be packaged to allow for; air, rail, ship and truck freight. Courier services will also be in place to allow for express delivery. Location of manufacturing facility will have good distribution options to aid the speed of delivery.

A 8.15.1 - No limitations on shelf life however lubrication and oil may need to be added to moving components before shipping. If organic or degradable materials are used then there may be a reduced shelf life this will be considered in the material choices.

A 8.15.2 - Product will be stored in a warehouse in the manufacturing facility ready for distribution and shipping. The environment in the storage facility will be controlled so product does not suffer from corrosive or detrimental conditions.

A 8.16 Installation

A 8.16.1 Product is in modular form so it can be installed in pipe entrance or can use a separate jig to assemble and launch product into the pipe.

A 8.16.2 Must be able to install vertically and horizontally and at any angle.

A 8.16.3 Need a maximum of 5 workers to install and clear simple instructions will be provided. The ease of installation will be highly considered in the design of the product.

A 8.17 Customer and User

A 8.17.1 - Customer will be either the owner of the pipeline in a small company or the head of pipeline maintenance in a larger company. Rarely will the user be the purchaser for this reason the product will have unique attractive functions differentiating itself from the competition.

A 8.17.2 -Users will be maintenance personnel. However if the product is used to provide a service then the company will send out trained staff to use the product on the inspected pipeline.

A 8.17.3 - Estimate of 85% of the users will have at least 5-years' experience within the pipeline industry.

A 8.18 Safety

A 8.18.1 - Safety will come from standards and legislations

A 8.18.2 - Have an automatic break in the machine so that the robot does not fall down a pipe and cause damage to the pipe or cause harm or death to users.

A 8.18.3 - After break is activated there will be a methodology to remove the product from inside the pipe.

A 8.19 Testing

A 8.19.1 - Testing will be done on prototypes and full CAD and FEA will be done before production.

A 8.19.2 - Materials and components purchased from outside suppliers will be tested. Approximately 3% of every batch bought will be tested.

A 8.19.3 - All products bought will be tested and inspected before shipping to ensure quality and reliability.

A 8.19.4 - Every component in 500 will be destructively tested to test for tensile strength and material properties.

A 8.20 Standards and Regulations

All standards and regulations can be found in **appendices B section B32**

A 8.21 Patents

After conducting a thorough search of patents, in the world and the EU, that relate to the product, the patents outlined in the appendix may need to be considered so that the product does not infringe upon on them.

For a full list of patents that the product may infringe see **appendices B section B33**

A 8.22 Political and Social Implications

A 8.22.1 - Promotes efficiency in the generation / transportation of energy.

A 8.22.2 - Reduces chance of dangerous failure of pipes and causing damage to surrounding assets or employees. Also reduces the chance of unscheduled down time.

A 8.22.3 - Efficiency in the pipeline reduces the rate of rise of the utilities bills for customers.

A 8.22.4 - The company will create well-paid jobs that increase the quality of life for the employees and benefit the UK economy.

A 8.23 Market Constraints

A 8.23.1 - Competitive products that have been on the market for a long time and have earned a good reputation and they could easily adapt their products to have similar unique functions to this product.

A 8.23.2 - Product is only aimed for European market due to legislation however could be sold in countries that have lower or the same standards as the EU.

A 8.24 Sustainability

A 8.24.1 - The product will aim to have a low as possible impact on the environment by the minimalist use of: land, material, waste, energy, water and toxic substances. Or generation of: waste, air pollution.

A 8.24.2 - Manufacturing of the product and creation of the company will bring well-paid jobs to the area. The product selling overseas will add to the export value of the British economy. The company will have strategies and assessments to ensure that the business is running optimally and will not go insolvent.

A 9 Concepts

A 9.1 Geometry / Form

Flexible Snake:

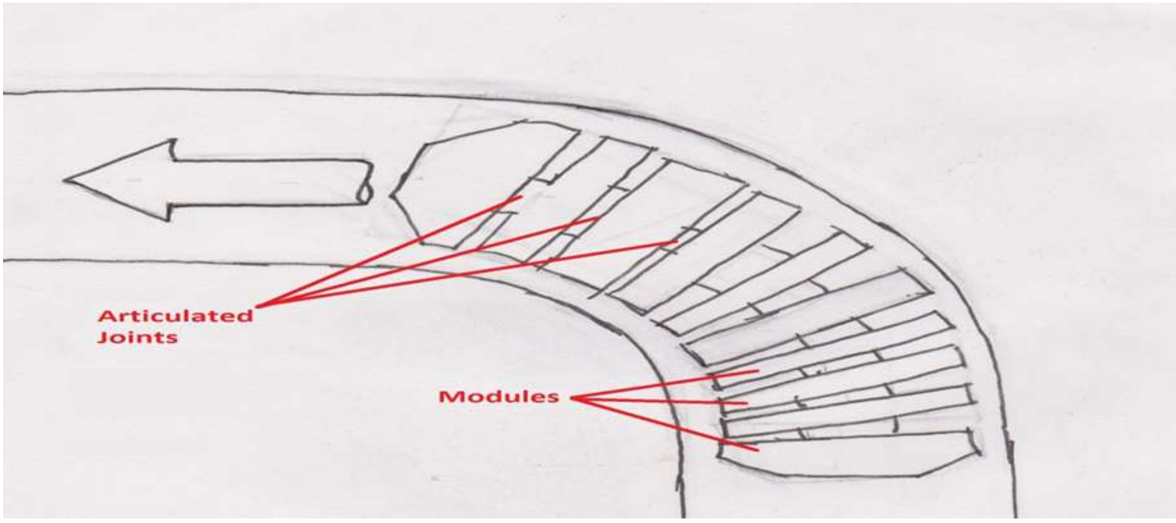

Figure A 4 – Flexible Snake Concept

The modules will house the components needed for the ILI to do all of its other functions. The articulated joints will give the ILI its flexibility and allow it to travel around bends. There are several options as to what type of joint could be used or if an elastomer could be suitable. The modules are small in width to reduce the likelihood of them pinching against each other during bends. This design is the most prevalent in the industry.

Towing Modules:

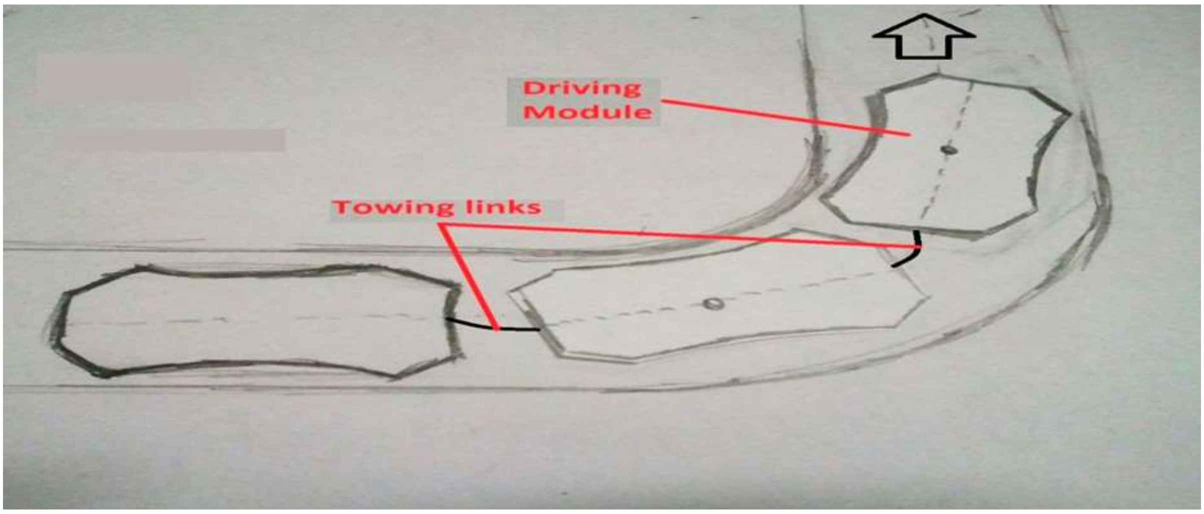

Figure A 5 – Towing Modules Concept

The driving module will be at the front and it will tow the sensor and locating modules behind it. There are many issues with this design the biggest being that if the ILI were to travel in a downward direction then the other modules will hit into each other another issue would be the slackening and tensioning of the towing cables. The modules are all the same size and shape this is to reduce manufacturing costs.

Single Unit:

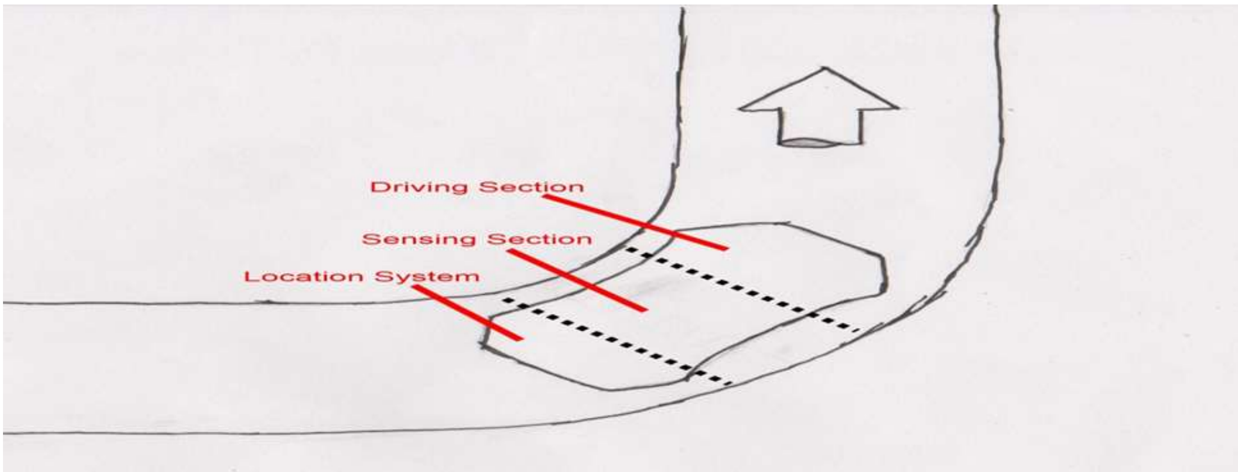

Figure A 6 – Single Unit Concept

In this design the technology will need to be very compact, this will most likely increase the price of the product and it would be difficult to manufacture however it would be the easiest to handle from the users point of view.

A 9.2 Driving Mechanisms

Continuously Variable Transmission:

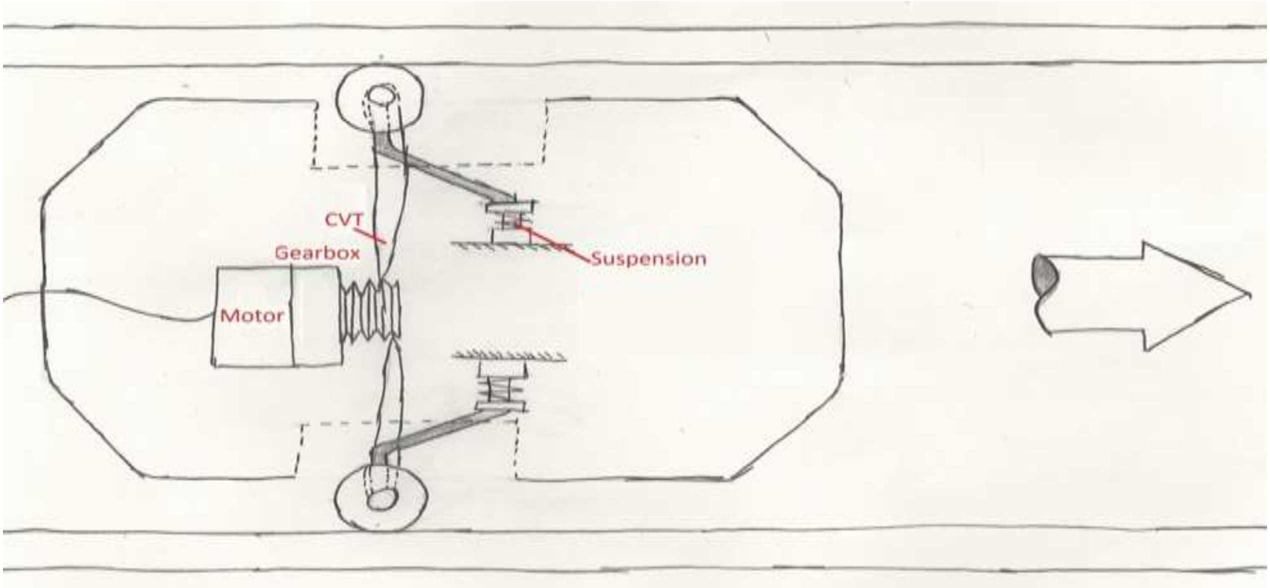

Figure A 7 – CVT Concept

Again the suspension provides the frictional force and allows for changes in diameter. The CVT transmits the motor's power to the wheels whilst allowing for the wheels to be at different distances. The gearbox attached to the motor may or may not be necessary depending on the motor and the CVT setup.

Magnetic Caterpillar Track:

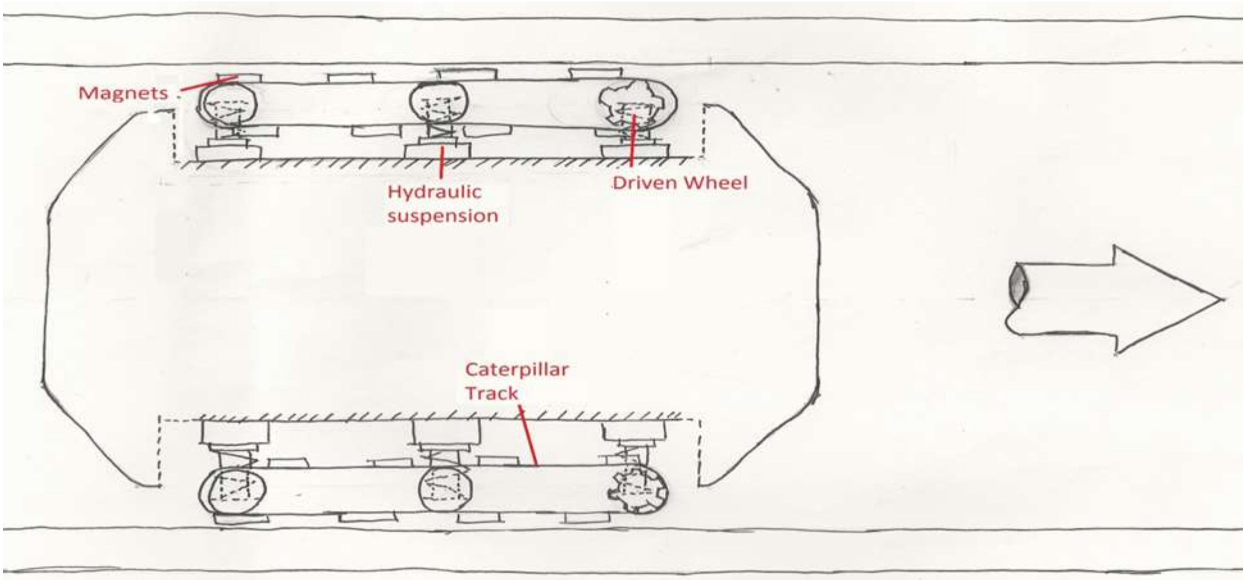

Figure A 8 – Magnetic Caterpillar Track Concept

This design would only work for ferrous material pipes. The magnets would need a coating to reduce the wear to them and also reduce damage to the pipe wall. This is a more complex design and may require more maintenance. The suspension allows for variable diameters and the magnetism would provide the traction. The driven wheel could either be powered by a motor on each wheel or a CVT set up could be used as designed in the two designs above.

Sliding Wedges:

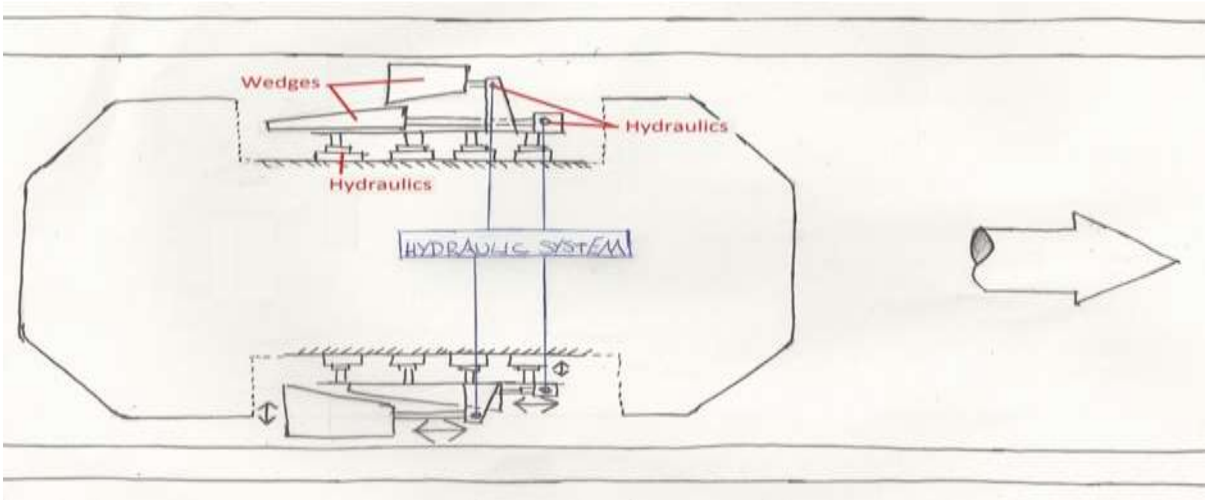

Figure A 9 – Sliding Wedges Concept

Here two wedges will slide past each other to grip the pipe and move along it. They will be powered by a hydraulics system. Half of the set of wedges will work at 180º phase cycle to the other half of sets. This will allow for the fastest amount of motion as half of the wedges will be in contact with the wall and moving the ILI forward whist the other half are resetting to the correct position, it also means that at no point there will be not be enough traction so that the ILI may slip or fall. The main issue with this design is that it creates a large amount of stress acting perpendicular to the pipe direction also it is the slowest design.

A 9.3 Sensor System

Whisker:

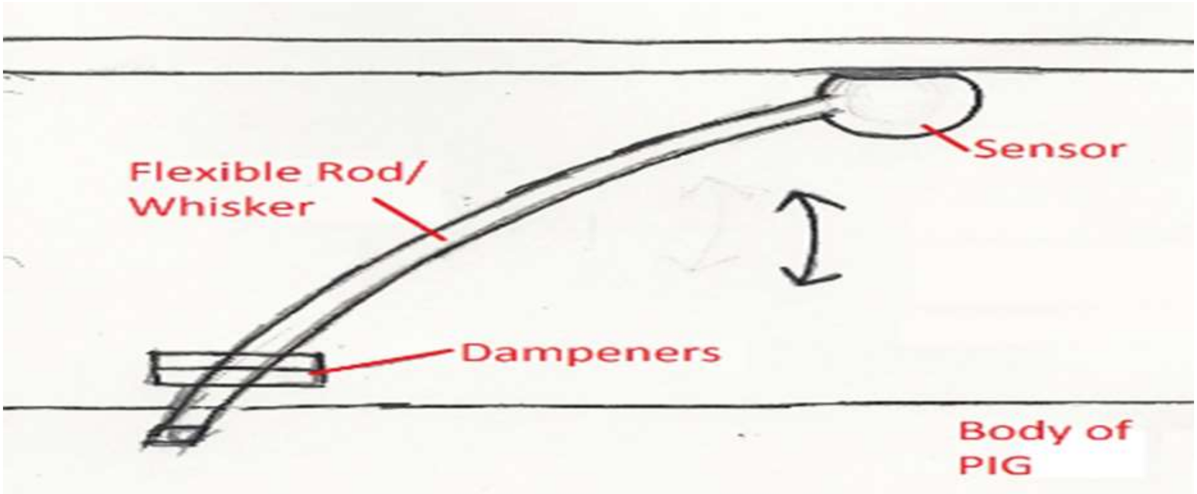

Figure A 10 – Whisker Concept

The thin flexible rod will always want to return to its natural upright position due to the elastic properties of the material. This ensures that it will stay in contact with the wall as long as the bending does not cause the material to exceed its elastic limit. The dampeners are to reduce the vibrations and motion when there is a change in diameter or if the sensor gets knocked by features inside the pipe

Compression Spring:

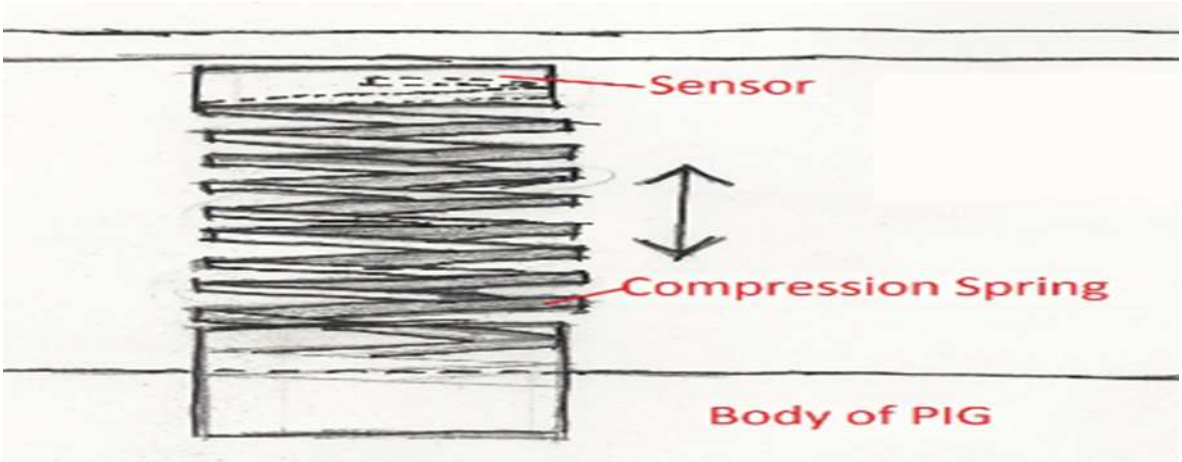

Figure A 11 – Compression Spring Concept

The sensor sits on top of a constant or variable pitch helical compression spring. The amount of displacement the spring can take will determine how well it performs in different diameter pipes. The main issue with this is the need for a dampening system as the cyclic motion could cause wear to the sensor and leave areas of pipe unanalysed

Hydraulic Ram:

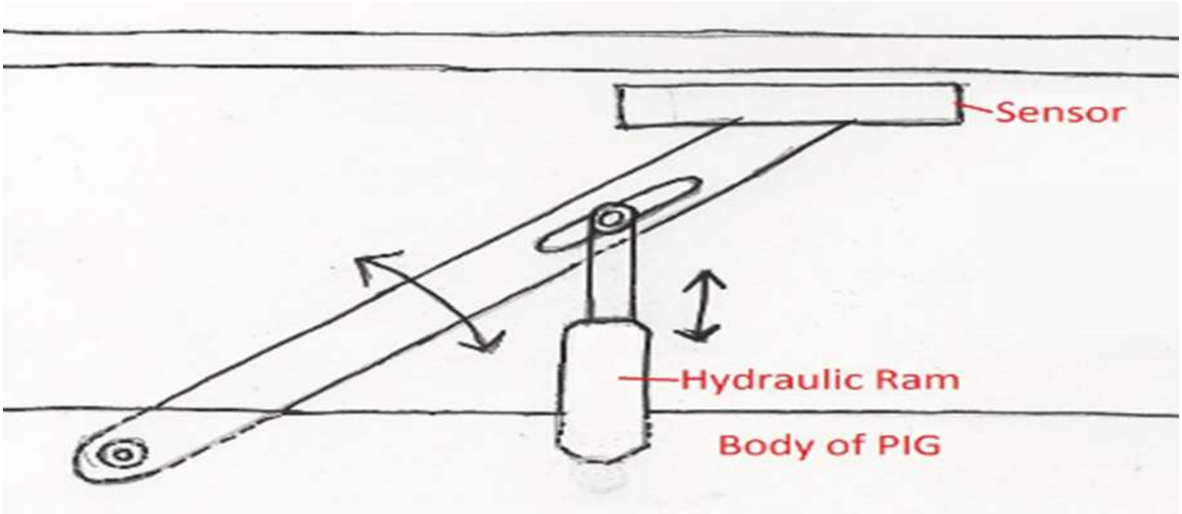

Figure A 12 – Hydraulic Ram Concept

The hydraulic ram will provide the upward force and the pin joint where the rod meets the body of the ILI/ PIG. There will be a groove in the rod where the hydraulic ram is connected to allow for horizontal movement. The groove could equally be horizontally at the pin joint in the body of the ILI/ PIG.

A 9.4 Location System

Wire Drawn:

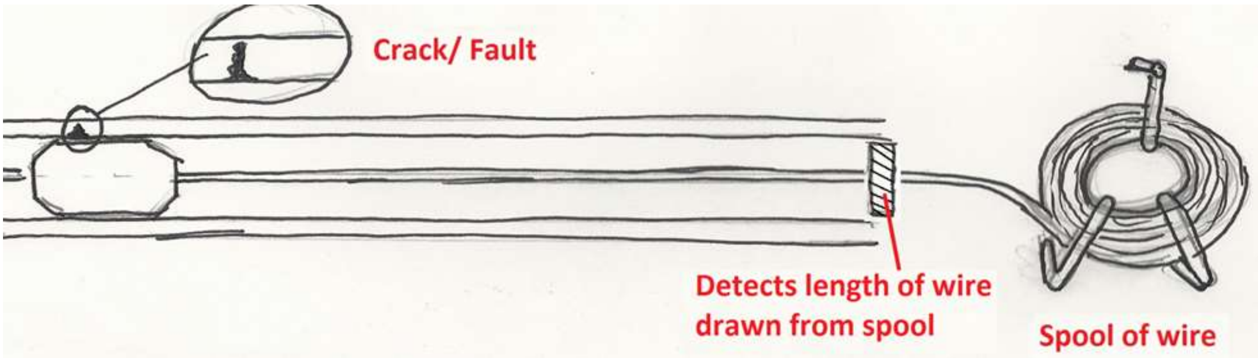

Figure A 13 – Wire Drawn Concept

In this design there is a device which the power and/or signal cable are fed through. The device detects the amount of wire drawn through it. The device could also need to detect the speed and plot this against the sensors readings to calculate the location. However this may be impractical as the product will need to carry the weight of the wire and this wire may get stuck on features inside the pipeline

Ultrasound:

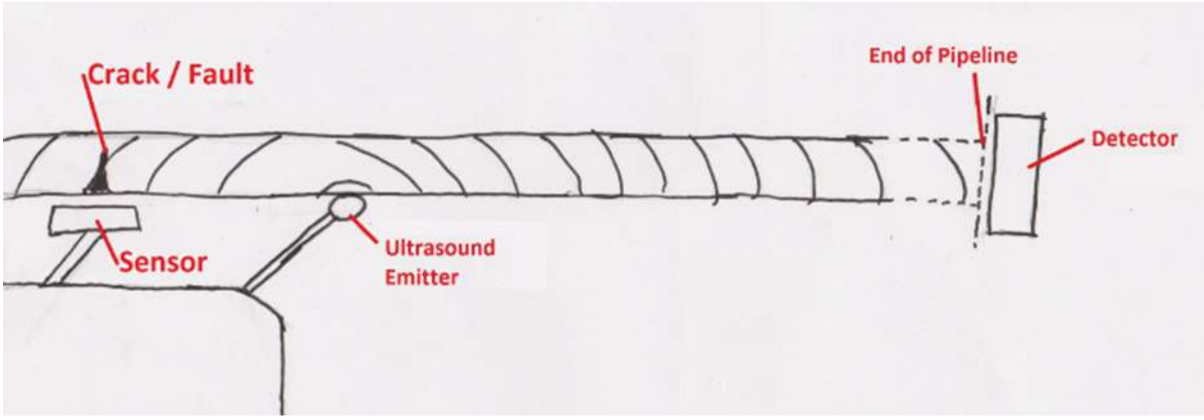

Figure A 14 –Ultrasound Concept

Whenever a crack/fault or unacceptable wall thickness is detected the ultrasound emitter could send a wave into the pipes wall. This signal can be detected at the insertion point of the ILI. Knowing the speed that the wave travels in the pipe material and if the emitter and detector take time reading the distance in the pipe can be calculated. The main issue with this is that the ultrasound may interfere with the ultrasound sensor used for detecting faults.

Infrared Cameras:

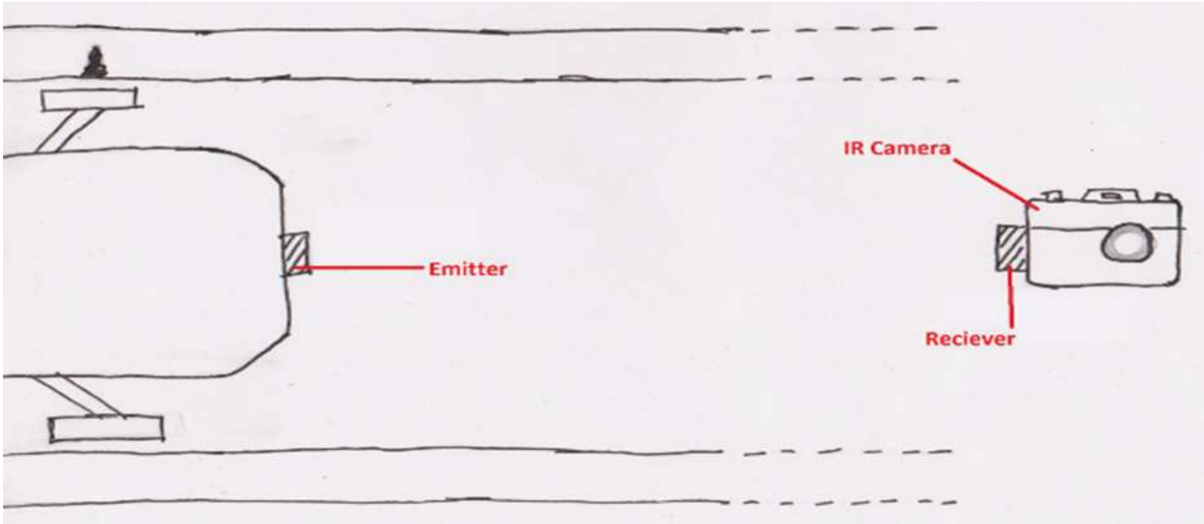

Figure A 15 – Infrared Camera Concept

Infrared cameras could be set up at locations outside the pipeline and if two cameras take the same image and knowing the focus the location can be accurately measured. A signal emitter will need to be attached to the ILI to tell the cameras to take a photo when a fault is sensed. Triangulation would also work in a similar manner and could use other signals other than IR. The main issue with this is there will a lot of data analysing after the operation or software could be implemented, it is also impractical to set up this system.

A 10 Concept Selection

There are a large number of combinations, using the concepts generated, that could make the complete ILI so it is necessary to find the best or most suitable concept this can be done by scoring the concepts. Since there can be any combination of concepts it is preferable to score each concept under its function or task using a selection criteria that has the most desirable properties. The concept that will be taken forward will be the highest ranked concept that will be highlighted at the bottom of the table.

A 10.1 Geometry / Form

Selection Criteria	Weight %	A Single Unit Rating	A Single Unit Weighted Score	B Flexible Snake Rating	B Flexible Snake Weighted Score	C Individual Modules Rating	C Individual Modules Weighted Score	D Hybrid Rating	D Hybrid Weighted Score
Pinch against itself in bends	35	3	1.05	3	1.05	3	1.05	4	1.4
Pinch against pipe in bends	35	3	1.05	3	1.05	2	0.7	4	1.4
Manufacturability	15	2	0.3	2	0.3	2	0.3	3	0.45
Ease of handling	15	3	0.45	2	0.3	1	0.15	4	0.6
	Total Score		2.85		2.7		2.2		3.85
	Ranking		2		3		4		1
	Continue?		No		No		No		Yes

Table A 6 – Geometry Concept Selection

A 10.2 Driving Mechanism

Selection Criteria	Weight %	A Indv. Powered Wheels Rating	A Weighted Score	B CVT Rating	B Weighted Score	C Magnetic Caterpillar Tracks Rating	C Weighted Score	D Sliding Wedges Rating	D Weighted Score
Give sufficient traction in all directions of travel	40	4	1.6	3	1.2	4	1.6	4	1.6
Must not cause wear or damage to pipes or fittings	15	4	0.6	4	0.6	2	0.3	3	0.45
Allow for variable speeds	5	4	0.2	3	0.15	2	0.1	1	0.05
Level of reliability	15	3	0.45	2	0.3	3	0.45	2	0.3
Allows for reverse / backward motion	3	5	0.15	4	0.12	3	0.09	1	0.03
Allow horizontal speed > 1m/s	5	4	0.2	4	0.2	3	0.15	1	0.05
Ease of maintenance	3	5	0.15	3	0.09	2	0.06	1	0.03
Corrosion resistance	6	3	0.18	3	0.18	2	0.12	2	0.12
Vibration & noise	8	4	0.32	4	0.32	2	0.16	3	0.24
Total Score			3.85		3.16		3.03		2.87
Ranking			1		2		3		4
Continue?			Yes		No		No		No

Table A 7 – Driving Mechanism Concept Selection

A 10.3 Sensor System

		Concepts							
		A		B		C		D	
		Pantograph		Whisker		Spring		Hydraulic Ram	
Selection Criteria	Weight %	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Wear to sensor	15	4	0.6	2	0.3	3	0.45	4	0.6
Wear to pipe	10	4	0.4	3	0.3	3	0.3	3	0.3
Contact with pipe surface	35	5	1.75	2	0.7	3	1.05	4	1.4
Friction and heat	10	3	0.3	4	0.4	4	0.4	3	0.3
Compatibility with pipes features or fittings	15	5	0.75	2	0.3	1	0.15	4	0.6
Ease of maintenance	6	3	0.18	4	0.24	3	0.18	3	0.18
Vibration	9	4	0.36	2	0.18	1	0.09	4	0.36
	Total Score		4.34		2.42		2.62		3.74
	Ranking		1		4		3		2
	Continue?		Yes		No		No		No

Table A 8 – Sensor System Concept Selection

A 10.4 Location System

		Concepts							
		A		B		C		D	
		Odometer		Wire Drawn		Ultrasound		Infrared Camera	
Selection Criteria	Weight %	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Accuracy of location	50	5	2.5	3	1.5	2	1	2	1
Interference with sensors	10	5	0.5	4	0.4	1	0.1	5	0.5
Reliability	25	4	1	3	0.75	3	0.75	2	0.5
Readability of information given	15	3	0.45	4	0.6	2	0.3	3	0.45
	Total Score		4.45		3.25		2.15		2.45
	Ranking		1		2		4		3
	Continue?		Yes		No		No		No

Table A 9 – Location System Concept Selection

Appendices B

Final Report

By Peter Dobson

Table of Contents – Appendices B

B 1 Steam Pipeline Fixtures and Fittings

B 1.1 Drainage

Throughout the length of a steam pipeline heat will be lost to the environment even if insulation is applied to the pipelines there will still be losses. These losses will cause steam to condense in the main steam line. The condensate will cause the steam to become wet as it entrains water particles reducing the pipelines ability to transfer heat efficiently. If condensate is allowed to build up then the cross sectional area for the steam to travel through is reduction causes an increase in steam velocity which can be to hazardous levels. (Spirax Sarco, 2013).

B 1.1.1 Trap Pockets

Trap pockets are drainage points along the main steam line where condensate is collected. These pockets must be sized correctly to allow for maximum drainage of condensate. For steam mains with a diameter greater than 250 mm the pocket diameter must be just greater than half of the diameter of the steam mains. It is not important to take into consideration steam mains with a smaller diameter as the product will not be able to travel through these pipes (Spirax Sarco, 2013). There is a danger of the ILI falling into the pockets so a temporary filler will need to be inserted, this can be a plastic plug inserted, as the base plate on the pocket is bolted on.

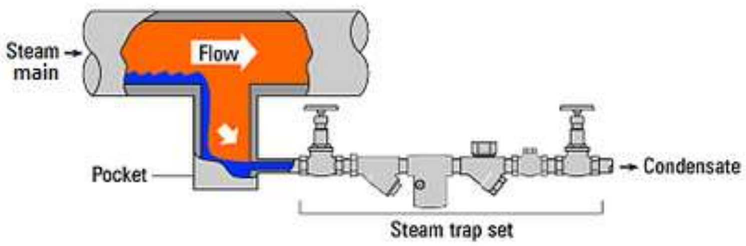

Figure B 1 – Trap Pocket Diagram (Spirax Sarco, 2013)

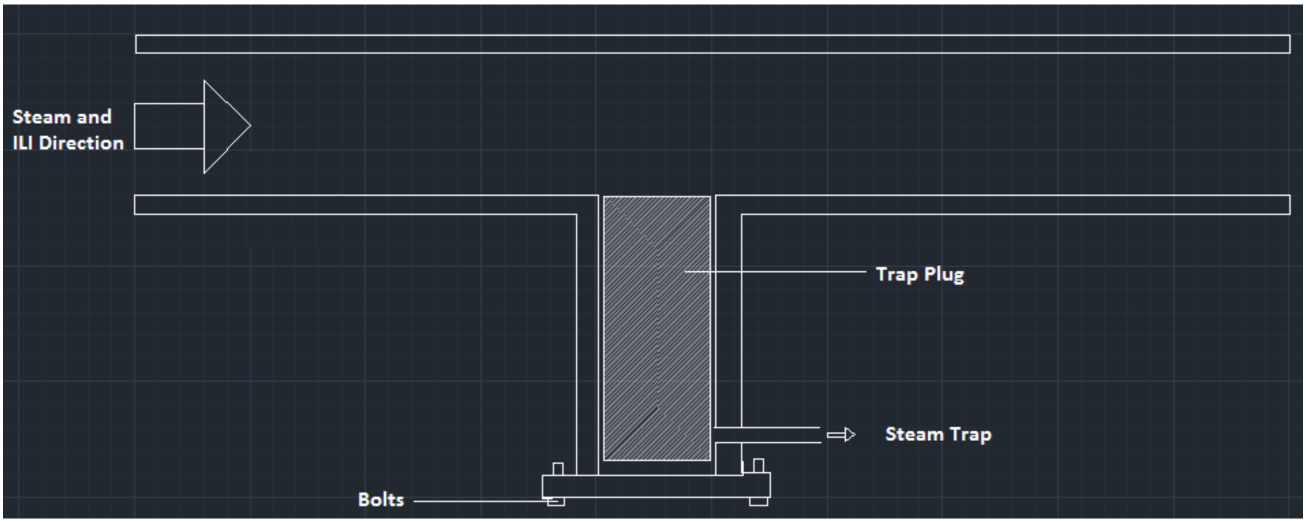

Figure B 2 – Trap Plug Diagram

B 1.1.2 Reduction in Pipe Diameter

A Reduction in pipe diameters can either be done by using a concentric or eccentric pipe reducer. A concentric pipe reduction is where the reduction is distributed evenly around the circumference of the pipe and the centre lines of pipeline before and after the reduction are still aligned. An eccentric pipe reduction is where only one side, top or bottom, of the pipeline is reduced and the stays in line, this means that the centre lines of the pipeline before and after the reduction are not aligned. See Figure B3 (Spirax Sarco, 2013).The ILI will be able to move and scan through both of these types of reducers.

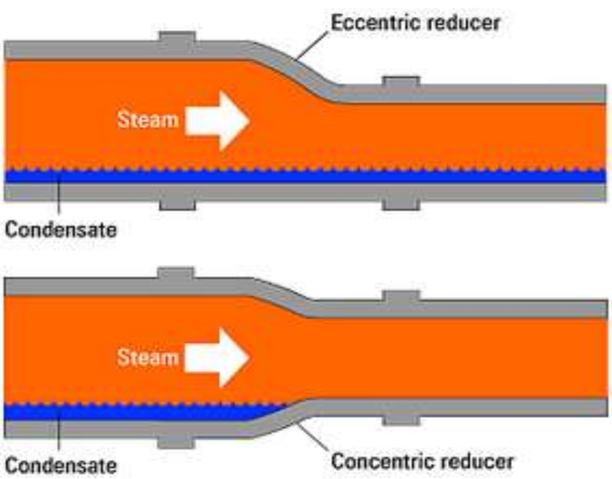

Figure B 3 – Pipeline Reduction (Spirax Sarco, 2013)

B 1.1.3 Branch Lines

Branch lines are normally taken from the top of the steam main as they are supposed to carry the driest of steam however connections are made at other orientations but this results in wet and dirty steam which may affect the equipment attached to the branch line. If the branch lines are fitted from the top then there is no danger of the ILI getting stuck however if it is fitted from the bottom then the design considerations taken from the steam pockets will allow the ILI to manoeuvre over these branch lines. (Spirax Sarco, 2013)

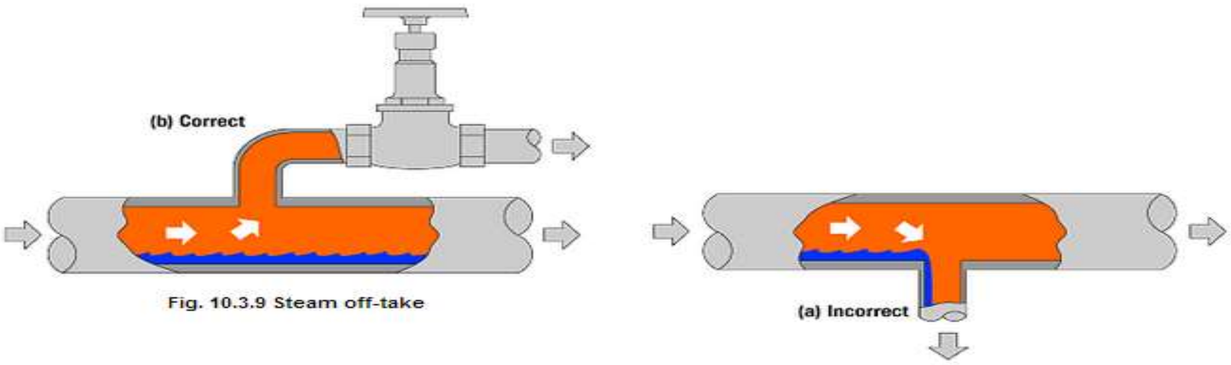

Figure B 4 – Branch Lines (Spirax Sarco, 2013)

B 1.1.4 Steam Separators

Steam separators are used to remove the moisture from wet steam they also remove air, which lowers the overall temperature and leads to inefficiency. They eliminate water hammer and its effects and they can be less expensive than increasing the pipe diameter or drain pockets. The ILI will not be able to manoeuvre around this type of fitting so steam separators will need to be removed and temporarily replaced with a section of straight pipeline, this is a simple task as the separators are bolted on by flanges however will increase the time and cost of the inspection operation. (Spirax Sarco, 2013)

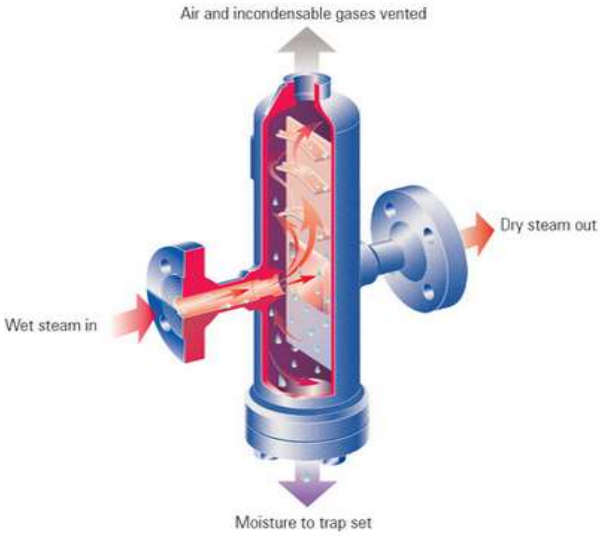

Figure B 5 – Steam Separators (Spirax Sarco, 2013)

B 1.1.5 Strainers

Strainers are fitted to pick up debris that occurs in the steam flow this can be because of accidental depositions from workmen during construction or maintenance. Strainers also collect corrosion products and carbonates from hard water. The disadvantage of strainers is that they can produce wet steam. As with the steam separators the strainers in the inspected pipeline will need to be removed and replaced with a straight piece of pipeline secured by bolts in the flange fitting. (Spirax Sarco, 2013)

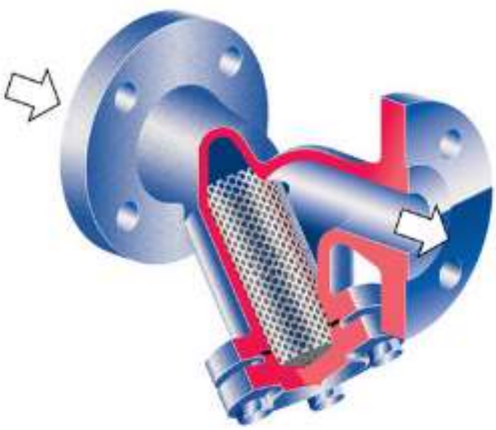

Figure B 6 – Strainer (Spirax Sarco, 2013)

B 1.2 Expansion

Steam pipelines are installed at temperatures much lower than the temperatures at which they are subjected to under operation. Increasing temperature causes expansion in pipelines; this expansion causes stresses in certain areas, such as joints and fittings. To accommodate for this movement the system has to have a degree of flexibility. Often when installing a new pipeline a spacer is added, which is half the length of the total expansion, between two flanges. When it is fully installed the spacer will be removed and the flanges will be pulled together, cold drawing the pipeline. This has the effect of instead of the pipeline being stressed maximally in one direction at high operational temperatures it will be stressed half the amount at maximum temperature and the same value but opposite direction of stress when the pipeline is cold at installation temperatures. If expansion of pipelines is not permitted by natural flexibility then an expansion fitting will be used. (Spirax Sarco, 2013)

B 1.2.1 Full Loop

Full loop is a full 360˚ turn of a pipe, they should be fitted horizontally to avoid condensate build up and the downstream side has to pass below the upstream side. This type of expansion fitting is rarely used today as they take up space, however power plants or facilities with large outside distribution systems still tend to use this as the cost is low. The ILI will be able to drive through this loop as long as it has a radius greater than 1.5 of the pipeline diameter. (Spirax Sarco, 2013)

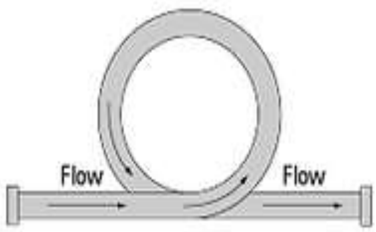

Figure B 7 – Full Loop (Spirax Sarco, 2013)

B 1.2.2 Horseshoe Loop

Horseshoe loop again if space is available this type of expansion fitting is used. Pressure does not cause the flanges to blow apart as occurs in the full loop however there is a straightening effect which does not cause misalignment of flanges. If this is installed vertically then a trap pocket must be placed on the upstream side of the loop. The design of the ILI will mean that it cannot pass through this type of loop due to the sharp bends. (Spirax Sarco, 2013)

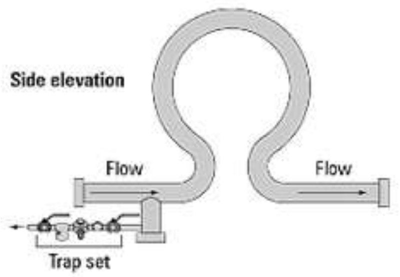

Figure B 8 –Horseshoe Loop (Spirax Sarco, 2013)

B 1.2.3 Expansion Loop

Expansion Loop can be manufactured by welding straight pieces of pipeline and elbow joints. The ILI will be able to manoeuvre through this type of expansion fitting as long as industry standard radius angles are followed and the angle is 90 degrees or greater during design of the fitting. (Spirax Sarco, 2013)

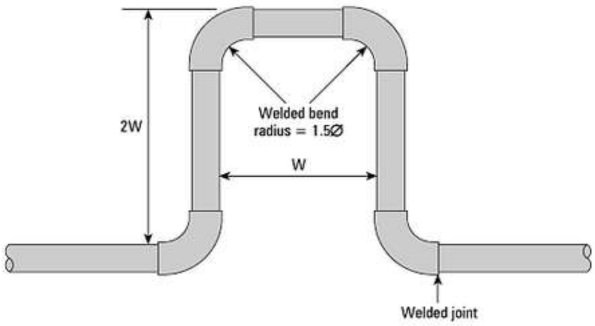

Figure B 9 – Expansion Loop (Spirax Sarco, 2013)

B 1.2.4 Sliding Joint

Sliding joints are sometimes used as they up a small amount of space. The ILI may be able to drive through this joint however this depends on the wall thickness of the siding sleeve as it creates a step that will have to be overcome the size of wheels used will also affect this it would be optimal of the end of the sleeve section was sloped. Again the sliding joint could be removed and a piece of straight pipe could temporarily replace it; they should be easy to access as regular maintenance is needed due to the gland packing wearing. (Spirax Sarco, 2013)

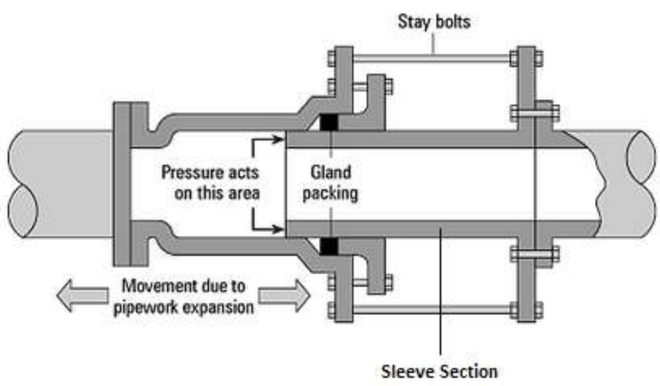

Figure B 10 – Sliding Joint (Spirax Sarco, 2013)

B 1.2.5 Expansion Bellows

Expansion bellows do not need packing that the sliding joint needs however they often need reinforcement as they cannot take large loads. Whether the ILI will be able to move through the bellow without damaging it will depend on the thickness and length of the bellow section. If it is decided that the bellow can take the load of the ILI then there is no reason why the ILI would get stuck, if not then it will have to be replaced with a section of section of pipeline. (Spirax Sarco, 2013)

Figure B 11 –Expansion Bellow (Spirax Sarco, 2013)

B 1.3 Valves

The ILI will be able to drive through ball valves when they are in the fully open position. It is not possible for the ILI to travel through or around butterfly valves, even if the valve is in the open position this may damage the ILI and valve as it may not be able to detect the disc rotated on its side. The ILI will also be able to manoeuvre through gate valves as long as the gate is fully retracted leaving the valve open, the ILI will be able to pass over the seat for the valve.

Figure B 12 –Butterfly Valve (TT Pumps 2012)

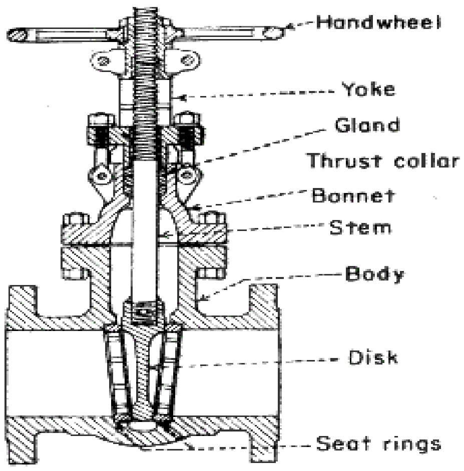

Figure B 13 – Gate Valve (MechanicalQuiz, 2013)

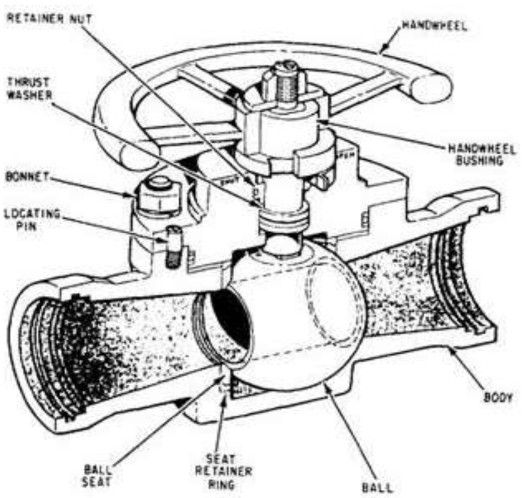

Figure B 14 – Ball Valve (TPub, 2012)

B 1.4 End of Steam Main

The end of a steam main line is connected to an automatic air vent which is a vertical pipeline which taps of air, water and condensate. The ILI will have electronics to detect this sudden drop so that it does not fall which would cause large amounts of damage to the vent and would possibly cause un-repairable damage to the ILI. (Spirax Sarco, 2013)

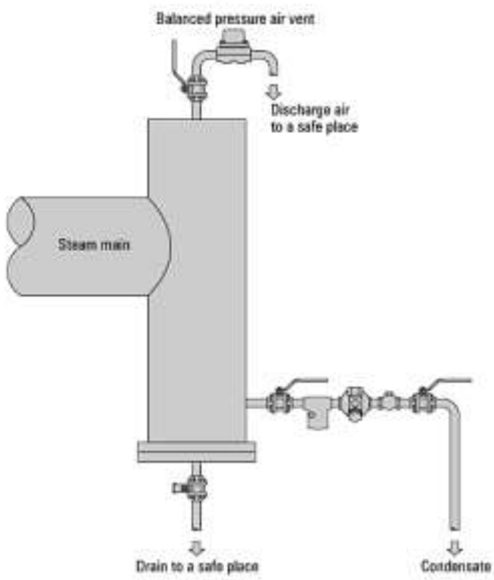

Figure B 15- End of steam main (Spirax Sarco, 2013)

B 2 Steam Pipeline Sizing

In Europe pipes are identified by their nominal sizes which are related to the pipes dimensions, this system is called “diametre nominel” or DN and these conform to an ISO standard. For pipelines the DN size is approximately the internal diameter size.

The purpose of a steam distribution system is to supply steam at the correct pressure to the point of use, therefor pressure drop is important when designing the system. Proper sizing of steam pipelines is important to reduce pressure drop. (BEE India, 2009)

Steam pipe sizing is based using velocity, pressure drop and cost. Low steam velocity usually relates to low pressure drop and results in more expensive larger diameter pipelines. High steam velocity usually relates to high pressure drop in smaller diameter pipes however pressure losses can be unacceptable. Various types of steam have different velocities. For wet steam velocities are around 20-30 m/s, saturated steam is 30-40 m/s and superheated is 50-70 m/s. (Miranda and Lopez, 2011)

For a given mass flow rate, the high specific volume of steam makes the pipe diameter bigger when compared to other fluids. Pipe routing for transmission of steam is designed to be as short as possible to reduce the pressure drop in the system caused by friction and thus saving energy. (BEE India, 2009)

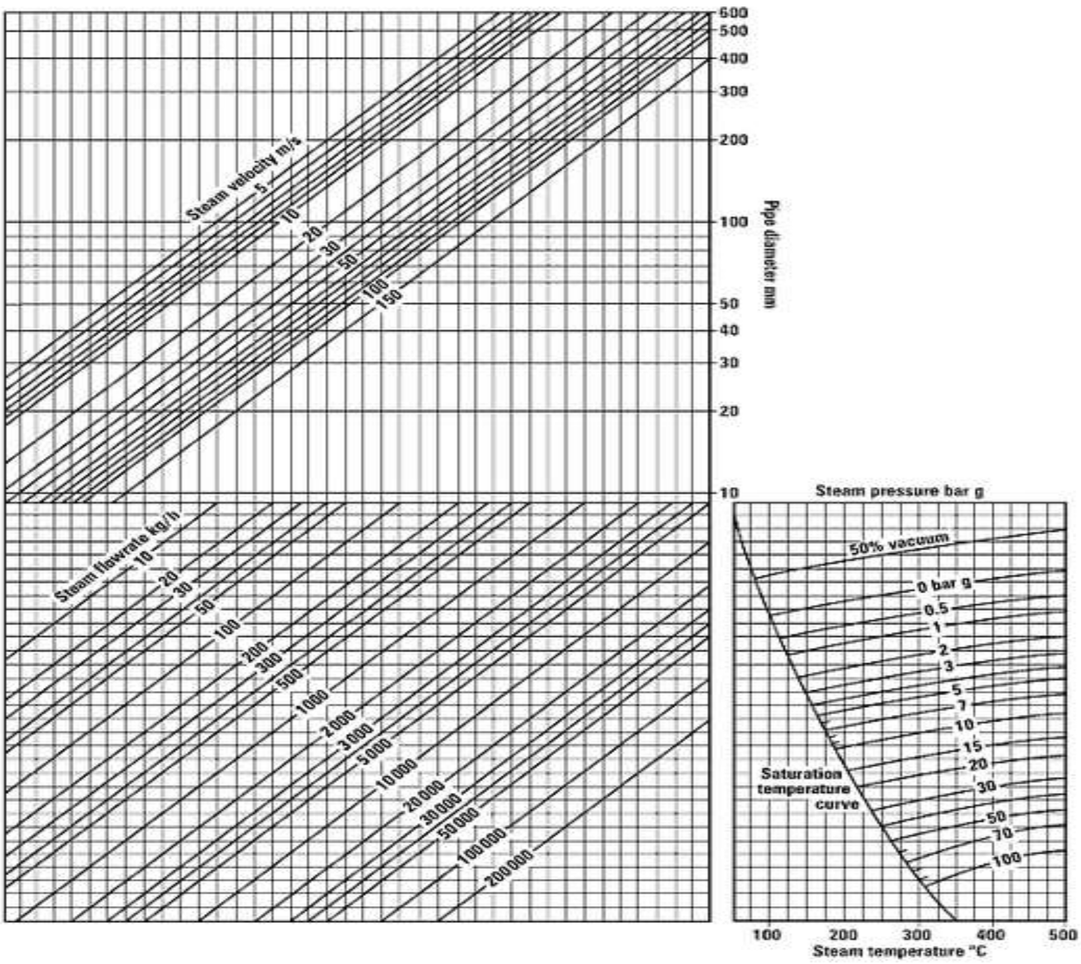

Figure B 16 – Steam Pipeline Sizing Chart (Spirax Sarco, 2013)

Using these graphs the maximum pipe diameter is 600 mm (approx. 24 inches). Through research of pipelines that are used in steam distribution this is the largest bore that has been studied extensively thus is makes sense to correlate this to the upper limit of the range of diameters the product will service. The lower limit will be around 400 mm (approx. 16 inches) this limit has been decided upon as it is the most feasible size it gives a diameter range of over 200mm, half the diameter of the lower range bore limit for the product. (Spirax Sarco, 2013)

B 3 Angular Velocity and Centripetal Force

Angular velocity (ω) in the bends needs to be known as using this the value of the centripetal force can be calculated to check if these forces affect the ILI significantly. The ILI will experience a different centripetal force as the bend radius is different for different points on the ILI. Three points across the width of the pipe have been taken; the inside, middle and the outside, these cause the radius in the equation to vary. The linear velocity of the ILI is specified as 0.25m/s as this is its maximum speed.

Angular Velocity

The formula to calculate angular velocity is:

$$\omega = \frac{v}{r}$$

Angular velocity in a 400 mm diameter pipeline bend:

Inside: r= 600 mm: ω= 0.417 rads/s

Middle: r= 800 mm: ω= 0.313 rads/s

Outside: r=1000 mm: ω= 0.25 rads/s

Angular velocity in a 600 mm pipeline bend:

Inside: r= 900 mm: ω= 0.278 rads/s

Middle: r= 1200 mm: ω= 0.208 rads/s

Outside: r=1500 mm: ω=0.167 rads/s

Centripetal Force

The equation to calculate centripetal force (F) is:

$$Centripetal\ force = mass\ x\ centripetal\ acceleration$$

Centripetal acceleration (α) is calculated by:

$$\alpha = v\ \omega = \frac{v^2}{r}$$

Therefore:

$$Centripetal\ Force = m\ v\ \omega$$

B 4 MFL Sensing Technologies

For the pipeline to be properly inspected for cracks the knowledge of how the MFL sensing technology is essential. The orientation of the magnetic field to the crack is very important, in ILIs there are two orientations that the magnetic fields can be established, longitudinally and circumferentially. A longitudinal magnetic field can be induced to a pipeline by using the longitudinal field that occurs in solenoids or using permanent or electro magnets. A circumferential magnetic field can be set up by passing a current around the inside wall of the pipe. Sensing in both of these orientations gives the best likelihood of the crack being detected because if the crack is parallel to the flux lines then it will go undetected.

An orientation of 45 to 90 degrees of the flux lines to the crack is needed for it to be detected.

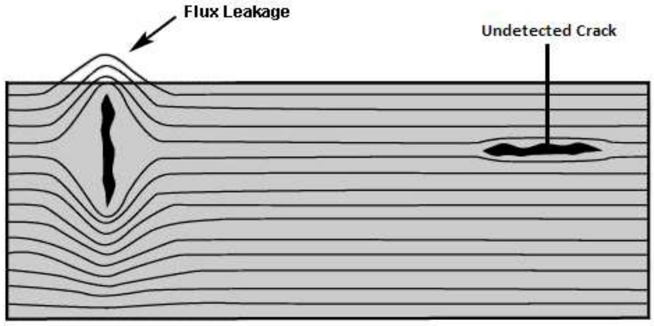

Figure B 17 – Orientations of detection effects (NDT, 2013)

Indirect magnetisation is commonly used in MFL ILIs. A strong external magnetic field is established to induce a magnetic field in an arc section of the pipeline. Permanent magnets are not often used for MFL probes, even though they are inexpensive, as the field strength cannot be controlled however electro magnets do possess this capability and they are widely used in industry. Electro magnets in the form of an adjustable horseshoe magnet is used when the two poles of the magnet are placed on the inside wall of the pipe a magnetic field is induced between the north and south poles and the pipeline becomes briefly magnetised. (NDT, 2013)

When there is a crack in a magnet a magnetic pole will be formed on each side of the crack. The magnetic field will spread out in the air surrounding the crack, as air cannot hold as much magnetic flux density as steel. The magnetic field around the crack will cause a deflection in the magnetic field created by the electro magnet this deflection is then recorded by the sensors as an indication of a flaw. (NDT, 2013)

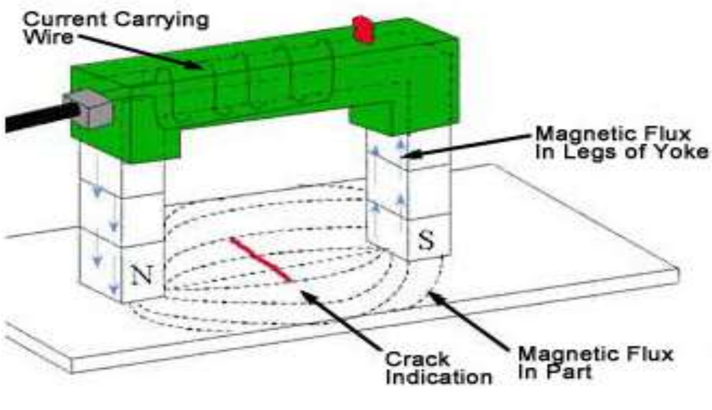

Figure B 18 - Indirect Magnetisation (NDT, 2013)

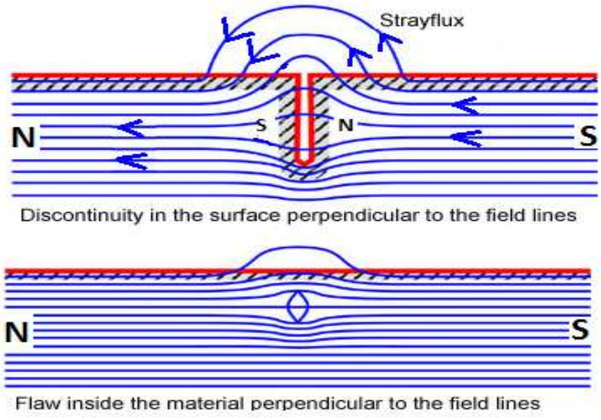

Figure B 17 – Polarization of Flaw (QNET, 2011)

In MFL ILIs there is a similar arrangement to the horseshoe magnet shown in Figure B 17however unlike probes used in industry permanent magnets are used these magnets are attached to steel brushes that make contact with the pipeline. The sensor is either an induction coil or Hall probe and it sits between the two poles of the permanent magnet. There is a circular array of these sensors on the ILI to inspect the whole of the pipeline and with stronger magnets used a greater wall thickness can be assessed.

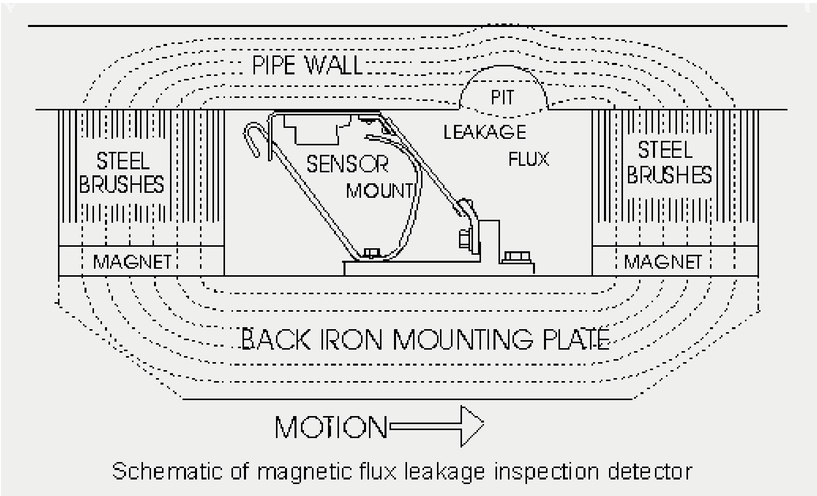

Figure B 18 – ILI MFL Sensor (Queen's University, 2006)

B 5 Sensor Width Calculation

$$\boldsymbol{l = r\theta}$$

$$\boldsymbol{\theta = \frac{95x10^{-3}}{(300x10^{-3})}}$$

$$\boldsymbol{\theta = 0.317\, rads = 18.1^{\circ}}$$

B 6 Reaction Force with Wall

It is useful to know the value of the static friction so that the reaction force between he wheel and the pipeline can be calculated. Wet friction will be looked as there can be a thin film of water on the pipeline's wall which would cause slipping if the calculations were done with dry friction.

The aim is to calculate the value for the reaction force (R) (see diagram XX) so that if the ILI fails then the ILI can be held stationary vertically in the pipeline so that it does not fall and cause damage to itself or the pipeline.

The coefficient of wet static friction between steel and polyurethane, which is the material on the rim of the wheels, is 0.2 (this value doubles to 0.4 for dry friction, so the reaction force would be half of this value calculated below) (Engineering Toolbox, 2013). When resolving the forces the frictional force is eighth of the weight of the ILI which is: 30g / 8 = 36.79N.

$$F_r = \mu R$$

$$R = \frac{F_r}{\mu}$$

$$R = \frac{36.79}{0.2}$$

$$R = 183.9\ N$$

B 7 Rolling Resistance

Rolling resistance or rolling friction is a retarding force on the wheel or rotating object. Energy is dissipated due to the friction at the contact point, the elastic properties of the materials and due to the roughness of the rolling surface. It is very important not to get rolling resistance confused with sliding friction as sliding friction gives a higher frictional force meaning that a larger pushing/driving force is needed, this is the main advantage of a wheel. There is an inertial force needed to get the object moving up to a desired speed but at constant velocity this force decreases, the force needed for constant velocity is what the motor and transmission need to provide. (Lippert and Specktor, 2012)

The formula for rolling resistance is:

$$F_{RR} = c_I \frac{W}{r}$$

Where:

F_{RR} = Rolling friction (N)

c_l = rolling resistance coefficient, with dimension length (units must be the same as used for radius).

W = weight or normal reaction force

r = radius of the wheel.

N.B. - The values for rolling resistance coefficient are experimental and they are not widely available to the public. Even though the rolling resistance changes with speed the coefficient for a speed of 0.25m/s could not be found so the value of 3mph (1.34 m/s), from Figure B19, will have to be used. The wheels used will have a polyurethane tread however there is a range of rolling resistance coefficients due to different chemistries of polyurethane, so I have taken the mean value given in

Figure B19, which is 0.0435 inches. The diameter of the wheels used is 75mm; this is a radius of 1.47 inches.

Calculating Rolling Force

To help quantify rolling resistance in industrial wheels, there is the "coefficient of rolling friction." This is a number that has been empirically determined for different materials, and can vary by the speed of the wheel, the load on the wheel, and the material the wheel is contacting. In the chart below, it is not surprising that the softest tread material (rubber) has the highest coefficient of friction, while the hardest material (forged steel) has the lowest.

**Polyurethane has a range of coefficient values depending on the specific poly material selected.*

Assumptions

Total Load: 1200 lbs

Floor Material: Steel

Wheel Speed: 3 mph

Tread Material	Floor Material	Coefficient of Rolling Friction (inches @ 3mph)
Forged Steel	Steel	0.019
Cast Iron	Steel	0.021
Hard Rubber	Steel	0.303
Polyurethane	Steel	0.030 - 0.057*
Cast Nylon	Steel	0.027
Phenolic	Steel	0.026

Figure B 19 – Rolling Resistance Explanation and Figures (Lippert and Specktor, 2012)

Horizontal Motion

I have estimated that the driving module will weigh around 20kg and when moving horizontally in a pipe it all this mass will over two driving arms.

$$F_{RR} = 0.0435 \ \frac{\left(\frac{20x9.81}{2}\right)}{1.47}$$

$$F_{RR} = 2.90 \ N$$

Vertical Motion

It has been previously calculated that the normal force for the ILI to stay stationary whilst in a vertical section of pipeline is 183.9N (if pipeline wall is wet) and 91.97 (if pipeline wall is dry). The wet value will be used in case there is a thin film of water on the inside walls of the pipeline.

$$F_{RR} = 0.0435 \ \frac{(183.9)}{1.47}$$

$$F_{RR} = 5.44 \ N$$

F_R = Reaction force

F_D =Driving force

F_{RR} = Rolling Resistance / Friction

W = Weight.

The total weight will be divided by the number of driving wheels in vertical ascension, eight wheels. As the total mass is estimated at 30kg then the weight at each wheel will be:

$$W = \frac{30}{8} x \, 9.81$$

$$W = 36.79 \, N$$

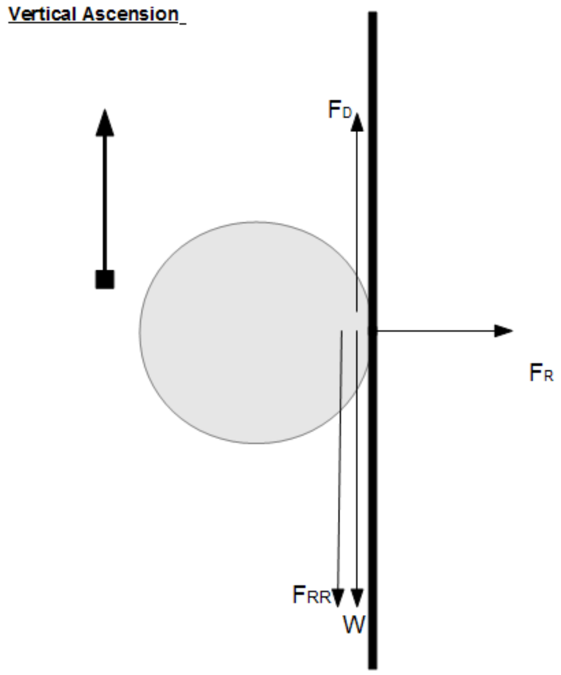

Figure B 20 –Vertical Ascension Forces

Since the vertical forces have to balance:

$$F_D = F_{RR} + W$$

$$F_D = 5.44 + 36.79 F_D = 42.23 \, N$$

B 8 Shear Stress on Drive Shaft

If the maximum driving force is 42.23 N and the wheel diameter is 75 mm then the torque is given by the equation:

$$T = F\,x\,r$$

$$T = 42.23\,x\,\frac{0.075}{2}$$

$$T = 1.58\,Nm$$

The angle of rotation can be found using:

$$\theta = \frac{Tl}{GJ}$$

Where:

l is the length of the shaft (50mm)

G is the modulus of rigidity or the shear modulus for the steel this is 81 GPa.

J is the polar second moment of area, this is calculated by:

$$J = \frac{\pi D^4}{32} J = \frac{\pi (0.01)^4}{32}$$

$$J = 981.7x10^{-12}\,m^4$$

The angle of twist is:

$$\theta = \frac{(1.58)(0.05)}{(81x10^9)(981.7x10^{-12})}$$

$$\theta = 993.4x10^{-6}\,rads$$

Since this value is in radians it needs to be converted back into degrees:

$$\theta = 993.4x10^{-6}\,x\frac{180}{\pi}$$

$$\theta = 0.057\,°$$

The shear stress can be calculated using:

$$\tau = \frac{Tr}{J}$$

$$\tau = \frac{(1.58)(0.005)}{981.7x10^{-12}}$$

$$\tau = 8.05\ MPa$$

The shear yield point has a relationship with the tensile yield point by a factor of 0.58. (Roymech, 2010) The steel has a tensile yield point of around 350 MPa so the shear yield point has a value of 203 MPa. This shows that the 10mm diameter is capable of taking the shear stress.

B 9 Motor Calculations and Specifications

If the wheel has to cover a distance of 250 mm in one second and the diameter of the wheel is 75mm then the angular velocity can be figured out.

The wheel has a circumference of 75π mm. So to cover 250mm it would take 1.06 revolutions in one second.

Using the angular velocity equation:

$$\omega = 2\pi N$$

Where N is the revolutions per second then the angular velocity would be 6.67 rad/s.

The power supplied to the wheels can be found by:

$$Power = T\omega$$

$$Power = 1.58\ x\ 6.67$$

$$Power = 10.53\ W$$

The motor chosen must be able to provide 10.53 W of power and 1.58Nm of torque through the transmission.

The specifications for the motor chosen can be seen below in table B1. Figures from here and the diagram will be used in late calculations.

Model	57BL01
Number of Poles	4
Number of Phases	3
DC Voltage	12 V
Rated speed RPM	2500
Speed after gearbox	125
Output Power Watts	15
Peak Torque1 N-m	0.18
Peak Current Amps	2.7
Body Length (L) mm	35
Mass kg	0.43
Diameter mm	35
Length mm	45

Table B 1 – Motor Specifications (Alibaba ,2013)

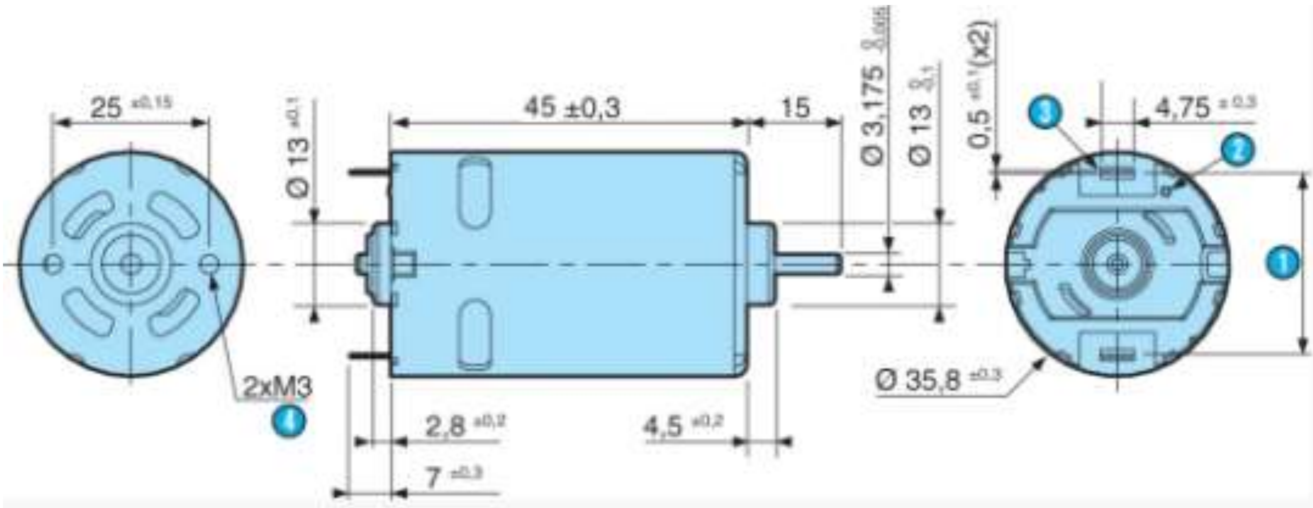

Figure B 21 – Motor Dimensions (Alibaba ,2013)

B 10 Research on Motors

Direct current motors are used where a wide range of precise torque and speed control is required. Traction is often performed by DC motors and special applications such as conveyor belts and lifts in mines use them (Petruzella, 2010, p91). There are three types of DC motor with regard to the manner of field excitation:

1) Shunt-wound, including permanent-magnet and separately excited motors.
2) Series-wound.
3) Compound-wound

Each type has distinctive torque and speed characteristics.

Shunt-wound and separately excited motors operate at speeds only a few per cent less than their no-load speed. As the speed falls the torque produced rises quickly they produce maximum power at half the no-load speed but at this point the heat produced in the armature is as large as the mechanical work being done by the motor itself. Sustained operation is only possible at speeds near the no-load speed. This is not ideal for traction as little torque is produced or there is the need for large gear reductions. Petruzella, 2010

Series-wound motors are used for traction applications, where a large starting torque is highly desirable for acceleration. A starter is needed in the motor as the combined resistance of the armature winding and field coils is very small as heavy gauge wire with few turns are used on the windings. The torque falls rapidly as speed builds up. The speed varies widely between no load and rated load so these motors cannot be used for constant speed with variable loads. Petruzella, 2010

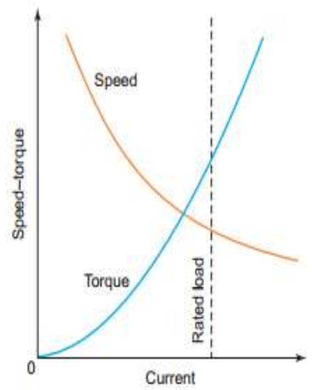

Figure B 22 – Speed-torque characteristics for series motor. (Petruzella, 2010)

Compound-wound motors have characteristics between series and shunt-wound motors. They have high starting torque and they do not run-away when there is no load. This is the reason why they will be used for the ILI. Their exact characteristics depend on the ratio of the shunt and series field turns and may be more similar to one than the other types of wound motors.

Brushless DC Motors (BLDCs) have become popular in a wide range of industries including electrical traction, automotive and industrial automation equipment. This rise in popularity is due to the fact that they do not have mechanical commutators and brushes this means that they have a long operating life, high reliability and operate quietly. They have a high power density, low inertia, leading to high dynamic response. The power losses occur in the stator where the heat can be transferred outside through the casing this also means that little heat is transferred to the driving shaft. (Petruzella, 2009)

B 11 Belt Length

The length of the belt drive can be calculated from these measurements:

The distance between the two centres of the drive shafts is H in Figure B23, this can be found out using Pythagoras' Theorem:

$$H^2 = 27.5^2 + 63.5^2$$

$$H = \sqrt{(27.5^2 + 63.5^2)}$$

$$H = 69.2\,mm$$

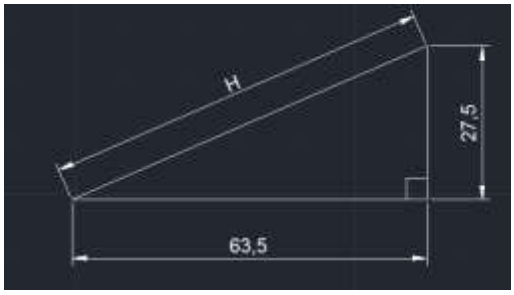

Figure B 23 – Distance between shaft centres

The length of the belt can be calculated using (Kharagpur, 2008):

$$L_0 = \frac{\pi}{2}(d_L + d_s) + 2C + \frac{1}{4C}(d_L - d_s)^2$$

L_0	Length of open belt	/
d_L	Diameter of larger pulley (attached to wheel)	= 39.3 mm
d_S	Diameter of smaller pulley (attached to motor)	= 20 mm
C	Centre distance between the two pulleys	= 69.2 mm

Table A 10 – Nomenclature for belt length equation

$$L_0 = \frac{\pi}{2}(39.3 + 20) + 2(69.2) + \frac{1}{4(69.2)}(39.3 - 20)^2$$

$$L_0 = \frac{148\pi}{5} + 138.4 + \frac{1}{4(69.2)}(372.49)$$

$$L_0 = 232.74\ mm$$

The velocity of the belt can be expressed by: (N_M is the RPM of the motor pulley)

$$v = \frac{\pi d_s N_m}{12}$$

$$v = \frac{\pi(20)(125)}{12}$$

$$v = 654\frac{mm}{s} \equiv 0.654\frac{m}{s}$$

B 12 Tension and Belt Size

Assuming that the coefficient of friction is the same for the driven and driver pulley and that the coefficient of friction is 0.6 between the rubber belt and the nylon pulley then the pulley that governs the design is decided by the larger value of α. α_L is the angle of wrap in the larger pulley and α_S is the angle of wrap in the larger pulley.

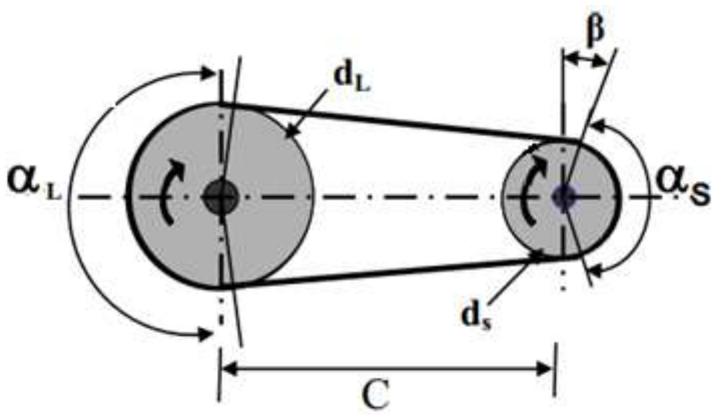

Figure B 24 – Belt Diagram ((Kharagpur, 2008)

$$\alpha_L = 180° + \beta$$

$$\alpha_s = 180° - \beta$$

Where: $\beta = \sin^{-1}\left(\frac{d_L - d_S}{2C}\right)$

$$\beta = \sin^{-1}\frac{39.3 - 20}{2(69.2)}$$

$$\beta = 7.97\,°$$

The larger α comes from the larger gear which has a wrap angle of 187.97 ˚this is also 3.28 radians. So this is the governing design pulley.

If the thickness (t) of the belt is 4mm then the width (B) needs to be calculated:

The density (ρ) of the rubber belt is 920kg/m^3.

The allowable stress for the belt is 5MPa.

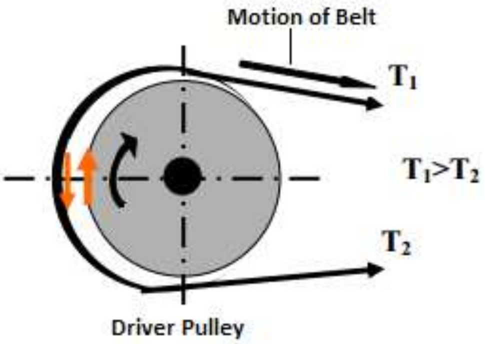

Figure B 25 – Correct Belt Tension (Kharagpur, 2008)

Using the equation that determines belt tension relationship:

$$\frac{(T_1 - mv^2)}{(T_2 - mv^2)} = e^{\mu\alpha} \qquad (1)$$

$$m = B\ t\ \rho \qquad (2)$$

$$m = (Bx10^{-3})(4x10^{-3})(920)$$

$$m = (3.68x10^{-3})(B)$$

Therefore:

$$mv^2 = (3.68x10^{-3})(B)(0.654)^2$$

$$mv^2 = 1.57B$$

Using equation (1) again:

$$\frac{(T_1 - 1.57B)}{(T_2 - 1.57B)} = e^{(0.6)(3.28)} = 7.156$$

The power equation (using the max power of the motor, 15W):

$$P = (T_1 - T_2)\ v$$

Rearranging and solving:

$$(T_1 - T_2) = \frac{P}{v} = 22.93$$

Using the permissible stress (5MPa) to find T_1:

$$\sigma = \frac{F}{A}$$

$$T_1 = \sigma A$$

$$T_1 = (5x10^6)(4x10^{-3})(Bx10^{-3})$$

$$T_1 = 20B$$

Substituting this back into equation (1):

$$\frac{(20B - 1.57B)}{(T_2 - 1.57B)} = 7.156$$

$$\frac{(20B - 1.57B)}{7.156} = T_2 - 1.57B$$

$$4.14B = T_2$$

Substituting this back into the power equation:

$$(T_1 - T_2) = 22.93$$

$$20B - 4.14B = 22.93$$

$$\boldsymbol{B = 1.44\ mm}$$

Therefore:

$$T_1 = 20(1.44) = 28.8N$$

$$T_1 - 22.93 = T_2$$

$$T_2 = 5.87N$$

So T_1 is greater than T_2 as is shown in Figure B25 Ideally the lower tension side of the belt would be above the higher tension side this would mean that the belt sags onto the driven gear due to the belt's own weight. This would increase the angle of wrap and therefore the system would be able to have a greater power transmission capacity.

A belt width of 1.44 mm is the minimum width belt that could be used. However belts are not normally thicker than they are wider and since the CSA of the belt was presumed to be a rectangle the width and the thickness can be interchanged. So the width of the belt is 4 mm and the thickness is 1.44 mm, however belts sizes are normally rounded up to the nearest millimetre so the thickness is 2 mm.

B 13 Arc Length and Shell Gap

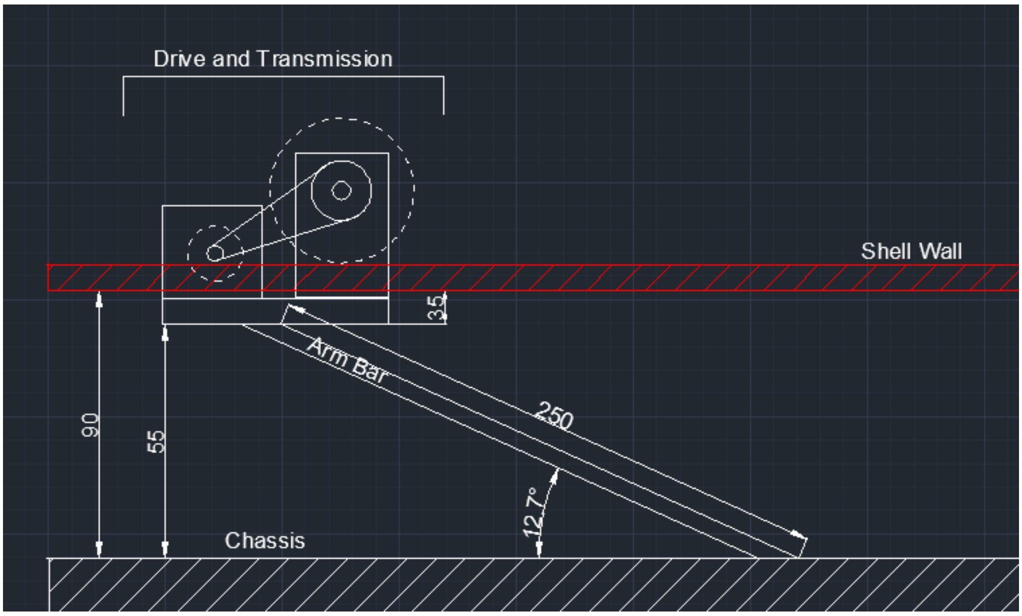

Figure B 26 - Arm Bars and Measurements

Figure B 26 shows that the drive and transmission system come 35 mm below the surface of the shell when the pipeline is at its minimum diameter of 400 mm. There is an angle of ($\sin^{-1}$(55/250) = 12.7 degrees between the arm bar, which supports the drive and transmission, and the chassis.

To find the angle when the ILI is inspecting a 600 mm diameter pipeline then Figure 24 B can be looked at:

Since the arm bar needs to cover 100 mm vertically then the total height above the chassis is 155 and the bar has not changed length so the angle is:

$$\theta = \sin^{-1}\left(\frac{155}{250}\right) = 38.3°$$

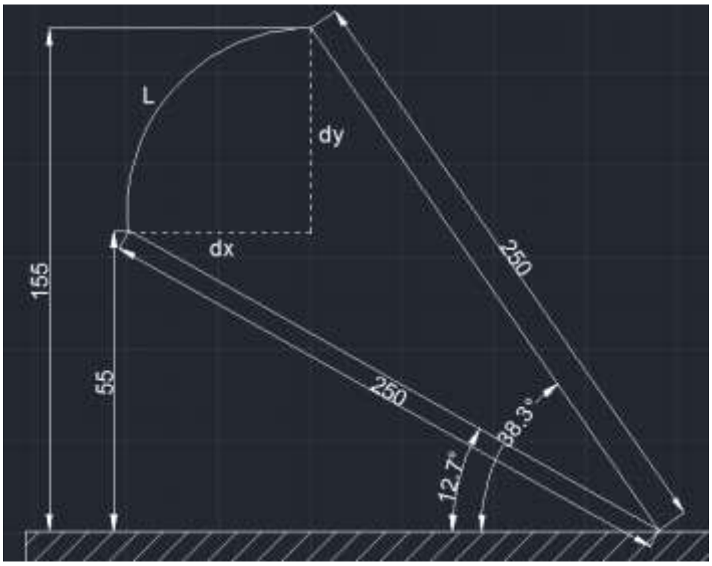

Figure B 27 – Angles due to Extension

The arc distance that the arm bar travels at the end can also be calculated, knowing that the angle is (38.3-12.7 =) 25.6 degrees, which is , using:

$$L = r\theta$$

$$L = 250\left(\frac{25.6\pi}{180}\right)$$

$$L = 111.7\,mm$$

The change in x is also important to decide the length of the gaps in the shell of the ILI that the drive system and arm bar need to travel through:

$$x_1 = 250\cos(12.7) = 243.9\,mm$$

$$x_2 = 250\cos(38.3) = 196.2\,mm$$

$$x_1 - x_2 = 47.7\,mm$$

Another 100 mm needs to be added to this because of the base plate and also for safety reasons to give adequate clearance. So the length of the drive gaps in the shell need to 147.7 mm which would be rounded up to 150 mm.

B 14 Location and Extension of MSD

It was initially though that the MSD could be placed perpendicularly to the chassis however this would mean that telescopic dampers would need to be used as the extension was greater than the hydraulic unit when not extended as well as telescopic dampers being needed the length of these dampers would need to be very small, around the magnitude of 10 mm, this size of MSD may not be able to be bought or it would be very expensive or impossible to manufacturer. To get around this issue the MSD will be placed at an angle to the chassis. There are two variables here; the angle between the MSD and the chassis and the distance between the pinned joint of the arm bar to the chassis and the pinned joint of the MSD to the chassis.

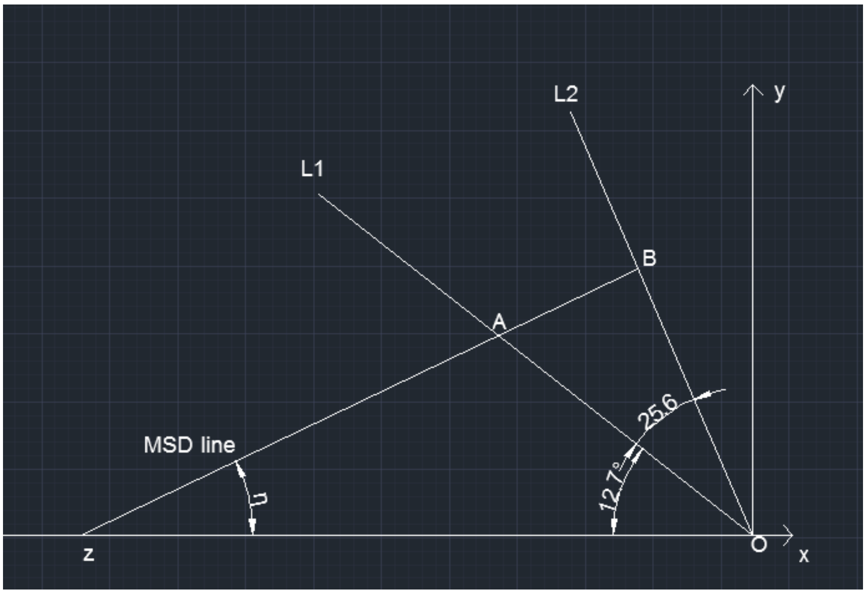

Figure B 28 – Diagram of MSD with Points to Reference

It was initially estimated that an angle of 20 degrees (denoted by η) and that the distance would be 200 mm (denoted by Z). The length of the MSD at a compressed state (distance between Z and A) needs to be found and so does the extension (distance of A to B), the location of the pinned joint where the MSD and arm bar connect is also realised (point A):

The easiest way to accomplish all of this is to use line equations by having the origin at the pinned joint of the arm bar and the chassis. Looking at Figure 28 B the MSD line represents the MSD, L1 represents the arm bar at its lowest point and L2 represents the arm bar at its highest point:

Finding point A when η = 20 degrees and Z = -200:

Equation of line MSD, in y=mx + c form:

Gradient = dy/dx = tan(20) / 1 tan 20 = + 0.364

Point Z is known as (-200,0) so c is:

$$y = 0.364x + c$$

$$0 = (0.346)(-200) + c$$

$$c = 72.8$$

So MSD line equation is:

$$y = 0.346x + 72.8$$

Equation for line L1 is:

Gradient = - (tan 12.7) = -0.225

Since goes through the origin c=0 , so the equation is:

$$y = -0.225\ x$$

The point where these two lines intersect is the location of A:

$$y = y$$

$$-0.225\ x\ = 0.346x + 72.8$$

$$x =\ -123.6\, mm$$

$$y = 27.8\, mm$$

So they meet at (-123.6, 27.8). So the length along L1 that the pin joint is:

$$Length =\ \sqrt{(123.6^2 + 27.8^2)} = 126.7\ mm$$

The length of the un-extended MSD is:

Horizontal distance = -200-(-123.6) = 76.4 mm

$$Length =\ \sqrt{(76.4^2 + 27.8^2)} = 81.8\ mm$$

The extension (E) can be calculated using the cosine rule:

The length (l) was calculated as 125.7 mm and the angle is 25.6 degrees, see Figure B 29.

So:

$$E^2 = l^2 + l^2 - 2(lxl)\cos 25.6$$

$$E\ = 56.57\ mm$$

This is a good result as the extension is less than the length of the MSD, so telescopic MSD is not needed, however the angle of 20 degrees is shallow and the vertical force provided by the MSD is less than the horizontal. This is undesirable and a greater angle, preferably above 45 degrees, would help alleviate this issue so an excel spread sheet was created to change

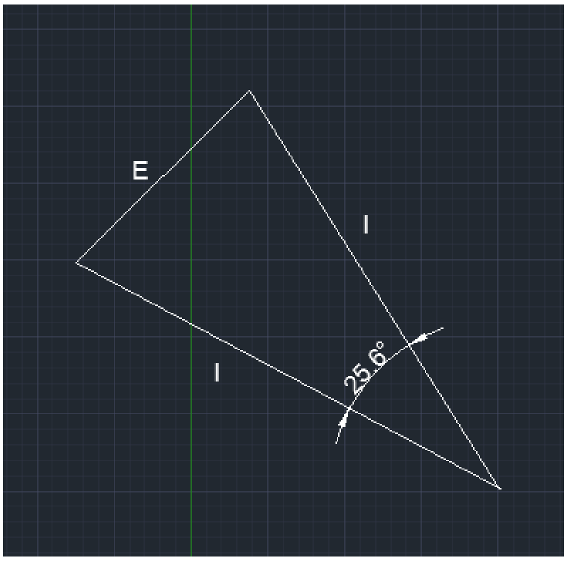

Figure B 29 – Extension of MSD

the variables to more favourable values. These values are shown in the main report in section 5.12.

B 15 Forces on Arm Bars

When the drive and transmission system is at its lowest point the angle of the bar against the chassis is 12.7 degrees. The force that the MSD needs to exert on the arm bar to achieve 183.9 N vertically for adequate friction to allow the ILI to move vertically is:

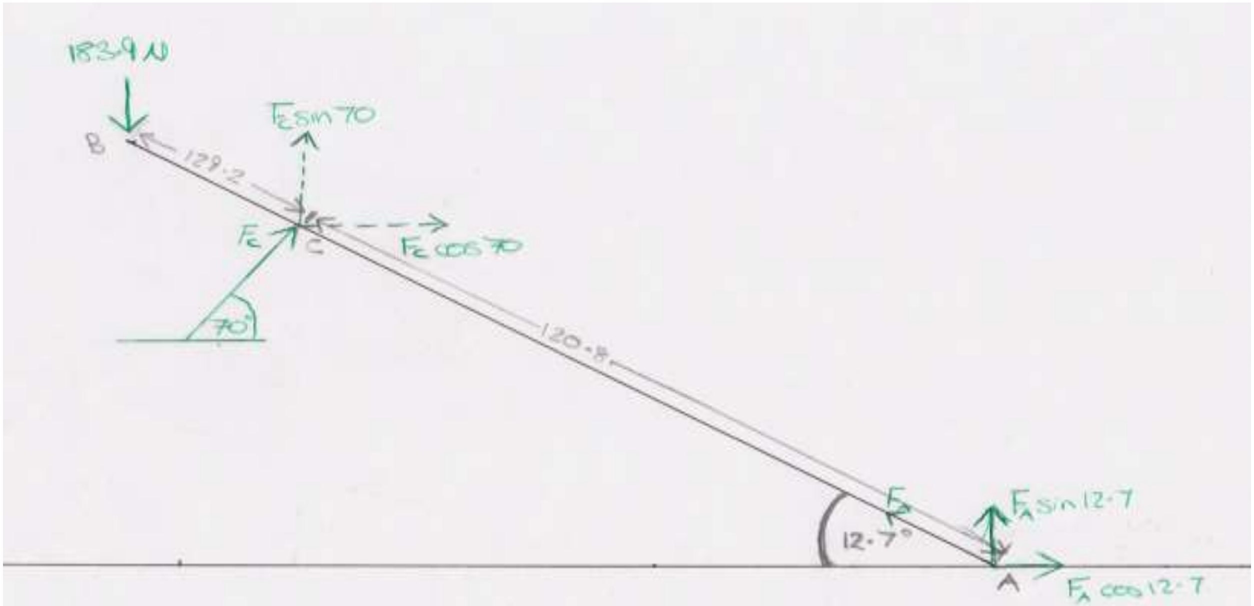

Figure B 30 – Forces on Arm Bar at Lowest Height

The bar is in equilibrium:

$$\sum Forces\ Horizontally:$$

$$F_c \cos 70 + F_A \sin 12.7 = 0$$

$$\sum Forces\ Vertically:$$

$$F_C \sin 70 + F_A \sin 12.7 - 183.9 = 0$$

$$\sum of\ Moments\, about\ A:$$

$$(F_C \sin 70)\ (120.8 \cos 12.7) + (F_C\ \cos 70\ )(120.8 \sin 12.7) = (183.9)(250 \cos 12.7)$$

$$F_C(119.78) = 44850.2$$

$$F_C = \mathbf{374.4\ N}$$

$$F_A = \frac{-F_C \cos 70}{\cos 12.7} = \mathbf{-131.26\ N}$$

When ILI is scanning a 600 mm pipeline then the angle between the arm bar and the chassis will be 38.3 degrees. When the arm bar is at this angle it is also necessary to check the amount of force needed by the MSD and the force on the pin at point A.

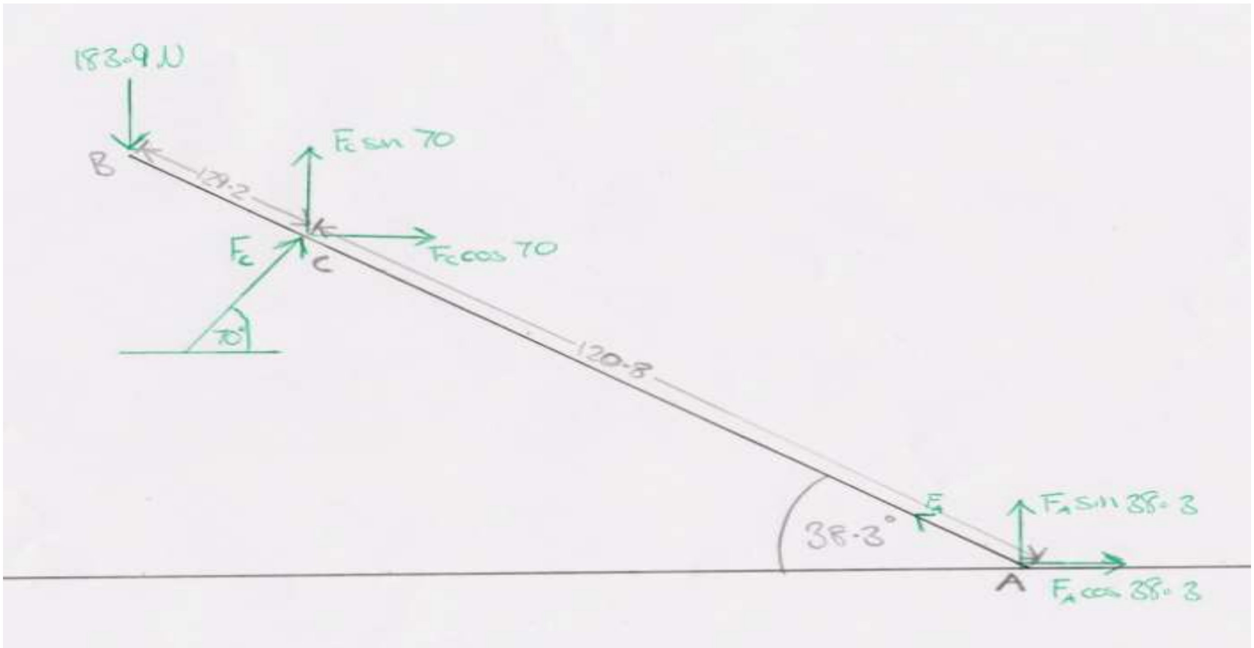

Figure B 31 – Forces on Arm Bar at Highest Point

The bar is in equilibrium:

$$\sum of\ the\ foces\ horizontally:$$

$$F_C \cos 70 + F_A \cos 38.3 = 0$$

$$\sum of\ the\ forces\ vertically:$$

$$F_A \sin 38.3 + F_C \sin 70 - 183.9 = 0$$

$$\sum of\ the\ moments\ about\ A:$$

$$(F_C \sin 70)(120.8 \cos 38.3) + (F_C \cos 70)(120.8 \sin 38.3) = (183.9)(250 \cos 38.3)$$

$$F_C(114.7) = 36080.1$$

$$F_C = \mathbf{314.6\ N}$$

$$F_A = \frac{-F_C \cos 70}{\cos 38.3} = \mathbf{-137.1\ N}$$

B 16 Design of MSD

B 16.1 The Spring

So the spring on the MSD will have to exert a force of 314.6 N when the ILI is scanning a 600 mm diameter pipeline and 374.4 N when it is scanning a 400 mm pipeline. The spring will have a compression of 60 mm.

To design a spring with the data given a spring index needs to be considered. Spring indexes vary from a range of 3 – 12. The spring index is the ratio between the spring's coil diameter and the diameter of the wire that is used to make the spring. A good spring index is around 6 to7 (Kharagpur, 2008). Otherwise manufacturing becomes difficult for low spring indexes or the curvature effect will be greater for larger indexes. It is also assumed that the diameter of the damper is 25 mm, the spring diameter must be larger than this, so a coil diameter of 40mm and a wire diameter of 6mm gives an index of 6.66, which is within the 6-7 index value.

The spring rate (k) can be found as it is:

$$k = \frac{\Delta F}{x}$$

$$k = \frac{374.4 - 314.6}{60x10^{-3}} = 990\frac{N}{m}$$

From this the number of active turns (N) can be calculated using:

$$N = \frac{Gd^4}{8D^3k}$$

Assuming that the shear modulus of steel (G) is 80 GPa then:

$$N = \frac{(80x10^9)(6x10^{-3})^4}{8(40x10^{-3})^3(990)}$$

$$N = 20.45\ turns$$

The compression spring will be both squared and ground as a better transfer of load is obtained. As the spring at will be compressed against two rigid plates on the damper, this means mean that the ends can be considered fixed. These type of ends decrease the number of active coils by approximately two so in reality N= 18.45 turns. (Shigley,2008)

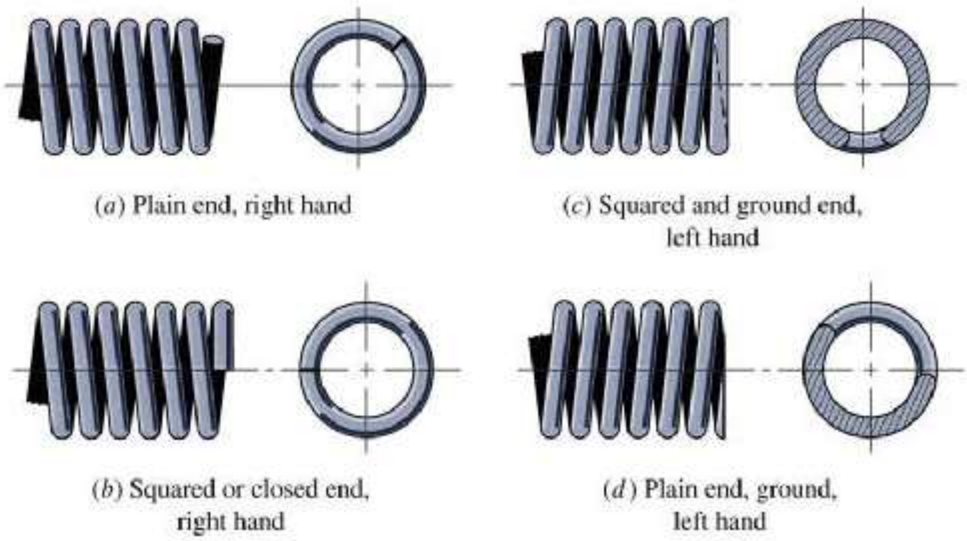

Figure B 32 – Spring Ends (Shigley, 2008)

B 16.2 Viscous Damper

The diameter of the damper was assumed to be 25 mm for the spring calculation however after the calculation the damper could have a maximum diameter of 34 mm (40 mm - 6 mm). And the length of the damper in a compressed state is 81.8 mm minus the length needed for the pin joints.

It is desirable to have a critically damped MSD so that no oscillations occur and the wheels are constantly in contact with the pipe wall. For critical damping the damping ratio (ϛ) is equal to 1 (Edwards, 2001).

The drive and transmission mass is calculated to be 1.574 kg and if it is assumed that the mass acts over point C (see Figure B31 or B30) then the mass that is parallel to the MSD is (1.574/cos20) equal to 1.671 kg, the value of k is the spring coefficient that was calculated to be 990N/m. In designing for viscous dampers it is important to find the damping coefficient, c.

$$\zeta = \frac{c}{2\sqrt{km}}$$

$$c = (\zeta)\left(2\sqrt{km}\right)$$

$$c = (1)(\ 2\sqrt{(990)(1.671)}$$

$$c = 81.3$$

The damping force is another aspect when selecting a viscous damper. It is also required that the extension/ compression of 60 mm can occur in 1.5 seconds:

$$F_{damping} = -c\frac{dx}{dt}$$

$$F_{damping} = -81.3\frac{(60x10^{-3})}{1.5}$$

$$F_{damping} = 3.252\ N$$

B 17 Knuckle Joint for MSD to Arm Bar

If the pin knuckle joint is carrying a compressive load of 374.4 N. The bending stress and the shear stress need to be calculated. If the diameter of the pin is 10 mm and a = 5mm and b = 10mm.

$$I = \frac{\pi d^4}{64}$$

$$I = \frac{\pi 10^4}{64}$$

$$I = 490.9\ mm^4$$

$$Area = 100\pi$$

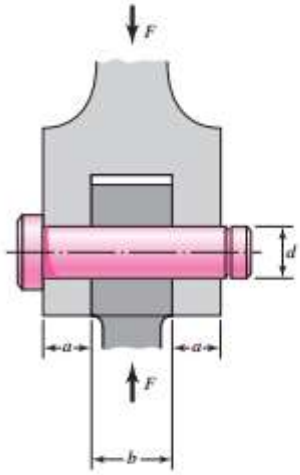

Figure B 33 – Knuckle Joint Diagram (Shigley ,2008)

See Figure B 33 for the loading, shear force and bending moment diagram:

Force F was turned into a UDL of 37.44 N/mm:

Bending moment is the area of the triangle in the shear force diagram below the horizontal line:

$$BM = \left(\frac{1}{2}(5)(-187.3)\right) + \left(\frac{1}{2}(-187.3)\left(\frac{10}{2}\right)\right)$$

$$BM = -936.5\ Nmm$$

The negative bending moment means that the pin is hogging.

The bending stress is:

$$\sigma = \frac{My}{I}$$

$$\sigma = \frac{(-936.5)(5)}{490.9}$$

$$\sigma = -9.536 \frac{N}{mm^2} = -9.536\ MPa$$

Max shear stress for a solid circular shaft is calculated by:

$$\tau_{max} = \frac{4}{3} x \frac{SF}{A}$$

$$\tau_{max} = \frac{4}{3} x \frac{-187.3}{100\pi}$$

$$\tau_{max} = -\ 0.795\ MPa$$

These stresses are far below the shear and yield stress of the steel material that will be used for the pin so a diameter of 10 mm is verified.

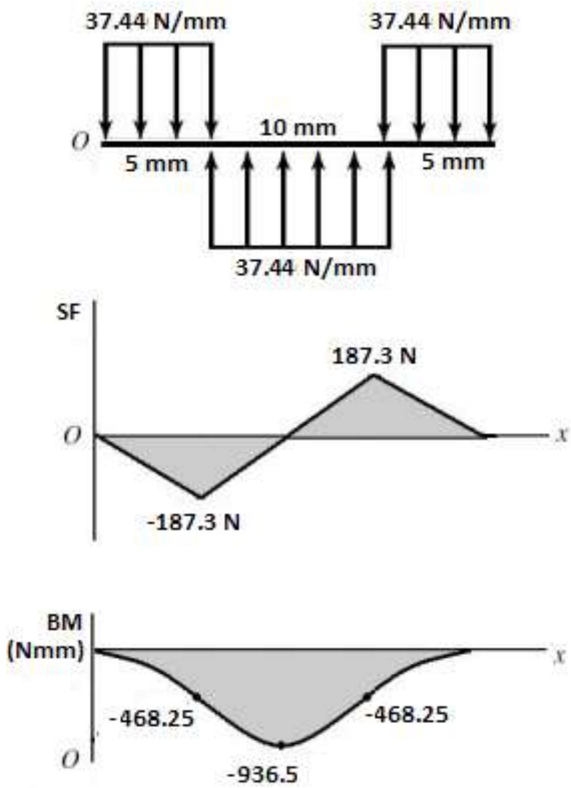

Figure B 34 –Shear Force and Bending Moment (Shigley, 2008)

B 18 Drive and Transmission Components

Driving System	Height	Width / Diamter	Thickness	Depth	Volume (mm^3)	Density (kg/m^3)	Mass (g)	Material	Cost (each) (£)	Number of Parts	No. parts x indv. cost
Wheels	/	75	/	50	/		250	Aluminium and Ployurethane	£ 7.50	8	£ 60.00
Wheel case	65	60	4	70	23974	7800	187	Steel	£ 1.50	8	£ 12.00
Motor	/	35	/	45	43295	/	430	Various	£ 10.24	8	£ 81.92
Motor case	45	45	4	55	55256	7800	431	Steel	£ 1.00	8	£ 8.00
Base plate	4	116	/	55	25520	2700	69	Aluminium	£ 0.30	8	£ 2.40
Bearings	/	25	/	3	1473	/	25	Various	£ 0.55	32	£ 17.60
Driving shaft	/	4	/	20	2513	7800	19	Steel	£ 0.20	8	£ 1.60
Driven shaft	/	10	/	50	3927	7800	30.6	Steel	£ 0.20	8	£ 1.60
Belt	2	232.74	/	4	18613	920	21	Natural Rubber and glass fibres	£ 1.40	8	£ 11.20
Driver Pulley	/	20	/	6	38148	2700	103	Aluminium	£ 2.80	8	£ 22.40
Driven Pulley	/	39.3	/	6	56296	2700	152	Aluminium	£ 2.80	8	£ 22.40
Transmission casing	45	116	1.5	8	29623	2700	80	Aluminium	£ 1.30	8	£ 10.40
Base plate eye joint	/	35	/	10	18519	2700	50	Aluminium	£ 1.20	8	£ 9.60
Torsion Springs	/	12	1	3	1410	7800	4	Steel	£ 0.15	16	£ 2.40
						Total Mass:	1571			Total Cost:	£ 263.52

Table B 2 – Components of the Drive and Transmission System.

B 19 Eye of Joint between Chassis and Module

Figure B35 shows the fork eyes for the rubber joint that will be used to connect the chassis and shells of the three modules. A maximum force of the combined estimated weight of the two modules (10 kg x 9.81) and a safety factor of 1.5 for impact loading which would occur when the ILI is changing direction, such as when it is moving from horizontal to vertically downwards. So the total force applied to the eyes was 147.2 N in and simulations were done for the component in compression, Figure B35 and in tension, Figure B36. As the other fixtures on the chassis these fork eyes will be T-welded as well. The thickness of the fork eyes is 4 mm. As expected the highest stresses occur around the centre of the eyes, this is shown in figure B37.

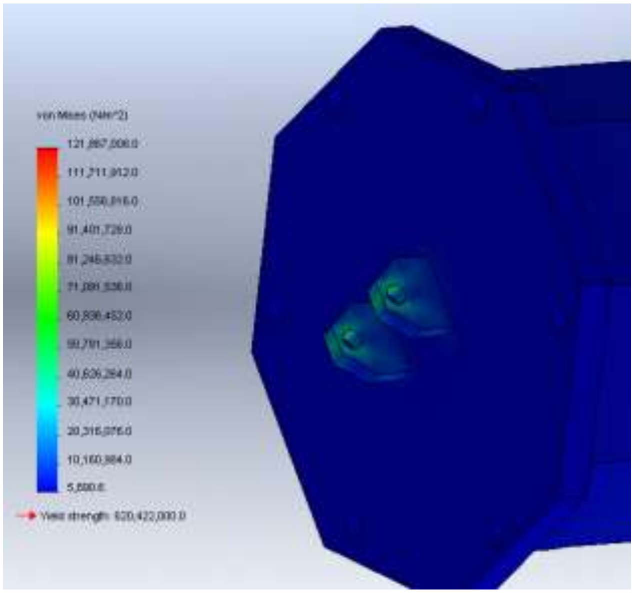

Figure B 36 – Module Link Compression

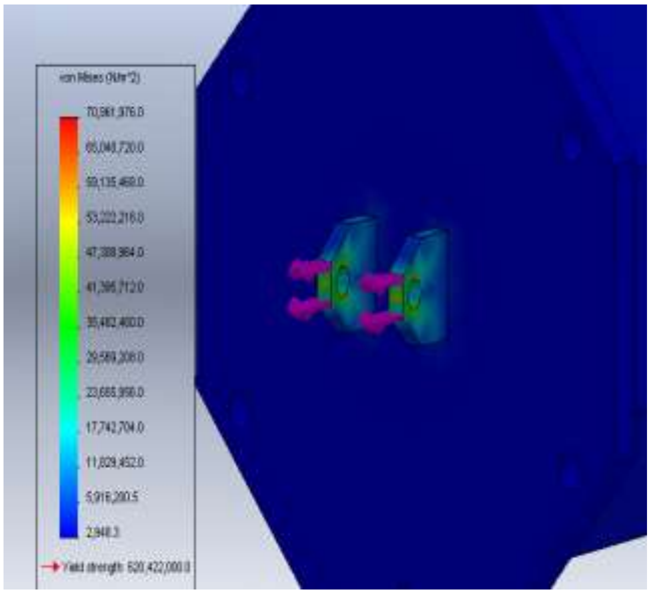

Figure B 35 – Module Link Tension

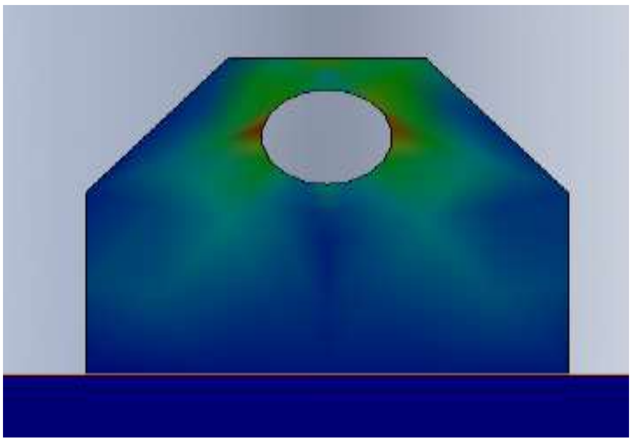

Figure B 37 – Location of Highest Stress

B 20 Module Linkages

Initially it was thought that the modules should be linked together using a universal joint (UJ) however they are more expensive than other solutions. They would also require maintenance and they could get seized by corrosion products that will fall onto the joint. The wiring going through the universal joint was another challenge that can avoided by a different solution. The alternative chosen is to have a flexible elastomer joint between the joints however the main disadvantage to elastomers compared to a steel UJ is that elastomers have much worse tensile and shear strength. The shear strength and bending stresses are important for elastomers such as rubber and an additive may be needed to increase the strength. This will be. An advantage to an elastomer joint is that the wiring can be fed through a bore hole through the centre of the elastomer. Elastomers have poor tensile and shear properties however they can be improved with additives such as adding carbon black and orientated steel wires in butyl rubber.

For example a rubber shaft of 400mm length with a load of 20 g (the weight of the driving module) at the fracture point and assuming that it the shaft fractures at the end that is fixed to the driving module. The diameter of the shaft is 30 mm and has a 10 mm bore for wiring to be threaded through. Then the flexural strength, or modulus of rupture, is:

$$\sigma_{FS} = \frac{F_f L}{\pi(R^3 - r^3)}$$

$$\sigma_{FS} = \frac{20g\ x\ 400}{\pi(15^3 - 5^3)}$$

$$\sigma_{FS} = 7.68\ MPa$$

This is much lower than the 17MPa modulus of rupture that CES gives for 50% carbon black filled butyl rubber (CES, 2013). The carbon black also improves the fracture toughness for the butyl rubber so that it can resist developing cracks.

B 21 Further Motor Research

In section 5.10 the motor chosen is a 15 watt compound motor, a full table of properties of the motor can also be found in this section. Eight of these motors will be used to provide motion to drive the wheels and the control of these motors is necessary to facilitate the best possible motion in different conditions in the pipeline. As well as control of the motors sensible logic control and flow diagrams are needed to reduce the risk of the ILI getting stuck in the pipeline, see **section B22**.

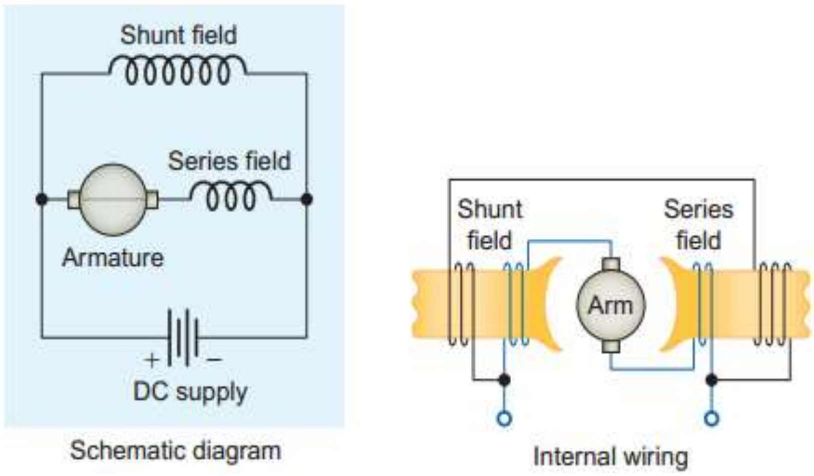

Figure B 38- Compound Motor Windings (Petruzalla, 2010)

Reverse

The direction of rotation of a wound DC motor depends on the direction of the field and the direction of the current flowing though the armature. If either the direction of the field current or the direction of the current flow through the armature is reversed then the motor will reverse however if both of these were reversed then the motor would not change direction, this would happen if the applied voltage polarity was switched. The industry standard is to reverse the current through the armature and maintain the current though the series and shunt windings in the same direction. For compound wound motors this ensures that both fields are used for either direction of rotation. The schematic for this circuit can be seen in Figure 38 B. Switching the polarity in the armature and not the windings means that there will not be a charge build-up in the windings, as they act as inductors, and a flyback diode will not be needed across the motor to prevent arcing at the switch. (Petruzalla, 2010)

To switch the polarity in the armature digitally a solid state relay (SSR) could be used as they can control an analogue DC power supply using a digital signal. They are better than a mechanical relay in the ILI as SSRs are not affected by mechanical shock, vibration and electromagnetic fields however the main disadvantage to them is that they have a high resistance and can create heat so often a heat sink is attached to them. (National Instruments, 2011).

Braking

Another advantage of utilising PWM is that is can be used to control back EMF. Back EMF is the voltage produced by a spinning armature that brings the motor to a stop this is induced as the motor is effectively reversed and becomes a generator the time for the motor to switch to a generator depends on the charge stored in the windings.

As stated in the reverse section above the H-bridge control circuit can use PWM the connection is shown in section 5.16. The back EMF can also provide regenerative braking as long as the design allows for bidirectional power flow, however there is no control of recharging the battery through back EMF and it can cause damage so this will be avoided

Another braking that DC motors can use is dynamic braking this is where the armature and a separately excided shunt field is disconnected from the power supply and is switched to a high resistance, see diagram B39. It is possible to increase the amount of braking by reversing the current in the series winding for the compound motor. (Vasudevan and Rao, 2006)

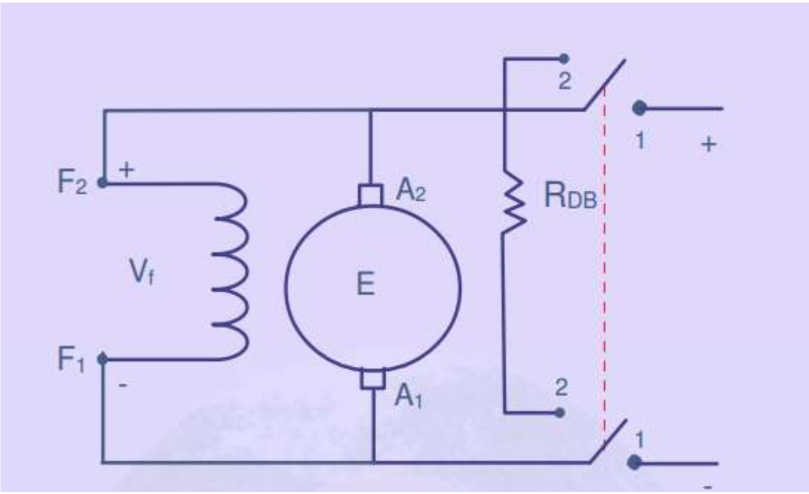

Figure B 39 – Dynamic Braking (Vasudevan and Rao, 2006)

B 22 Flow Diagram for Drive System

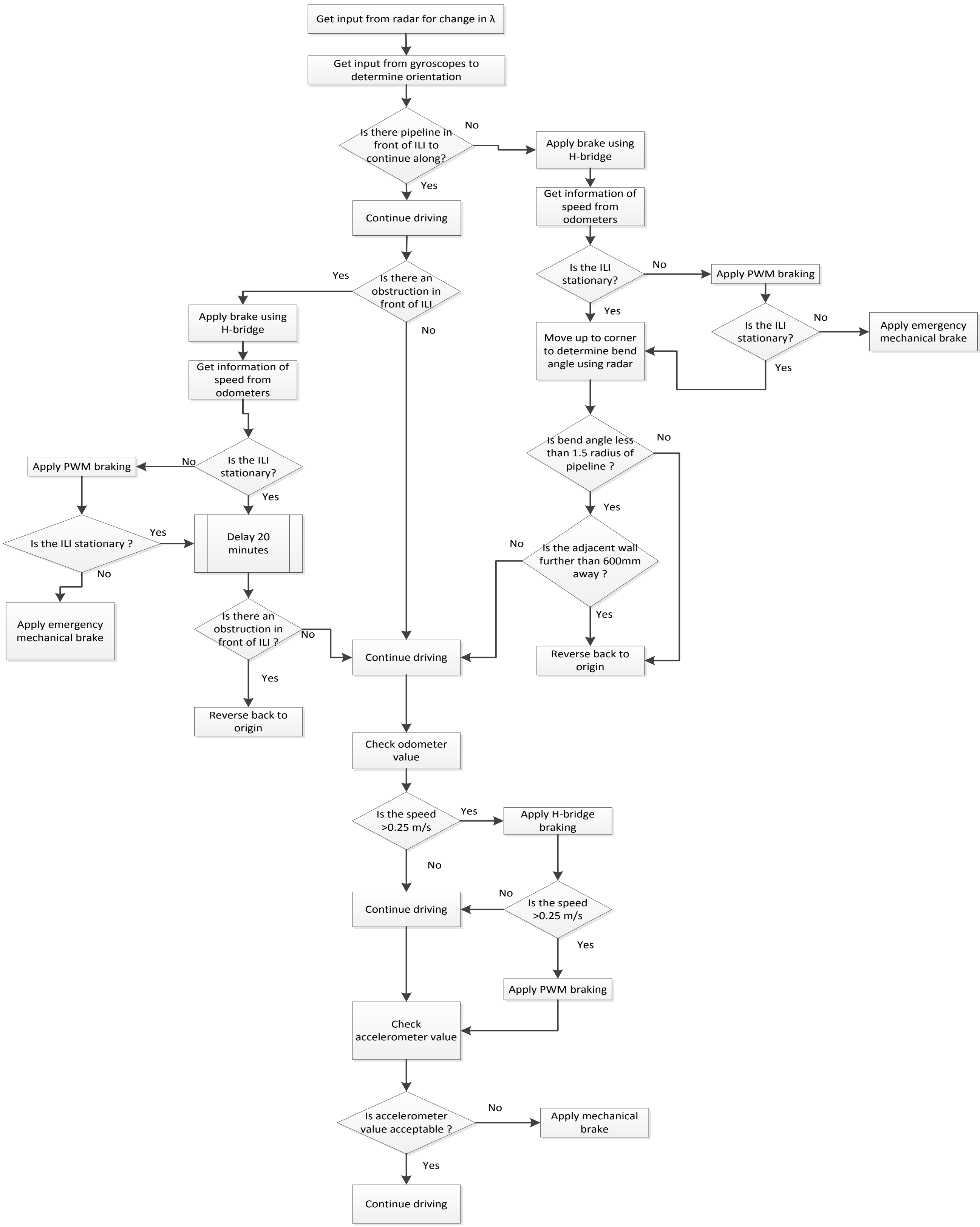

Figure B 40- Flow Diagram for Drive System

The ILI uses the change in wavelength from the radar to determine if there is an obstacle or the size of the pipeline and also to determine the bend radii. They gyroscopes are used to determine the orientation of the ILI and so that the ILI can tell if it is possible to drive forward. There are three possible outcomes for the ILI; it can continue driving as it is supposed to function and continue scanning the pipeline for faults, it can detect an obstruction or impassable pipeline and then reverse back to the point that it was inserted, if the ILI realises that it is falling or if braking is failing then it will apply the mechanical brake. The pipeline must be checked so that there are no large steps along its path, the large step will mean that the ILI is capable of driving over and passed the step but not be able to reverse back over it. This would mean that the ILI would continuously move back and forward between the step and the point where it decided to reverse back and the ILI would have to be removed from the pipeline by taking a section of pipeline out.

B 23 Proximity Sensors

B 23.1 Inductive Sensors

These detect the presence of a metallic object such as the pipeline. A coil creates a high frequency oscillation and this creates a field in the surrounding object. If a metallic object is present then this causes a change in the amplitude of the oscillation. The operating distance depends on the size of the coil and the targets shape and size. The maximum operating distance for these type of sensors is 50mm which does not give enough time for the ILI to stop so these are not an option, this is also an issue with capacitive and magnetic sensors. (Fargo, 2013)

B 23.2 Radar

Radar can use radio waves or the higher frequency microwaves. Radar works by transmitting pulses of high intensity and high frequency pulses the transmitter then switches off and the receiver is then turned on and it detects the returning pulses it then uses the time between the outgoing and return signal and the Doppler shift then it can calculate the distance and speed of the objects. More information on radar in the main report under section 5.17.

B 23.3 Active Ultrasonic

Active ultrasonic could be used. However in this application they have many issues with them. They could interfere with the ultrasonic sensor in the sensing module even if they have different frequencies. The target they require must be large and flat, which would be useful in detecting the perpendicular wall of the end of the steam main however this is not useful for detecting corners and even of the ball valves are closed they are not of a flat shape. The sensors are also affected by vibrations and uneven surfaces that can cause scattering which may be inside the pipeline due to corrosion. The main advantage to ultrasonic sensors when compared to optical or IR sensors is that they are less affected by reflective surfaces such as metal or water films and droplets. (Banner, 2006)

B 23.4 Infrared Diffusion Reflective Sensors

These sensors can offer sensing an object of almost any material up to a distance of 10 meters. The IR has the advantage over optical/visible light in dusty environments which may occur due to corrosion products and vibrations from the ILI. The diffusion reflectors use a light reflected off the target to determine the distance it is away, these type of sensors do not need a highly reflective surface for the beam to return. The disadvantage to them is that they can only detect a distance away which would be useful to determine how far away the opposite perpendicular wall is at the end of the steam main or at a bend however the sensor needs to be able to determine how sharp the corners are. (Trossen Robotics, 2013)

B 24 Battery Power

Calculations need to be done to determine how big the battery should be for a given distance that the ILI needs to travel.

It is estimated that the MFL sensors use 0.3 W each and the UT sensors use 0.4 W each and the on board computer and SSD use 1.5W (Raspberry Pi, 2013) and 0.3 W respectively the odometers also use 0.115 W each. It was calculated in section 5.10 that each motor needed 10.53 W to climb the pipeline vertically, the ILI will not be climbing vertically all of the time so the motors will have different output power at different elevations and have differential amounts of power sent to every motor, such as in horizontal motion the lower most motors will be doing more work than the upper most due to gravity. A guideline needs to be established to determine the different power going to the motors at different elevations.

It is calculated that without the motors the power output from the sensors and the computer and the SSD is 16.13 watts, using the figures above.

The motors will always need power even if the ILI is descending as power needs to go the windings in the motor to allow for braking and PWM which can be used for back EMF by varying the opposite voltage across the armature. The minimal amount of power to the motors needed is when the motor is on an downward inclined slope such that the inclination does not cause a significant acceleration due to gravity so that a constant velocity can be maintained. It has been estimated that this inclination is around 5 degrees below the horizontal this is taking friction and the pipelines surface into account. It is also estimated that during horizontal motion the ILI will need to use about a third of the power to the motors when compared to vertical ascension, which is 3.51.

Assuming that as inclination increases so does the power needed to the motors in an exponential fashion. Using these two values an equation was calculated in the form of $y=ab^x$ where a is 3.51 and b is 1.0123 and y is the power needed for each motor and x is the angle of inclination. For different angles of ascension the power to each motor is shown in table B3.

$$y = 3.51\,(1.0123)^x$$

Angle of inclination (x)	0	15	30	45	60	75	90
Power (y)	3.51	4.21	5.06	6.07	7.3	8.76	10.53

Table B 3 – Inclination and Power Needed

This table can be used to estimate the power needed to the motors for individual inspections as steam pipelines have different layouts. It can also be assumed that the power needed for braking the motor when the angles are below the horizontal is roughly two third given in Table B3, as voltages need to be increased to implement back EMF and braking.

A typical steam pipeline system may be around 2 kilometres long so 4 kilometres long including the journey back in reverse, where the sensors and SSD can be turned off, the maximum speed of the ILI is aimed to be at 0.25 m/s. So the total inspection is calculated to take 4.44 hours. The typical pipeline is:

75% horizontal,

5% at 15˚ elevation above horizontal and 5% at 15 ˚ depression to the horizontal,

5% vertical ascension and 5% vertical descent.

And 3% at 60 ˚ ascension and 2% at 45 ˚ ascension.

Percentage	Angle	Distance (m)	Time (hrs)	Power (watts per motor)		Watt hours
75%	0 (horizontal)	3000	3.333333333		3.51	11.7
5%	15 +	200	0.222222222		4.21	0.935555556
5%	15 -	200	0.222222222	2/3 x 4.21 =	2.81	0.624444444
5%	90 +	200	0.222222222		10.53	2.34
5%	90 -	200	0.222222222	2/3 x 10.53 =	7.02	1.56
3%	60 +	120	0.133333333		7.3	0.973333333
2%	45 +	80	0.088888889		6.07	0.539555556
Total	/	4000	4.444444444		/	18.67288889
Total Watt Hours = watt hours x 8 motors =			149.3831111			

Table B 4 – Total Watt Hours for typical pipeline

This means that the battery must be able to provide around 150 watt hours for the motors alone plus the power needed for the other electronics ((16.13 W x 4.44/2)+ (1.5 W x 4.44/2)) = 39.14 W.

So the battery capacity must be at least 188.5 Wh however a safety factor of 1.4 will be added to this as some pipelines will be longer than 2km and different pipelines have different layouts and the ILI may need to stay longer in the pipe than expected due to obstructions the extra capacity can also be used for the segmented section of the battery where the motors run in reverse to get the ILI back to the insertion point if the main electronics fail. A Li-ion battery of 263.9 watt hours is needed. Li-ion batteries are also temperature sensitive so the battery will use the driving module chassis, which is made of aluminium an excellent conductor and has a large surface area, as a heat sink.

A spread sheet can be used to calculate the amount of power the ILI needs to complete an inspection of a certain pipeline and certain capacity batteries can be used for different inspections depending on the pipelines layout.

A 12.8 V Li-ion battery of a capacity of 265 watt hours can be supplied by JEGS and it costs £ 794 and it has a mass of 4.31 kg (JEGS, 2013). It will be able to fit into the chassis which has a width of 190 mm, the battery's physical dimensions are:

Length	165 mm
Height	125 mm
Width	176 mm

Table B 5 – Dimensions of battery (JEGS, 2013)

B 25 Computer

As the ILI is untethered the data collected from the MFL and UT sensors needs to be stored so that it can be downloaded when the ILI is recovered after the inspection operation as the technology to transmit data through a steel wall pipe does not exist currently. The need to store data means that the ILI has to contain a CPU or data logger, data storage media, software and power supply. All of these components mentioned have not been specifically designed for pipeline ILI so they have to be adapted from other applications this is why the electronic system needs to be custom designed.

Single Board Computers (SBC) (embedded PC) are widely used in ILIs. An SBC is a miniaturised PC that has the necessary peripherals and memory to hold an operating system and custom application software. SBCs can range in size from standard computers/laptops to the size of a credit card and they continue to increase in speed and decrease in size, following Moore's law. Microcontrollers are an alternative to an SBC, microcontrollers are a single chip computer system they are not as powerful as SBCs but they are very flexible and programmable. Using custom firmware these microcontrollers can be programmed to do a variety of tasks that would normally take a dozen ICs. (Warnes, 2003)

B 26 Data Acquisition

Data acquisition is the process of capturing signals from world to normally input to a discrete processor. Transducers are the sources of these signals on the ILI these transducers are the MFL UT and odometer sensors. The MFL and UT transducers are of a crystal type and the odometer is of a resistive type. Transducers often give a low amplitude signal that needs boosting however these signals are susceptible to internally and externally generated noise and other environmental conditions such as temperature and vibrations can have an impact on the signal quality.

A method to partially solve the noise issue is to have two output wires from the transducer run together, this means that the induced noise will be roughly the same in both wires giving a 'common mode' signal. A differential amplifier would ideally only amplify the difference between the two signals and reject the noise. The gain is the ratio of R_f to R_i multiplied by the difference between V_2 and V_1, when looking at diagram B41.

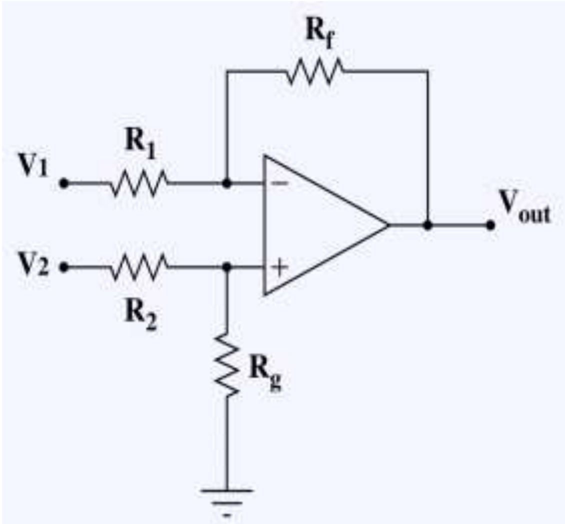

Figure B 41 – Differential Amplifier (Allaboutcircuits, 2007)

B 27 Stainless Steel Properties

Stainless steel, ferritic, AISI 430, wrought, annealed

Composition detail

C (carbon)	0	-	0.12	%
Cr (chromium)	16	-	18	%
Fe (iron)	79.3	-	84	%
Mn (manganese)	0	-	1	%
Ni (nickel)	0	-	0.5	%
P (phosphorus)	0	-	0.04	%
S (sulfur)	0	-	0.03	%
Si (silicon)	0	-	1	%

Mechanical properties

Young's modulus	195	-	205	GPa
Flexural modulus	* 195	-	205	GPa
Shear modulus	75	-	81	GPa
Bulk modulus	144	-	159	GPa
Poisson's ratio	0.275	-	0.285	
Shape factor	61			
Yield strength (elastic limit)	245	-	345	MPa
Tensile strength	430	-	600	MPa
Compressive strength	205	-	370	MPa
Flexural strength (modulus of rupture)	205	-	370	MPa
Elongation	17	-	30	% strain
Hardness - Vickers	150	-	195	HV
Hardness - Rockwell B	75	-	85	
Hardness - Rockwell C	* 0	-	10.7	
Hardness - Brinell	155	-	192	MPa
Fatigue strength at 10^7 cycles	225	-	249	MPa
Fatigue strength model (stress range)	* 123	-	203	MPa

Figure B 42 – Properties of selected stainless steel (CES,2013)

B 28 Assembly Step by Step Instructions

Driving Module

Step 1: Screw knuckle joint chassis eyes to the chassis. The screws go from the inside of the chassis to the outside and into the eyes.

Step 2: Screw the flange on the front and back faces of the chassis so that the shell can be bolted on to this in the next step.

Step 3: Insert brackets for electronics inside the chassis and align and screw in the brackets from the outside of the chassis.

Step 4: Insert the chassis into the shell and bolt the back and front face plates to the chassis. The face plate sits on a lip and groove on the shell. The back plate is the one with the eyes for the module linkage joints.

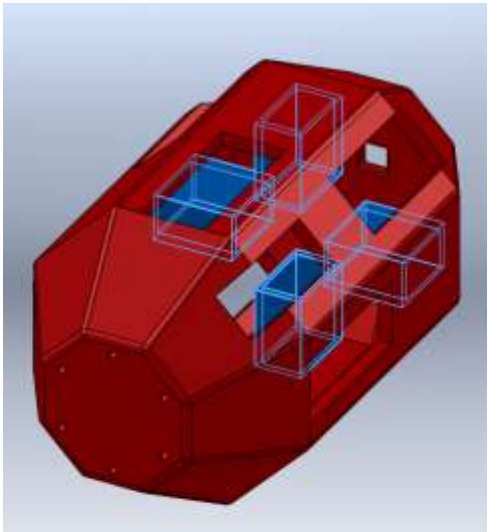

Figure B 43 – Showing Packers

Step 5: Insert the hollow four rectangular packers in between the shell and the chassis and secure by screwing in from the outside of the shell and also screw them in from the back of the chassis. These are highlighted in Figure B43.

Step 6: Attach the bought in MSD to the arm bar.

Step 7: Attach the arm bar and the MSD to the eyes on the chassis that were attached in step 1. This needs to be done for both the drive arms and the odometers.

Step 8: Start with the base plate and screw in the eye for the knuckle joint. Flip the base plate over.

Step 9: Insert the motor into the motor casing and secure with screws. Then screw the motor casing to the base plate.

Step 10: Screw the wheel case into the base plate then attach the wheel to the casing, insert the bearings between the drive shaft and wheel case and insert and secure the wheel's drive shaft.

Step 11: Attach the belt over one of the pulleys then secure both pulleys to the drive and driven shafts. Then place the bearings on.

Step 12: Slide the transmission cover on and secure to the motor housing and the wheel casing. Then feed wires though the non-threaded hole in the base plate and slide covering over wires.

Step 13: Feed the covered wires through the hollow arm bar and at the point where it is attached to the MSD glue the wires to the steel. Then feed the wires out of the arm bar that is near the chassis and feed the covered wires into the chassis. Figure B44 shows the wiring through the arm bar. The yellow line is the covered wires that are running inside the arm bar and the dotted green line is where the wires are exposed and the blue circle is the location of where the wires need to be glued to the steel

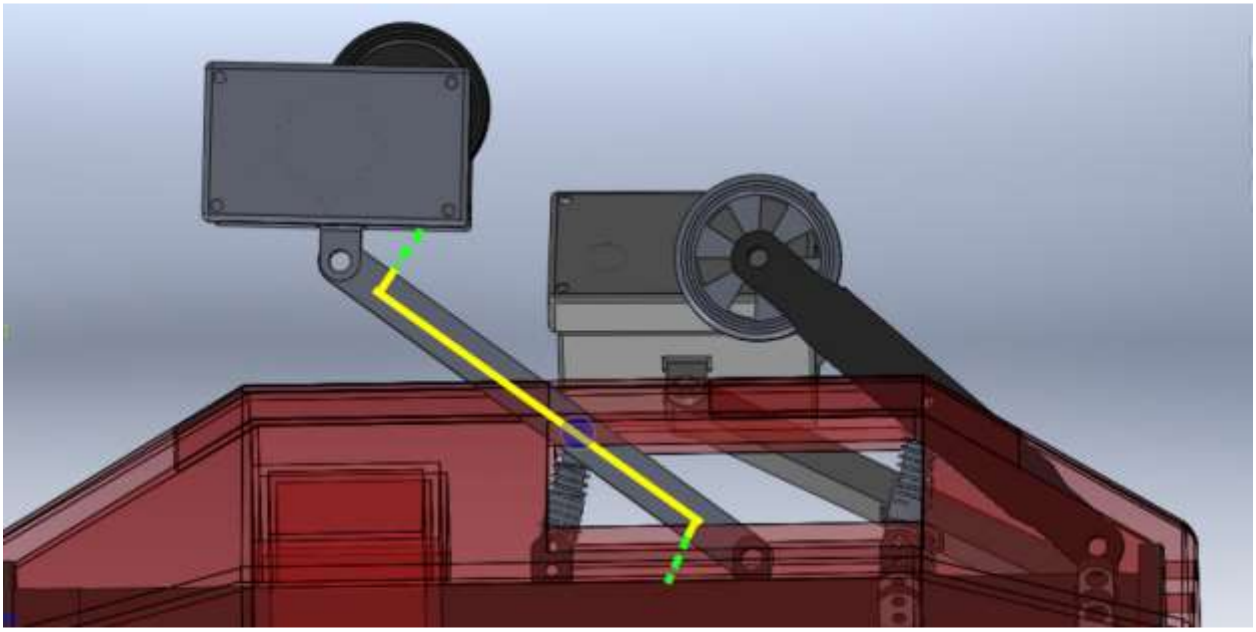

Figure B 44 – Wiring Diagram for Drive System

Step 14: Attach the assembled drive and transmission system to the bar via the knuckle joint and insert the torsion springs either side of the joint and secure the joint.

Step 15: Attach the odometer wheels to the odometer bars and do the same wiring as outlined in step 13.

Step 16: Detach front plate from chassis connect and insert electronics and secure to brackets then reseal front plate back onto chassis.

MFL and UT Modules

These two modules are assembled in very similar ways the only real difference is the sensor type that is attached at the end of the arm bars. So the two modules have been grouped together for the description of how they are assembled.

Step 1: Screw knuckle joint chassis eyes to the chassis. The screws go from the inside of the chassis to the outside and into the eyes.

Step 2: Screw the flanges backmost flange for the spring on to the chassis then slide the smaller diameter end of a polymer spring over the chassis. Screw the foremost flange onto the chassis and slide the second spring over as done with the first one.

Step 3: Screw the flange on the front and back faces of the chassis so that the shell can be bolted on to this in the next step.

Step 4: Bring the shell over the chassis and bolt the front and back plated onto the flange mentioned in step 3.

Step 5: Attach the rectangular packers as done in step 5 for the driving module.

Step 6: Attach the MFL/UT sensor to the eye of the knuckle joint and insert two torsion springs either side of the eye. (The sensors are bought in from a supplier and come already attached to a base plate and assembled.)

Step 7: Feed the wiring through the arm bars as done for the driving module glue is needed as the spring will be threaded through the bars instead of the MSD joint, see Figure B 44 and step 13 for a reference.

Step 8: Place the arm bars in the eye joints and insert pin only half way without securing.

Step 9: Feed the end of the spring through the arm bar joints.

Module Linkages

At this stage all of the modules are assembled and they just need linking now the last part is to attach the rubber module linkages. It is best to work from the backmost module forward because of the wiring. As before the wiring will need sufficient covering as between the outside of the chassis and shell to the rubber module linkage. The wiring needs to be fed into the rubber joint first and into the next module then the mechanical attachments can be used.

B 29 Full Price Breakdown

Driving Module

Part No.		Unit Cost (£)		Quantity	Total Cost (£)	
Driving System						
DSA1	Wheels	£	7.50	8	£	60.00
DSA2	Wheel case	£	1.50	8	£	12.00
DSA3	Motor	£	10.24	8	£	81.92
DSA4	Motor case	£	1.00	8	£	8.00
DSA5	Base plate	£	0.30	8	£	2.40
DSA6	Bearings	£	0.55	32	£	17.60
DSA7	Driving shaft	£	0.20	8	£	1.60
DSA8	Driven shaft	£	0.20	8	£	1.60
DSA9	Belt	£	1.40	8	£	11.20

DSA10		Driver Pulley	£	2.80	8	£	22.40
DSA11		Driven Pulley	£	2.80	8	£	22.40
DSA12		Transmission casing	£	1.30	8	£	10.40
DSA13		Base plate eye joint	£	1.20	8	£	9.60
DSA14		Torsion Springs	£	0.15	16	£	2.40
	Suspension for Driving System						
DSB1		Arm bars	£	1.30	8	£	10.40
DSB2		MSD Spring	£	0.60	8	£	4.80
DSB3		MSD Damper	£	3.00	8	£	24.00
DSB4		Pins	£	0.10	24	£	2.40
	Chassis & Shell						
DSC1		Main chassis	£	12.00	1	£	12.00
DSC2		Eyes	£	0.80	20	£	16.00
DSC3		Electronics bracket	£	6.00	1	£	6.00
DSC4		Plate	£	1.60	2	£	3.20
DSC5		Flange	£	1.10	2	£	2.20
DSC6		Shell	£	22.00	1	£	22.00
DSC7		Shell packer	£	2.00	4	£	8.00
	Electronics						
DSE1		SSD	£	200.00	1	£	200.00
DSE2		Rasberry Pi	£	25.00	1	£	25.00
DSE3		Motor Controls	£	3.00	8	£	24.00
DSE4		Software	£	1,000.00	1	£	1,000.00
DSE5		Radar	£	17.00	6	£	102.00
DSE6		Odometers	£	15.00	2	£	30.00
DSE7		Odometer arm bar	£	1.50	2	£	3.00
DSE8		Odometer MSD	£	3.00	2	£	6.00
DSE9		Battery	£	794.00	1	£	794.00
DSE10		Wiring	£	8.00	1	£	8.00
			Total Cost of Driving Module:			£	2,192.00

Table B 6 – Product cost breakdown of driving module

MFL Unit

Part No.		Unit Cost (£)	Quantity	Total Cost (£)
Chassis and Shell				
MFA1	Main Chassis	£ 10.00	1	£ 10.00
MFA2	Eyes	£ 0.80	20	£ 16.00
MFA3	Plate	£ 2.40	2	£ 4.80
MFA4	Flanges for plates	£ 1.50	2	£ 3.00
MFA5	Flanges for spring	£ 1.50	2	£ 3.00
MFA6	Shell	£ 10.00	1	£ 10.00
MFA7	Shell packers	£ 3.00	5	£ 15.00
MFA8	Module link	£ 8.00	1	£ 8.00
MFA9	Polymer spring	£ 9.00	2	£ 18.00
Sensors				
MFB1	MFL Sensors	£ 9.00	20	£ 180.00
MFB2	Arm bars	£ 1.30	20	£ 26.00
MFB3	Eye joints to arm bar	£ 0.80	20	£ 16.00
MFB4	Torsion springs	£ 0.15	40	£ 6.00
MFB5	Pins	£ 0.10	40	£ 4.00
MFB6	Wiring	£ 6.00	1	£ 6.00
		Total Cost of MFL Unit:		£ 238.00

Table B 7 – Product cost breakdown of MFL module

UT Unit

Part No.		Unit Cost (£)	Quantity	Total Cost (£)
Chassis and Shell				
UTA1	Main Chassis	£ 10.00	1	£ 10.00
UTA2	Eyes	£ 0.80	20	£ 16.00
UTA3	Plate	£ 2.40	2	£ 4.80
UTA4	Flanges for plates	£ 1.50	2	£ 3.00
UTA5	Flanges for spring	£ 1.50	2	£ 3.00
UTA6	Shell	£ 10.00	1	£ 10.00
UTA7	Shell packers	£ 3.00	5	£ 15.00
UTA8	Module link	£ 8.00	1	£ 8.00
UTA9	Polymer spring	£ 9.00	2	£ 18.00
Sensors				
UTB1	UT Sensors	£ 16.00	20	£ 320.00
UTB2	Arm bars	£ 1.30	20	£ 26.00
UTB3	Eye joints to arm bar	£ 0.80	20	£ 16.00
UTB4	Torsion springs	£ 0.15	40	£ 6.00
UTB5	Pins	£ 0.10	40	£ 4.00
UTB6	Wiring	£ 6.00	1	£ 6.00
			Total Cost of UT Unit:	£ 378.00

Table B 8- Product cost breakdown of UT module

B 30 Full Weight Breakdown

Driving Module Weight

Part No.		Material	Mass (g) /unit	Quantity	Total mass (g)
Driving System					
DSA1	Wheels	Aluminium and Polyurethane	250	8	2000
DSA2	Wheel case	Steel	187	8	1496
DSA3	Motor	Various	430	8	3440
DSA4	Motor case	Steel	431	8	3448
DSA5	Base plate	Aluminium	69	8	552
DSA6	Bearings	Various	10	32	320
DSA7	Driving shaft	Steel	19	8	152
DSA8	Driven shaft	Steel	30.6	8	244.8
DSA9	Belt	Natural Rubber and glass fibres	21	8	168

DSA10		Driver Pulley	Aluminium	103	8	824
DSA11		Driven Pulley	Aluminium	152	8	1216
DSA12		Transmission casing	Aluminium	80	8	640
DSA13		Base plate eye joint	Aluminium	20	8	160
DSA14		Torsion Springs	Steel	4	16	64
	Suspension for Driving System					
DSB1		Arm bars	Steel	200	8	1600
DSB2		MSD Spring	Steel	80	8	640
DSB3		MSD Damper	Various	100	8	800
DSB4		Pins	Steel	10	24	240
	Chassis & Shell					
DSC1		Main chassis	Aluminium	4400	1	4400
DSC2		Eyes	Steel	30	20	600
DSC3		Electronics bracket	Aluminium	205	1	205
DSC4		Plate	Aluminium	190	2	380
DSC5		Flange	Steel	130	2	260
DSC6		Shell	Polypropylene	1850	1	1850
DSC7		Shell packer	Polypropylene	80	4	320
	Electronics					
DSE1		SSD	Various	125	1	125
DSE2		Rasberry Pi	Various	90	1	90
DSE3		Motor Controls	Various	20	8	160
DSE5		Radar	Various	15	8	120
DSE6		Odometers	Various	130	2	260
DSE7		Odometer arm bar	Steel	200	2	400
DSE8		Odometer MSD	Various	220	2	440
DSE9		Battery	Various	4310	1	4310
			Total mass for Driving Module:			31924.8

Table B 9 - Product weight breakdown of driving module

Sensor Module Weight

Part No.			Material	Mass (g)/unit	Quantity	Total Mass (g)
	Chassis and Shell					
MF/UT A1		Main Chassis	Aluminium	2250	1	2250
MF/UT A2		Eyes	Steel	20	20	400
MF/UT A3		Plates	Steel	40	2	80
MF/UT A4		Flanges for plates	Steel	130	2	260

MF/UT A5	Flanges for spring	Steel	180	2	360
MF/UT A6	Shell	Polypropylene	1020	1	1020
MF/UT A7	Shell packers	Polypropylene	40	5	200
MF/UT A8	Module link	Butyl rubber	400	2	800
MF/UT A9	Polymer spring	Polyester	80	2	160
Sensors					
MF/UT B1	MFL Sensors	Various	80	20	1600
MF/UT B2	Arm bars	Steel	125	20	2500
MF/UT B3	Eye joints to arm bar	Steel	20	20	400
MF/UT B4	Torsion springs	Steel	5	40	200
MF/UT B5	Pins	Steel	10	40	400
		Total Mass for Sensor Module:			10630

Table B 10 - Product weight breakdown of sensor modules

B 31 Sustainability

Manufacturing has considered the amount of energy needed in different material processing for example it requires more energy to forge a shape than to extrude it. Unfortunately there are currently no feasible recycling technologies for Li-ion batteries as the battery recycling market is largely price driven and currently profits cannot be obtained from recycling Li-ion batteries. The most sustainable action with an un-recyclable battery is to downgrade it and use it for a less demanding use in the future after it is unfit for purpose in the ILI. (WMW, 2013)

The overall intent of the ILI is to inspect pipelines so that they do not fail during operation meaning that the boiler has to be switched off, which is sometimes not possible in coal fired stations, resulting in a waste of energy. In terms of the social sustainability of the ILI the avoidance of pipe ruptures means the potential saving of lives and injuries. The ILI will provide economic benefits because of the avoidance of pipe ruptures means that there is no unscheduled down time meaning high costs. It is also hoped that the development of this product will encourage research into corrosion and degradation of steam pipelines as there has been a stall in this area from around 15 years ago. Socio-economically the ILI will create manufacturing jobs and since the ILI is going to provide a service several high paid jobs will be needed in analysing the data that the ILI collects.

The importation of components means that the ILI factory does not need to house as much machinery or take up as much space this means saving in land and also in material tied up in products.

The product is intended to have a long lifespan so regular maintenance and testing is vital to the quality of the ILI, this also creates jobs. Spare parts for the product may become cheaper over time however the ILI may eventually succumb to having obsolete technology. It has been designed so that this does not happen for a long period as the sensors can be replaced with something new and the use of an on board computer means that software can be reprogrammed to meet the new technologies, this also means that the ILI will be able to keep up with new emerging competition in the future.

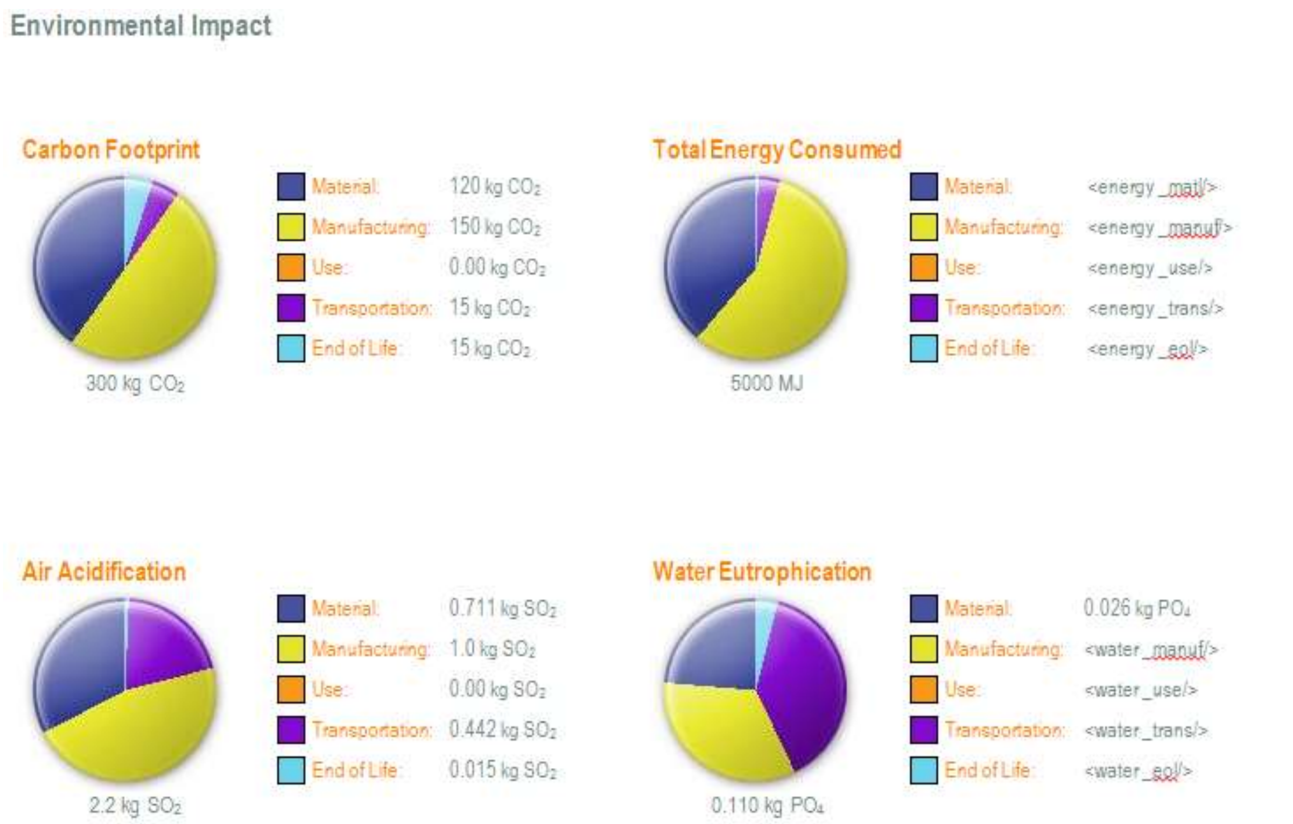

Figure B 45 – Pie Chart of Product Environmental Impact

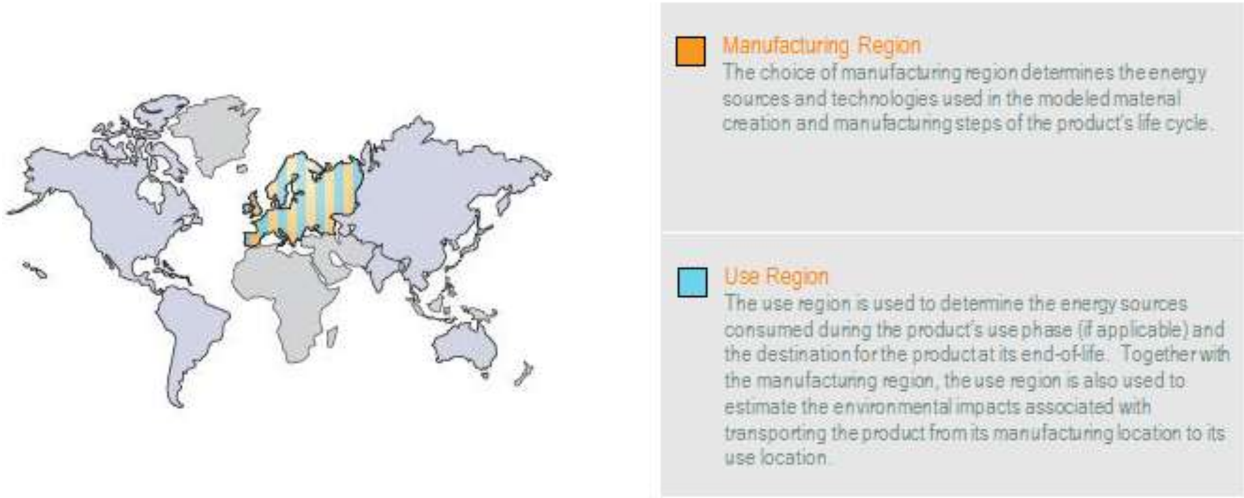

Figure B 46 -Manufacturing and Use Region s

B 32 Standards

INTERNATIONAL	
Fluid power systems and components. Graphical symbols and circuit diagrams. Circuit diagrams	ISO 1219-2:2012
Fluid power systems. O-rings. Inside diameters, cross-sections, tolerances and designation codes	ISO 3601-1:2012
Connections for general use and fluid power. Ports and stud ends with ISO 228-1 threads with elastomeric or metal-to-metal sealing. Threaded ports	ISO 1179-1
Design method for ductile iron pipes	ISO 10803:2011
Industrial valves. Isolating valves for low temperatures application. Part 1. Design, manufacturing and production testing	BS ISO 28921-1
Non-destructive testing of steel tubes. Automated electromagnetic testing of seamless and welded (except submerged arc-welded) steel tubes for the verification of hydraulic leaktightness	ISO 10893-1:2011
Non-destructive testing of steel tubes. Automated eddy current testing of seamless and welded (except submerged arc-welded) steel tubes for the detection of imperfections	ISO 10893-2:2011
Non-destructive testing of steel tubes. Magnetic particle inspection of seamless and welded ferromagnetic steel tubes for the detection of surface imperfections	ISO 10893-5:2011
EUROPEAN	
Metallic industrial piping. General	BS EN 13480-1:2012
Metallic industrial piping. Materials	BS EN 13480-2:2012
Metal industrial piping. Design and calculation	BS EN 13480-3:2012
Metallic industrial piping. Additional requirements for buried piping	BS EN 13480-6:2012
Liquid pumps. Safety requirements. Agrifoodstuffs equipment; Design rules to ensure hygiene in use	BS EN 13951:2012

Pressure equipment. Quantities, symbols and units	BS EN 764-2:2012
Unalloyed steel plumbing fittings. Fittings with press ends for unalloyed steel tubes	BS EN 10358
Industrial valves. Testing of metallic valves . Tests, test procedures and acceptance criteria. Supplementary requirements	BS EN 12266-2:2012
Pipes and fittings of longitudinally welded stainless steel pipes with spigot and socket for wastewater systems. Part 4. Components for vacuum drainage systems and for drainage systems on ships	BS EN 1124-4
Effects of electromagnetic interference on pipelines caused by high voltage a.c. electric traction systems and/or high voltage a.c. power supply systems	BS EN 50443:2011
Evaluation of a.c. corrosion likelihood of buried pipelines applicable to cathodically protected pipelines	BS EN 15280
Petroleum and natural gas industries. Pipeline transportation systems	BS EN 14161:2011
District heating pipes. Preinsulated bonded pipe systems for directly buried hot water networks. Pipe assembly of steel service pipe, polyurethane thermal insulation and outer casing of polyethylene	BS EN 253 AMD1
Ductile iron pipes, fittings, accessories and their joints for water pipelines. Requirements and test methods	BS EN 545:2010
Leak detection systems.	BS EN 13160

Table B 11 – International and European Standards (cen.eu ,2013) (iso.org,2013)

BRITISH	
Specification for mechanical fittings for use in the repair, connection and renovation of pressurized water supply pipelines. Requirements and test methods	BS 8561
Thermal insulation of pipework, ductwork, associated equipment and other industrial installations in the temperature range of -100°C to +870°C. Code of practice	BS 5970:2012
Pipeline systems. Steel pipelines on land and subsea pipelines. Code of practice for integrity management	PD 8010-4:2012
Specification for flanges and bolting for pipes, valves and fittings	BS 10:2009

Table B 12- British Standards (BSIgroup , 2013)

B 33 Patents

Description	Patent Number	Date
EUROPEAN		
An improved pipeline pig and launching apparatus	EP2454516 (A2)	23/05/2012
Pig receiver	EP2422890 (A1)	29/02/2012
Apparatus for moving a pig through a pipeline and a sealing device for such an apparatus	EP1046856 (A2)	25/10/2000
Pipeline pig with a speed control bypass	EP0955103 (A1)	10/11/1999
Autonomous mobile robot system for sensor-based and map-based navigation in pipe networks	EP0847549 (A1)	17/06/1998
Pipeline pig	EP0823293 (A2)	11/02/1998
Pig launcher/receiver for pipelines.	EP0616167 (A1)	21/09/1994
Pig for pipeline systems.	EP0474233 (A1)	11/03/1992
Elastomeric disc for use on a pipeline pig.	EP0427538 (A1)	15/05/1991
Pipeline pig.	EP0405075 (A1)	02/01/1991
Bend detector pig	EP0388554 (A2)	26/09/1990

Pipeline pig	EP0195797 (A1)	01/10/1986
A pipeline cleaning pig having magnetic pickup means.	EP0056892 (A1)	04/08/1982

Table B 13 – European Patents (IPO, 2013)

INTERNATIONAL

Loading apparatus of steam generation inspection robot	KR20120063228 (A)	15/06/2012
Creeping type robot for pipeline inspection	CN202252615 (U)	30/05/2012
Non-destructive inspection pipeline robot	CN202252613 (U)	30/05/2012
Six-freedom-degree pipeline robot	CN202252614 (U)	30/05/2012
Pipe robot	CN102392926 (A)	28/03/2012
Robot for inspection and/or processing of sewer pipe for four-wheeled driving trolley, has connection component for connecting cable, and signal connection provided between camera and component and formed in form of radio connection	DE102011018210 (A1)	22/03/2012
Pipe inner inspecting mobile robot and apparatus	KR20120023415 (A)	13/03/2012
Heat pipe inspection robot of steam generation for nuclear power generation	KR20120019224 (A)	06/03/2012
Balance-adjustable rolling type brush assembly of central air conditioning pipe cleaning robot	CN202146890 (U)	22/02/2012
Mobile Robot	KR20120014379 (A)	17/02/2012
In-tube creeping robot	CN202040480 (U)	16/11/2011
Robot for removing impurities by moving in pipe	WO2011132817 (A1)	27/10/2011
Peristaltic robot in pipe	CN102162565 (A)	24/08/2011
Multifunctional driving mechanism for pipe robot	CN201897039 (U)	13/07/2011
Method for improved crack detection and discrimination using circumferential magnetic flux leakage	US2009234590 (A1)	17/09/2009
Intelligent PIG	PCT/GB2002/002277	30/05/2002
Apparatus for use in a pipeline	WO9717566 (A1)	15/05/1997
Variable speed PIG for pipeline	CA2042338 (A1)	11/11/1992

Table B 14 – International Standards (IPO, 2013)

Acronyms

A-E	• ABS – Acrylonitrile Butadiene Styrene • AE – Acoustic Emission • BLDC – Brushless Direct Current (ref. to motors) • BMS – Battery Monitoring System • CAD – Computer Aided Design • CP – Cathodic Protection • CSA – Cross Sectional Area • CV – Constant Velocity • CVT – Continuously Variable Transmission • DN – Diametre Nominel or Nominal Diameter • EMAT – Electromagnetic Acoustic Transducer • EMF – Electro-motive Force • ER – Electrical Resistance • ET – Eddy Current Testing • EV – Electric Vehicle
F-J	• FAC – Flow Accelerated Corrosion • FEA – Finite Element Analysis • HDD – Hard Disk Drive • ID – Internal Diameter • ILI – Inline Inspection Tool • ISO – International Standards Organisation
K-O	• Li-Ion – Lithium ion • MFL – Magnetic Flux Leakage • MSD – Mass Spring Damper • NiCd – Nickel Cadmium • NiMH – Nickel-metal Hydride • OD – Outer Diameter
P-T	• PIG – Pipeline Inspection Gauge • PP – Polypropylene • PWM – Pulse Width Modulation • ROV – Remote Operated Vehicle • SBC- Single Board Computer • SCC – Stress Corrosion Cracking • SEM – Scanning Electron Microscopy • SSD – Solid State Drive • SSR – Solid State Relay • UT – Ultrasonic Testing
U-Z	• XRF – X-Ray Fluorescence

Nomenclature

$l \rightarrow Lenght$

$r \rightarrow (inside) Radius R \rightarrow Outside\ Radius$

$\theta \rightarrow Angle\ (could\ be\ in\ degrees\ or\ radians)$

$F_{RR} \rightarrow Frictional\ Rolling\ Resitance$

$c_I \rightarrow Rolling\ Resistance\ Coefficient$

$W \rightarrow Weight$

$F_R \rightarrow Reaction\ Force$

$F_D \rightarrow Driving\ Force$

$T \rightarrow Torque$

$G \rightarrow Modulus\ of\ Rigidity\ or\ Shear\ Modulus$

$J \rightarrow Polar\ Second\ Moment\ of\ Area$

$\tau \rightarrow Shear\ Stress$

$\omega \rightarrow Angular\ Velocity$

$N \rightarrow Number\ of\ (see\ equation\ used\ in)$

$VR \rightarrow Velocity\ Ratio$

$H \rightarrow Distance\ Between\ Two\ Shafts$

$l_0 \rightarrow Length\ of\ Open\ Belt$

$d_l \rightarrow Diamter\ of\ Larger\ Pulley$

$d_s \rightarrow Diamter\ of\ Smaller\ Pulley$

$C \rightarrow Centre\ Distance\ Between\ Pulleys$

$\alpha \rightarrow Angle\ of\ Wrap\ \ or\ Centripetal\ Acceleration$

$\beta \rightarrow Angle\ Between\ Contact\ Point\ and\ Vertical$

$t \rightarrow Thickness\ or\ Time\ (equation\ dependent)$

$\rho \rightarrow Density$

$m \rightarrow Mass$

$V \rightarrow Volume$

$v \rightarrow Velocity$

$P \rightarrow Power$

$\Sigma \rightarrow Sum\,of$

$k \rightarrow Spring\ Constant$

$\zeta \rightarrow Damping\ Ratio$

$c \rightarrow Damping\,Coefficient$

$BM \rightarrow Bending\ Moment$

$\sigma \rightarrow Stress$

$M \rightarrow Moment$

$I \rightarrow Second\ Moment\ of\ Area$

$SF \rightarrow Shear\ Force$

$A \rightarrow (Cross\ Sectional)Area$

$\sigma_{fs} \rightarrow Flexural\,Strength$

$F_f \rightarrow Applied\ Load\ in\ Rupture$

$E \rightarrow Young's\ Modulus$

$\varepsilon \rightarrow Strain$