In-line Pipe Inspection Robot

(ATOM)

By

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FINAL YEAR PROJECT REPORT

We hereby recommend that the dissertation prepared under our supervision by: Syed Moiz Ashraf (NUST-2012-01246), Muhammad Arslan Thaheem (NUST-2012-00258) and Muhammad Bilal Anjum (NUST-2012-01478) Titled: In-line Pipe Inspection Robot be accepted in partial fulfillment of the requirements for the award of Bachelors of Engineering in Mechanical Engineering degree with (A grade)

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Declaration

We certify that this research work titled "*In-line Pipe Inspection Robot"* is our own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Copyright Statement

Dedicated to our parents

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Chapter 1
Introduction

1.1 Background

Pakistan, like all other countries which are dependent on fossil fuel for fulfilling their energy requirements, has a vast network of pipelines running through its land. Oil and Gas worth millions of dollars gets transported through these pipelines. Yet unlike the developed countries, the inspection regime employed in Pakistan for the health inspection of these pipelines is primitive to say the least. Leaving hundreds of miles of pipelines, vulnerable to failure. Generally, pipelines failures occur because of variety of reasons including, but limited to, corrosion, crack development and geometrical deformation. The need for Non-Destructive Evaluation (NDE) of these pipelines is ever so more so that any discrepancies in pipeline's health can be pointed out prior to them leading to a pipeline failure.

1.2 Aims and Objectives

The aim of our project was initially to work on the development of Non Destructive Evaluation Techniques. But the absence of any feasible device needed for mounting the NDE Equipment meant that the first step was to develop an innovative vehicle which would be able to navigate in the standard Oil & Gas pipelines fairly easily. So the aims and objectives of our project finally evolved into following:

- Design and development of an innovative In-Line Inspection Vehicle which would be able to

  a. Transverse Linearly in the pipeline
  b. Handle Diametric Variations within pipelines
  c. Handle Standard Inclinations up till 45 degrees
  d. Conduct Visual Inspection (Initially)

1.3 Research Methodology

While designing the In-Line Inspection vehicle (ATOM), at every stage a literature review was conducted to find the best available solution available to the problem at hand. Then Team Atom either proposed an idea of its own and conducted a comparison of it with the best available solution or employed the best available mechanism after comparing it with other available options.

1.4 Thesis Structure

Following are the fundamental chapters which will be encompassed in this thesis

- **Chapter 2: Literature Review**
  - This chapter explains the methodology employed for conducting literature review, stages at which it was conducted, basic learning outcomes of the literature review and ideas taken from different available researches.

- **Chapter 3: Mathematical & Solid Modelling**
  - This chapter will give a brief overview of all the mathematical equations derived during the design of the In-line Inspection Robot. All the assumptions made while deriving those mathematical expressions will be explained in detail along with the terminologies used. All the solid modelling has been conducted in Solidworks and this chapter will include visuals taken from Solidworks while designing the robot.

- **Chapter 4: Analysis (FEM)**
  - All the stress analysis conducted after solid designing and all the kinematic analysis performed will be described here in this chapter in detail.

- **Chapter 5: Fabrication**
  - This chapter encompasses all the activities performed during the fabrication of ATOM

- **Chapter 6: Conclusion and Future Considerations**
  - Future work required to make ATOM a commercialized product have been discussed in detail in this chapter.

Chapter 2

Literature Review

2.1 Need for In-Line Inspection Tools

According to a survey, the annual costs associated with the structural damages resulting of corrosion are more than the combined cost incurred because of the natural disasters like Hurricanes and cyclones. Similar findings have been obtained in other developed countries like Japan and UK and that is why special emphasis is being laid in those countries for reducing the impact of corrosion on mechanical structures. Even though designers cater for corrosion while designing a pipeline and estimating it’s average pipelines, but corrosion is a kind of failure instigator which is very unpredictable in nature and can appear in any pipeline at any stage. Hence it is imperative that proper pipeline health monitoring regime is in place which can help point out increased corrosion rates, crack developments and other mechanical failures in time. So that important economical and human losses can be avoided.

The famous trans-Alaska pipeline (the backbone of American energy sector), which is a 800 mile conduit, was commissioned in late 1970s and was supposed to transport petroleum products till 2011. But due the presence of inspection regime including In-Line Inspection tools, the pipeline remained in such a good health that in 2003, after conducting a study, the pipeline was declared fit for service till 2034. Meaning that the pipeline got a new lease in life by almost 23 years.

2.2 Prevalent Inspection Regime in Pakistan

Although Pakistan has a hug network of pipelines yet inspection of pipelines for predicting failures remains an area which the oil & gas companies haven’t really been paying much focus on. Most production companies based in Pakistan have a Field Maintenance department which is charged with the responsibility of maintaining the pipelines in good health. There is a distinction between maintenance and inspection but the line separating the two phenomena appear very dim in Pakistan where both these concepts are considered alike. In reality, effective maintenance of pipelines isn’t possible without an effective inspection regime. Following are the few technologies which are used by production companies in Pakistan.

2.2.1 Ultrasonic Thickness Gaging

Ultrasonic Thickness Gaging is a very effective Non Destructive Testing technique which gives very accurate results about the thickness of the material being tested. It is a versatile measuring technology which needs to access only one side of the job (material under work), unlike how Vernier caliper and screw gauge function. Sound waves can be produced in a broad range of frequencies. Ultrasounds are sound waves which are higher than the audible frequency range and have a very low pitch. Ultrasonic testing is performed with sound waves ranging from 500 kHz to 20 MHz. A probe (called ultrasonic transducer) emitting Ultrasonic waves is attached with the material whose thickness is desired to be measured, the sound waves travel through the material and as soon as the material ends, a dissimilarity in materials appears, sound waves reflect back and are received by a receiver. Time taken by sound waves in traveling back to the receiver is calculated and since the speed of sound waves is known. The total distance travelled by the waves is calculated. This distance is equal to the thickness of the job. This method effectively gives the thickness of pipelines at different points and by comparing the thickness of pipeline at a particular point at one time and thickness at the same point at some time ago, corrosion rate can be calculated. This process can involve a lot of human errors since a human operator is handling the probe and is doing a lot of manual calculations. Also this process is not conducted all across the pipeline but at fixed points of pipeline which are apparent on ground. From the information received from these points, an estimate is made regarding the condition of regions of inaccessible portions of pipelines which may be buried underground or under sea water. This makes this method less effective and leaves pipelines vulnerable to failure. A better way of using this technique is to mount Ultrasonic thickness testing equipment on an In-Line Inspection tool.

2.2.2 Electrical Resistance Monitoring (ER Probes)

This is an “on-line” corrosion monitoring process which is widely used in Pakistan. The process is fairly simple to understand but has limitations of its own. This process involves the probes which are installed inside the pipeline with a sensing material which is pretty much similar as that of the pipeline. With time corrosion kicks in and these probes can be removed after particular time intervals, taken to the lab for analysis and rates of corrosion can be calculated. This technique is pretty useful for almost all types of corrosive environments. With time the sensing element in the probe decreases in size and the resistance changes. The initial resistance of the probe is compared with the resistance at a particular stage and this change in resistance helps measure the rate of corrosion.

The electrical resistance of a metal or alloy element is given by:

$$R = r \cdot \frac{L}{A}$$

Where

L = Element length

A = Cross sectional area

r = Specific resistance

2.2.3 Corrosion Coupons

This method employs one of the oldest techniques for measuring corrosion rate that is the Weight Loss technique. Coupons of particular metal are inserted in the pipeline and are removed after a given time interval, the decrease in the weight of these coupons is calculated and from it the corrosion rate is inferred. This process is simple in a way that it only requires an aptly shaped coupon, method of inserting that coupon in the pipeline and safe removal of it from the pipeline at desired time.

Following formulas are used for measuring the Corrosion Rate

$$\text{Corrosion Rate (CR)} = \frac{\text{Weight loss (g)} * K}{\text{Alloy Density (g/cm}^3\text{)} * \text{Exposed Area (A)} * \text{Exposure Time (hr)}}$$

The constant can be varied to calculate the corrosion rate in various units:

Desired Corrosion Rate Unit (CR)	Area Unit (A)	K-Factor
mils/year (mpy)	in^2	5.34×10^5
mils/year (mpy)	cm^2	3.45×10^6
millimeters/year (mmy)	cm^2	8.76×10^4

Table 2. 1: Desired Corrosion Rate Unit

2.2.4 Hydrostatic Testing

This is one of the most primitive techniques available for detecting cracks in the pipelines and has long been considered obsolete in developed countries due to its potentially hazardous effects on the pipeline's health. This process involves pumping of water at pressures much higher than the oil and gas contents in that pipeline are expected to flow. Generally at twice the pressures. This gives the engineers an idea if there is a leakage in the pipeline or not but while testing for leakage, this technique because of high pressures can initiate cracks which might cause failure in later stages.

All of the methods discussed up till now involve measuring corrosion rate only with no really scientific method allocated for crack detection and all of these methods are non–Inline methods which means that measurements can only be taken from specific points only.

2.2.5 Pipe Inspection Gauge

One of the In-Line Inspection tool which has been able to make its way in Pakistan's Oil & Gas Industry is Pipe Inspection Gauge, though not in its purest form though. Pipe Inspections Gauges, often referred to as PIGs are tools which run inside Oil & Gas pipelines with the flow of the fluid in the pipelines. At international level Smart PIGs which are mounted with state of the art gadgetry for inspection are now being used. But these PIGs come with an inherent problem, these PIGs cannot explore pipelines of all types. There are certain stages in pipelines like gate valves and T-Bends where these PIGs become redundant and have trouble in negotiating their way. This is exactly the reason why researchers had shifted their energies in developing In-Line Inspection autonomous robots which could not only navigate easily in the pipelines but can change their size according to the pipeline's diameter. Something these PIGs weren't able to do. Coming back to the scenario in Pakistan, PIGs are only being sued for cleaning purposes with no PIG developed locally for inspection.

Figure 2. 1: PIGs used in Pakistan

Companies like PARCO do use smart pigs for inspection of their pipelines but they do so after every 5 years and they acquire the services from a third party, which is thought to be an international party since no local company in Pakistan provides these services.

The scenario presented above makes it clear that Pakistani market is in need of a locally designed and developed In-Line Pipe Inspection Robot which could deal with the contours of the pipelines and provide live information about pipeline's health to the control room covering each and every inch of the pipelines, eliminating the risk of pipeline's failure.

After careful analysis of Non Destructive Technology employed in Pakistan it is apparent that the first thing needed for In-Line Inspection of pipelines is the development of an In-Line Inspection tool (vehicle). We conducted literature review about existing ILI tools and found out that at international level a large variety of these robots have been developed for diverse working conditions. Some robots preferred speed over everything while the design of others pays more emphasis on smaller size than on anything else.

2.3 Classification of In-Line Inspection Robots

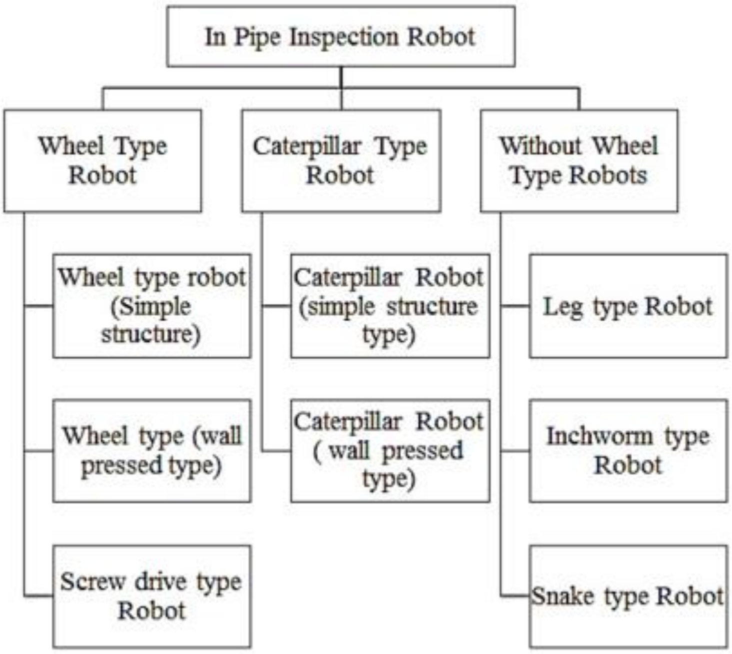


Figure 2. 2: Classification of In-Line Inspection Robots

2.3.1 Wheel Type Robots

These type of robots have wheels which help them in locomotion within the pipeline and enhance their stability. The number of wheels in this type of robot varies from case to case depending upon requirements in each case. These type of robots are further classifies since they are a broad classification themselves. Screw Type Robot uses the circular (much like screw) motion of the robot to travel inside the pipe. This type of robot has a stationary part and a rotor. The rotor rotates while the stationary part remains stationary balancing the rotation effect on the robot. These type of robots generate traction by pressing against the inside periphery of the pipeline hence increasing the normal force and hence the traction.

2.3.2 Caterpillar Type Robots

Among all the other types this is also a widely used robot type. These robots maybe belted or not depending upon the speed required. Generally they are seen belted. Belts provide better traction in slippery conditions in pipelines hence are preferable for some designers.

2.3.3 Without Wheel Type Robots

This again is a very broad category of ILI robots which includes highly articulate jointed robots allowing them great degree of ease in motion. Inchworm type and Snake Type robots are more known examples of this type. These are generally modular robots with each module performing a specialized function and all the modules are jointed together by articulate joints.

2.4 Comparison between Different Types of ILIRs

Performance indicator	Wheel type robot			Caterpillar type robot		Without Wheel Type Robot		
	Wheel type robot (Simple structure)	Wheel type (wall pressed type)	Screw drive type robot	Caterpillar Robot (simple structure type)	Caterpillar Robot (wall pressed type)	Leg type robot	Inchworm type robot	Snake type robot
Vertical Mobility	Poor	Very Good	Very Good	Fair	Very Good	Very Good	Fair	Fair
Steerablity	Very Good	Fair	Fair	Fair	Fair	Very Good	Fair	Fair
Size and shape adaptability	Poor	Very Good	Fair	Poor	Very Good	Very Good	Fair	Very Good
Flexibility of body	Rigid	Rigid	Less flexible	Rigid	Rigid	Rigid	Flexible	Flexible
Stability of robot	Poor	Very Good	Very Good	Fair	Fair	Fair	Fair	Fair
Moztion efficiency	Fair	Fair	Very Good	Fair	Very Good	Very Good	Very Good	Fair
Number of actuators	Fair	Fair	Less	Less	Less	More	More	More
Wireless control	Fair	Very Good	Fair	Fair	Fair	Poor	Poor	Poor

Table 2. 2: Comparison of different types of robot

On the basis of this comparison and keeping our conditions in mind we decided to design a wheel pressed robot which would give us maximum flexibility while navigating in the pipelines. The attachment of Non Destructive Evaluation gadgetry is not part of this project but will be employed once the mechanical prototype is fit for motion.

Chapter 3

Mathematical & Solid Modeling

Following are the main parts which have been first mathematically and then solid modelled

1. Lead Screw
2. Scissor Mechanism (Links)
3. Y-Elements
4. Platform
5. Over Head Links
6. Suspension System (Springs)
7. Wheels

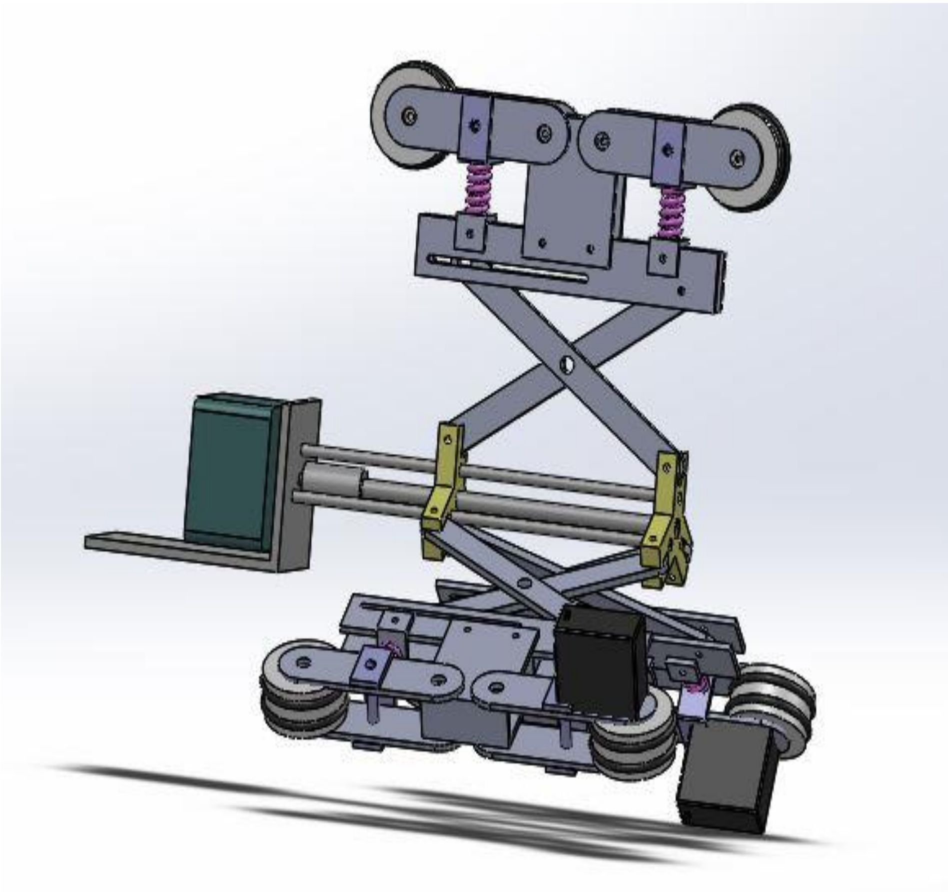


Figure 3. 1: 3D model of ATOM

Lead Screw

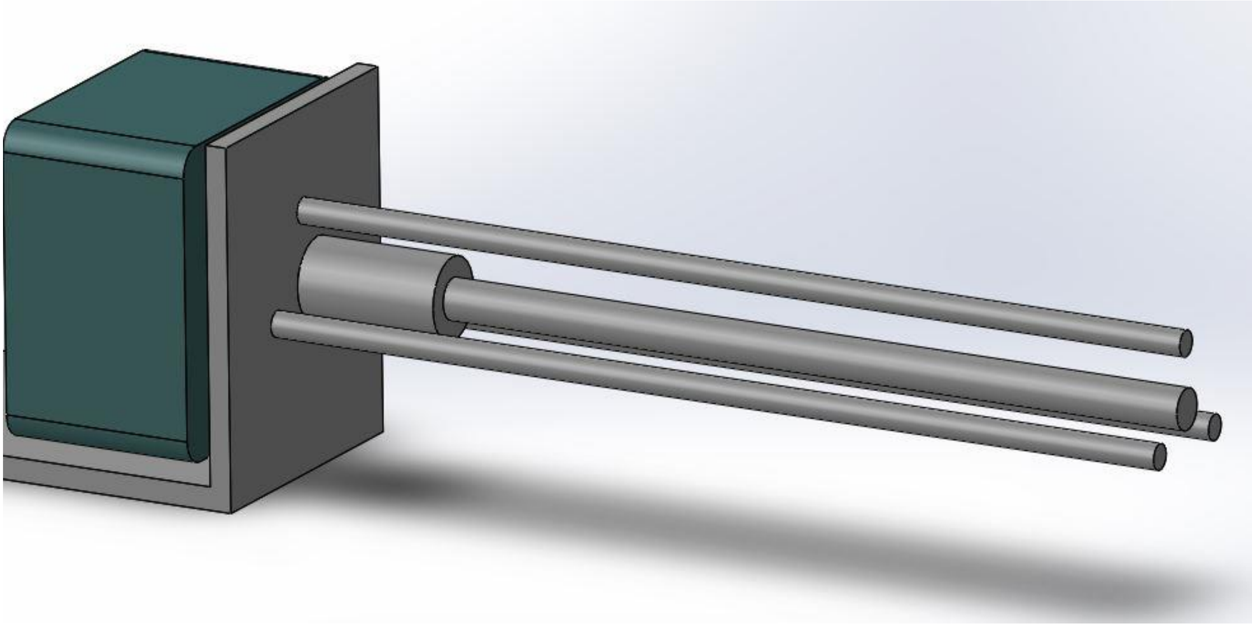


Figure 3. 2: Lead Screw

Scissor Links & Mechanism

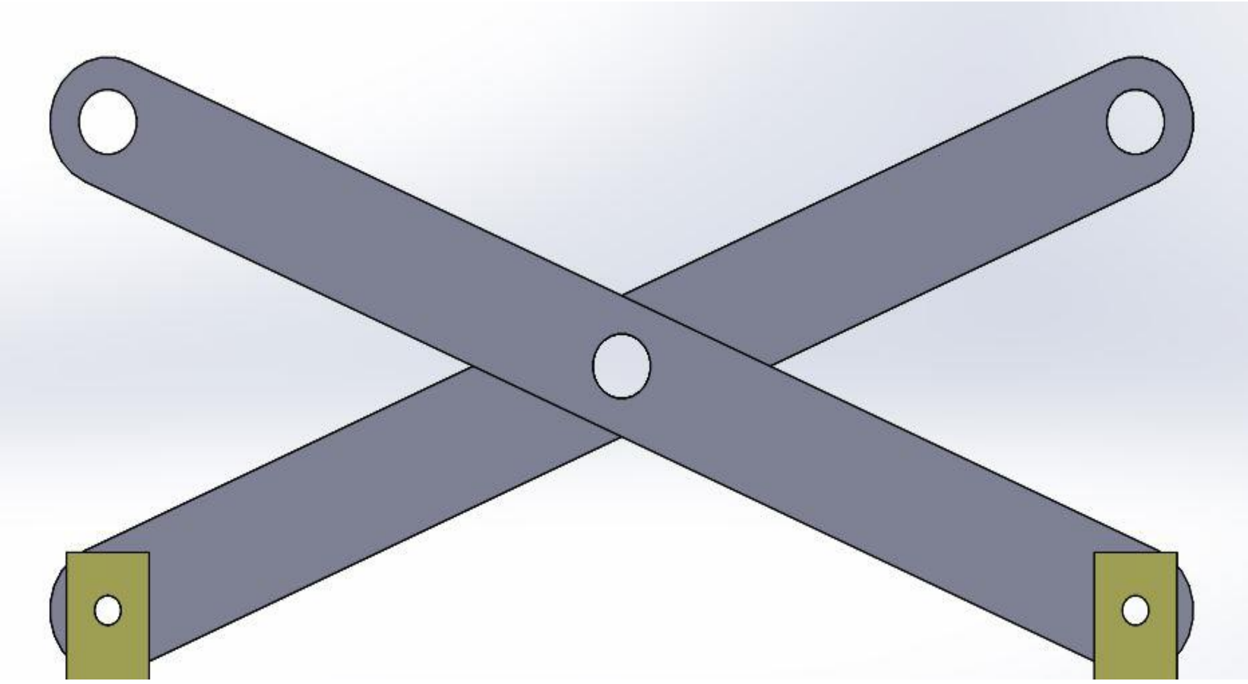


Figure 3. 3: Scissor Links & Mechanism (1)

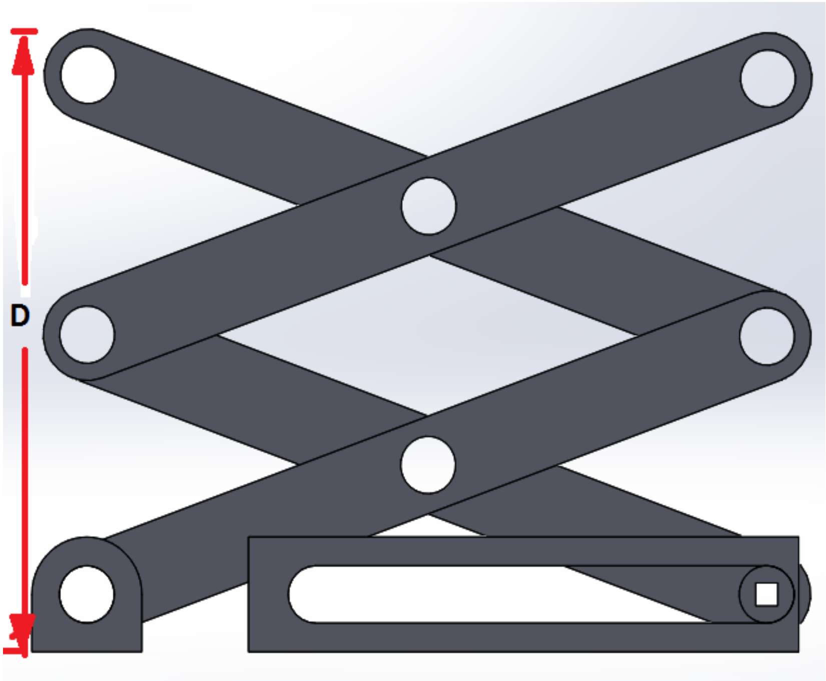


Figure 3. 4: Scissor Links & Mechanism (2)

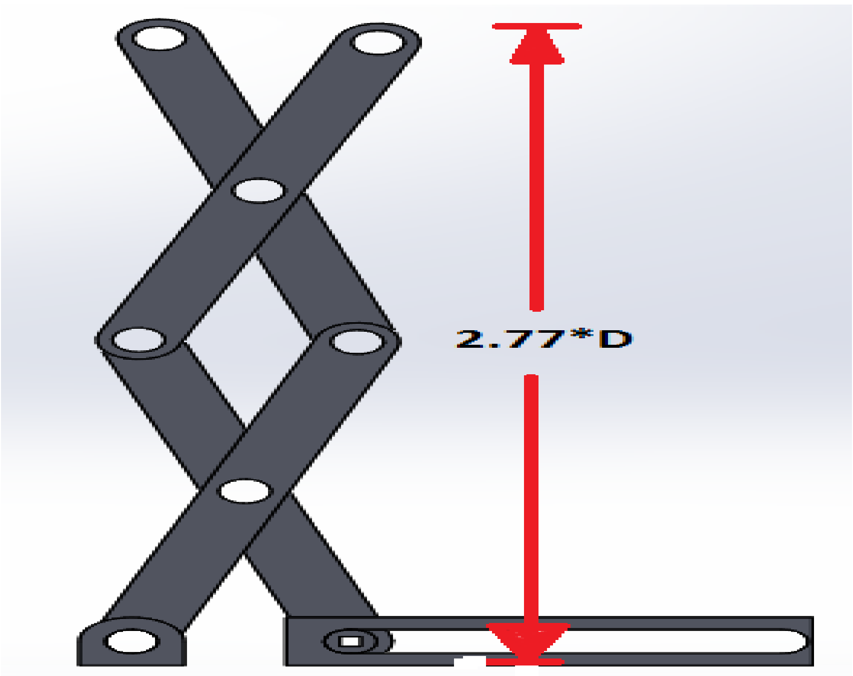


Figure 3. 5: Scissor Links & Mechanism (3)

Y- Elements

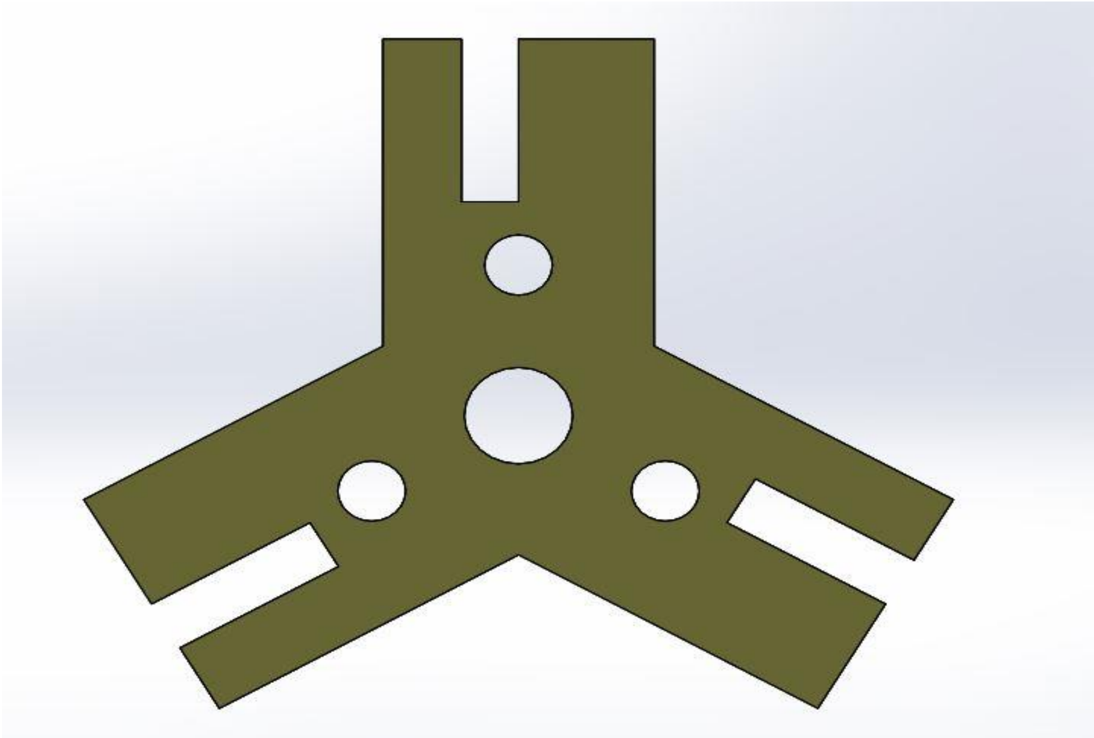


Figure 3. 6: Y-Element

Platform

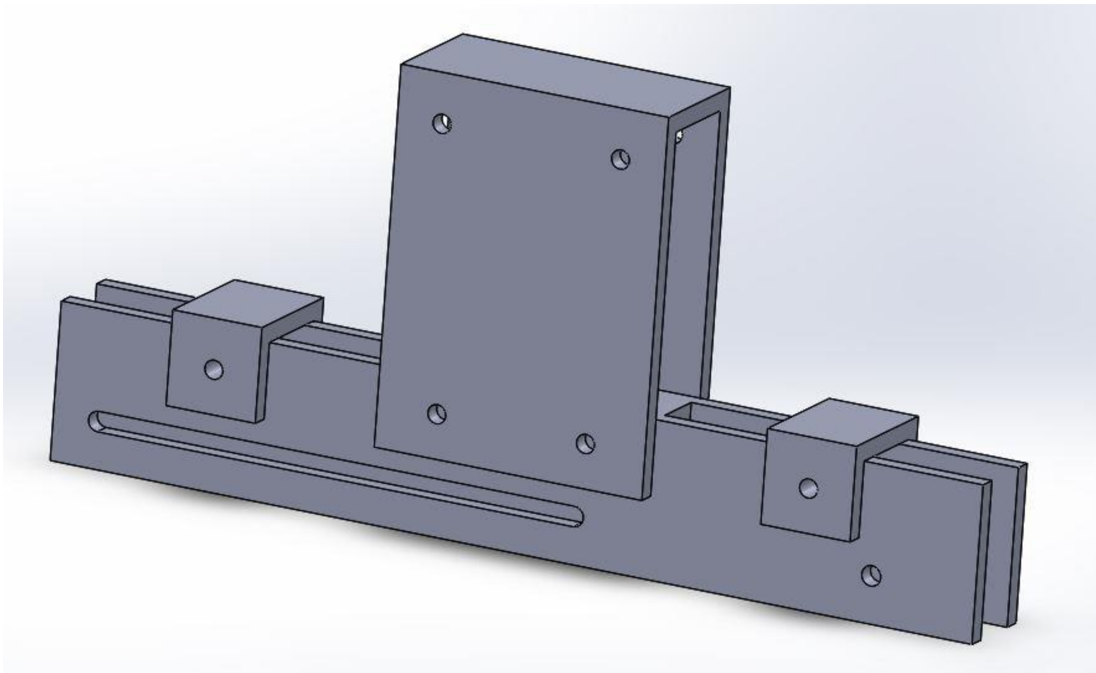


Figure 3. 7: Platform

Platform with Suspension System

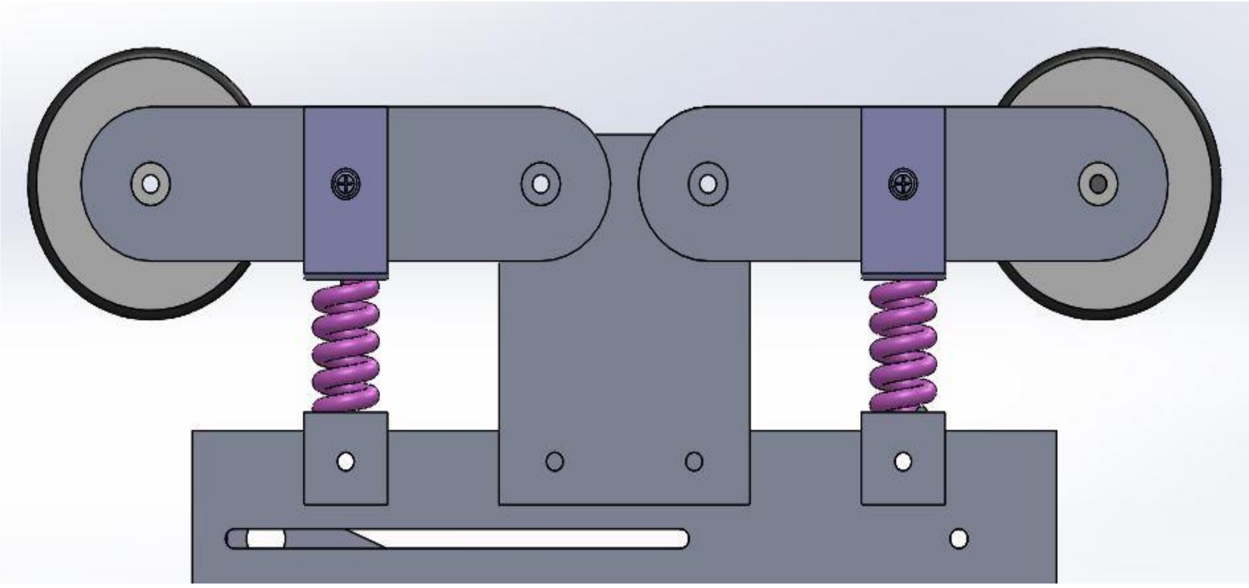


Figure 3. 8: Platform with Suspension System

Wheels

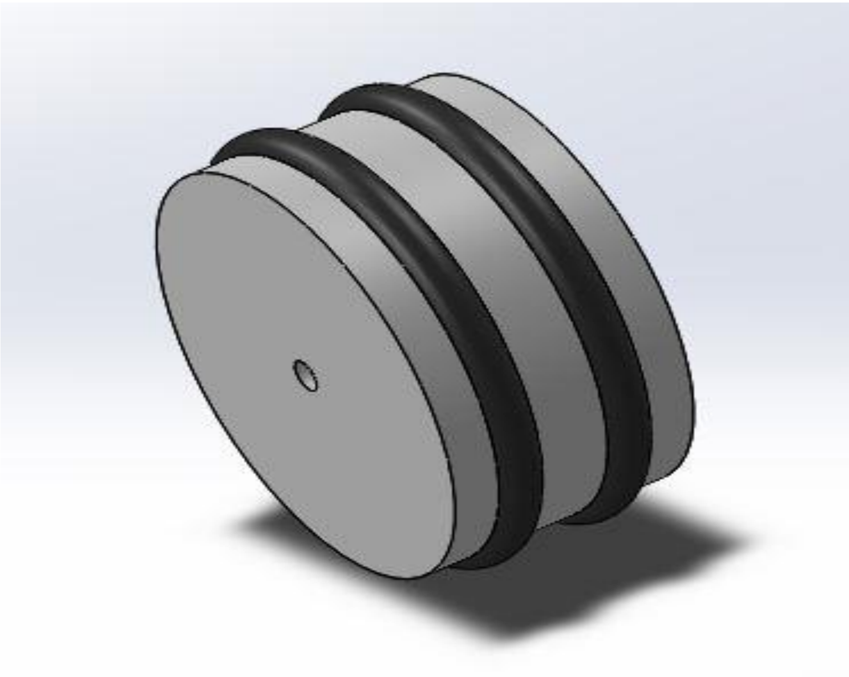


Figure 3. 9: Wheels

3.1 Lead Screw Design

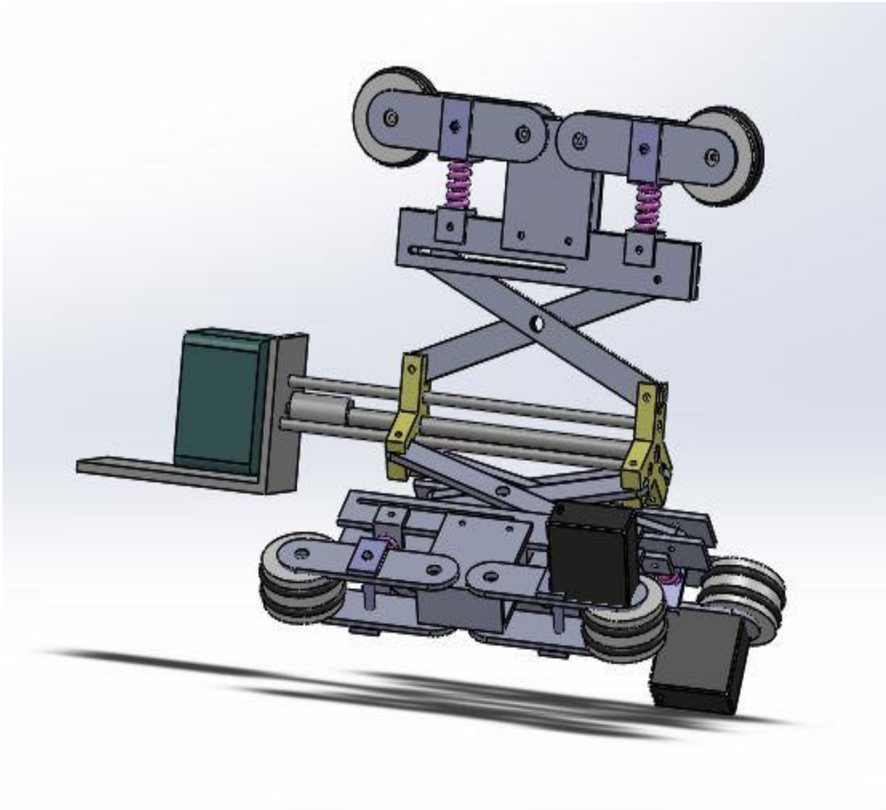
A leadscrew is a screw used as a linkage in a machine, to translate turning motion into linear motion. Because of the large area of sliding contact between their male and female members, screw threads have larger frictional energy losses compared to other linkages. They are not typically used to carry high power, but more for intermittent use in low power actuator and positioner mechanisms.

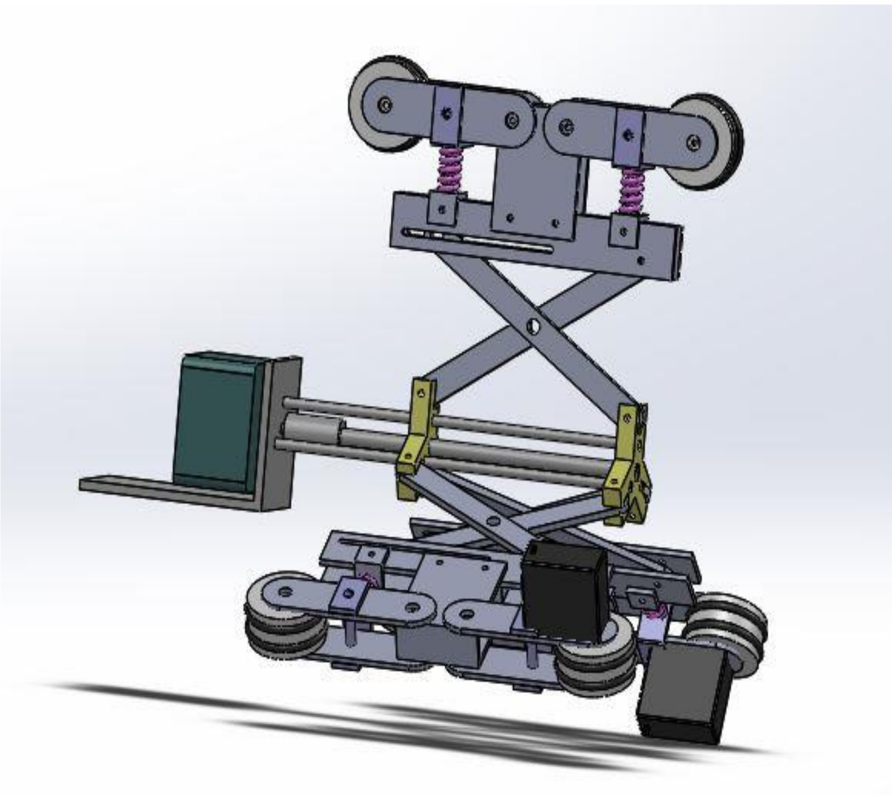
Lead screw is a self-locking mechanism and it allows the scissor mechanism to be locked at desired points. The main rival to lead screw is a balls crew which holds certain plus points over a common lead screw but after conducting a comparison for our environment, needs and availability, we decided to go with a lead screw rather than a ball screw.

3.1.1 Role of Lead Screw in Active Pipeline Diameter Adaptation

Lead screw is being used here in this robot to help change the diameter according to the pipeline's diameter. Lead screw is attached with a scissor mechanism (the details of which will be discussed in upcoming sections). As the lead screw rotates the Y-Element (also yet to be discussed) will translate linearly on the linear screw. We have two Y-Elements present in our system. One of the Y-Elements travels linearly over the lead screw while the other one sits stationary at the end of the lead screw. Scissor mechanism is attached on one side to the stationary Y-Element and on the other side is attached to the moving Y-Element.

Following illustrations help explain the active pipeline diameter adaptation and the role of Lead screw and Y-Elements.





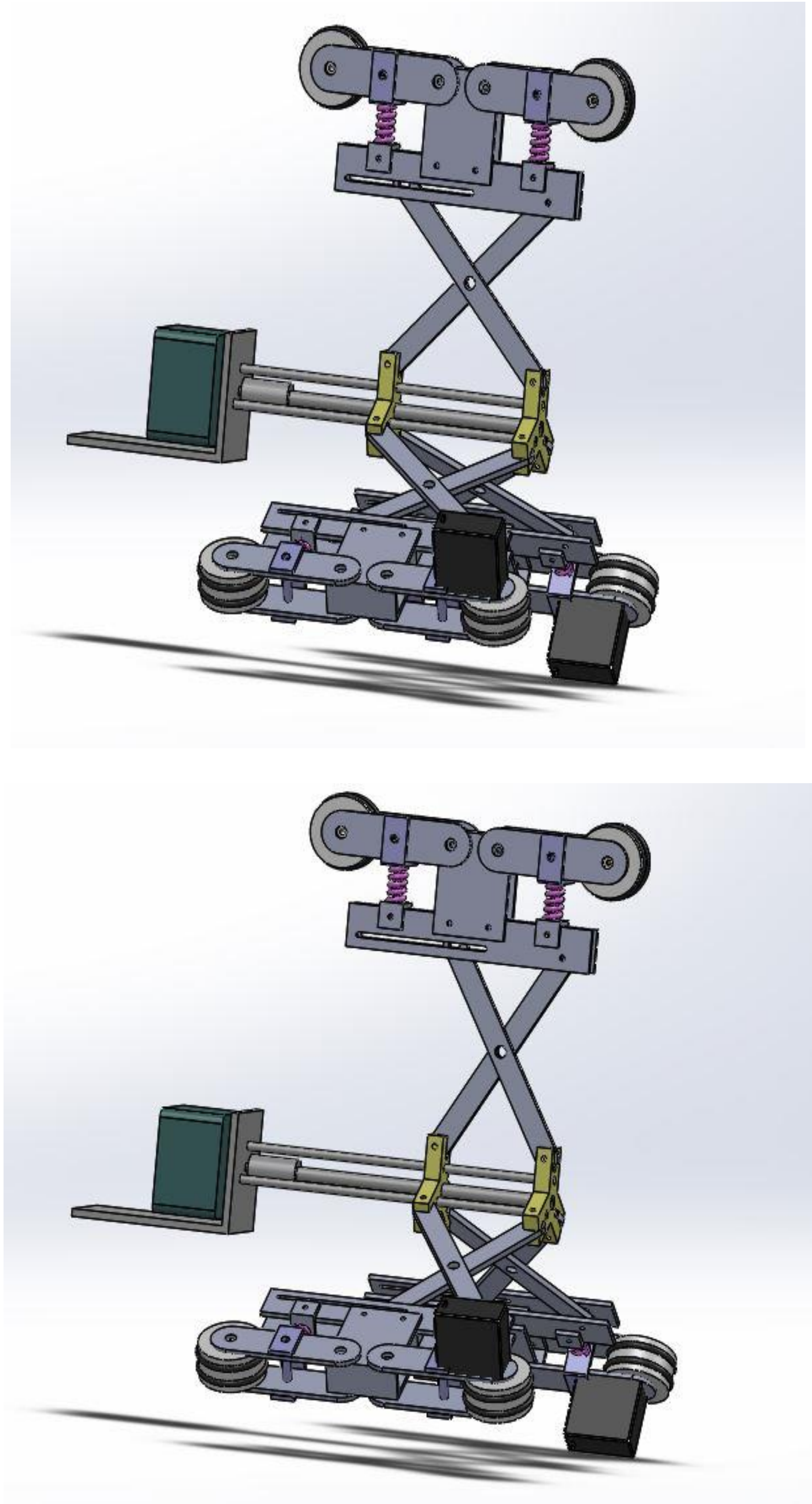


Figure 3. 10: Role of Lead Screw in Active Pipeline Diameter Adaptation

3.1.2 Design Specifications of Lead Screw

Screw Pitch:

For our application, we desire a resolution of 1 mm across each leg of the scissor mechanism whenever there is a diametric change in the pipeline.

Length of a Scissor Link = 14.7 cm

At $\Theta = 30^0$

Pipe Diameter = 13 inch

Pipe Radius = 16.5 cm

At $\Theta = 70^0$

Pipe Diameter = 18 inch

Pipe Radius = 22.96 cm

Vertical Displacement = 22.96 – 16.5 = 6.46 cm

Horizontal Displacement = 14.7 [cos (30^0) - cos (70^0)] = 7.70 cm

Horizontal: Vertical

7.70 cm: 6.46 cm

Pitch: 0.1 mm

Using this proportionality, Lead Screw Pitch = **1.25 mm**

Thrust:

The more thrust an application requires, the larger the diameter screw will be needed. That's because the screw is similar to a column subject to compression and tension.

We calculate the theoretical strength (in lbs) based on:

$$P_{cr} = \frac{14.03 \; x \; 10^6 \; x \; F_c \; x \; d^4}{L^2}$$

where P_{cr} = maximum load; F_c = end fixity factor (this is 0.25 for one end fixed, one end free; 1.0 for both ends supported; 2.0 for one end fixed, one end simple; and 4.0 for both ends rigid); d = root diameter of screw; and L = the distance between nut and load-carrying bearing.

When F_c = 1 (Both ends supported)

L = 15 cm = 5.91 in

d = 0.8 cm = 0.3152 in

$$P_{cr} = \frac{14.03 \; x \; 10^6 \; x \; 1 \; x \; 0.3152^4}{5.91^2} = 3964.86 \; lbs = 17445 \; N$$

In our case, the maximum axial applied load in 30 N so the lead screw will not buckle in our application.

Rotational Speed:

All screw mechanisms have a critical velocity — the rotational velocity limit of the screw after which vibrations develop due to the shaft's natural harmonic frequency. This is also commonly called "screw whip" and depends on the diameter and length of the screw between supports.

$$N = \frac{4.76 \; x \; 10^6 \; x \; F_c \; x \; d}{L^2}$$

where N = critical rotational speed, d = root diameter of screw, Fc is end fixity factor (0.36 for one end rigidly fixed, one end free; 1.00 for both ends supported; 1.47 for one end rigidly fixed, one end supported; and 2.23 for both ends rigidly fixed), and L = the length between bearing supports.

When F_c = 1 (Both ends supported)

L = 15 cm = 5.91 in

d = 0.8 cm = 0.3152 in

$$N = \frac{4.76 \ x \ 10^6 \ x \ 1 \ x \ 0.3152}{5.91^2} = 42955 \ RPM$$

To calculate the required rpm of a screw assembly,

$$N = \frac{60 \ x \ linear \ velocity \ (ips)}{Lead}$$

When,

Linear velocity = 0.5 cm/s = 0.197 in/s

Lead = Pitch = 1.25 mm = 0.0492 in

$$N = \frac{60 \ x \ 0.197}{0.0492} = 240 \ RPM$$

It is suggested that for most applications, the rotational speed is around 80% of the critical value but in our case, it is much lower than the critical RPM thus our lead screw will NOT undergo harmonic motion.

Helix Angle:

The helix angle can be found by unraveling the helix from the screw, representing the section as a right triangle, and calculating the angle that is formed.

We calculate the helix angle for a lead screw using:

$$\tan \lambda = \frac{l}{\pi d_m}$$

When,

l = 1.25 mm

d_m = 8 mm

Helix Angle = $\mathbf{3.10^0}$

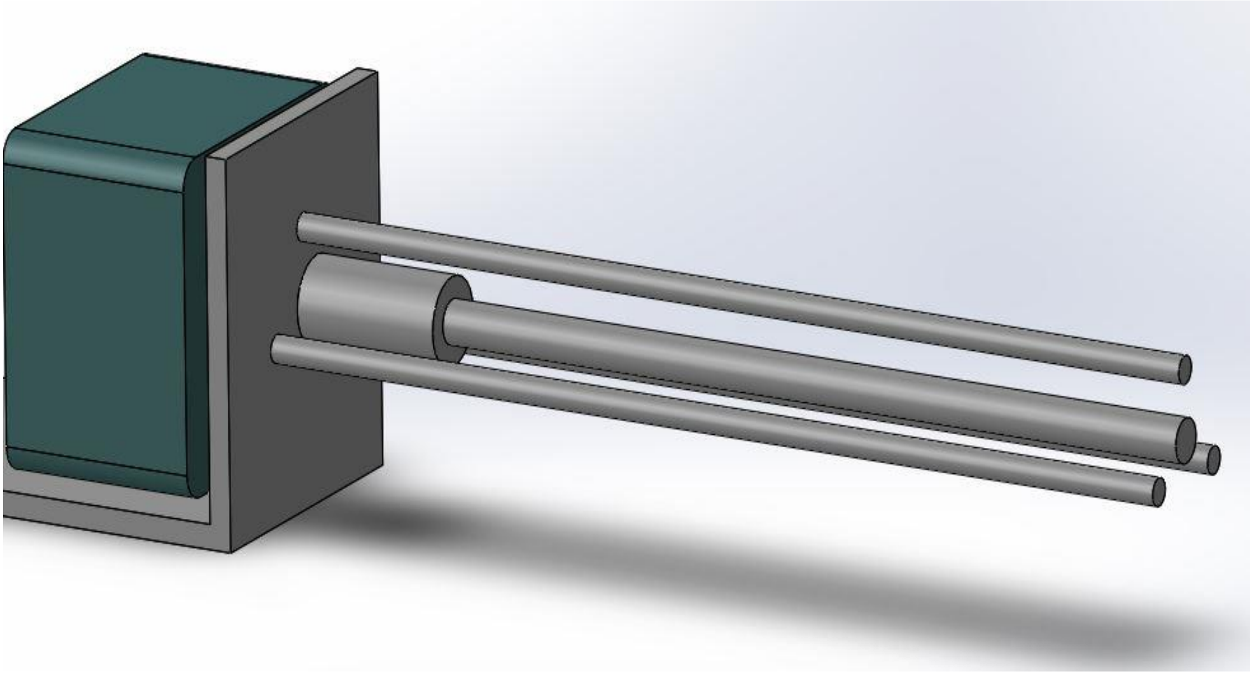


Figure 3. 11: Lead screw coupled with stepper motor

Lead screw is coupled with a stepper motor. Stepper motor is the basic source which is powering the lead screw. All the weight of the robot is basically lifted by this motor during the diameter adaptation.

3.1.3 Lead Screw Motor Torque Calculations

Stepper motors are DC motors that move in discrete steps. They have multiple coils that are organized in groups called "phases". By energizing each phase in sequence, the motor will rotate, one step at a time.

With a computer controlled stepping (Arduino), we can achieve very precise positioning and/or speed control. For our application, we require a motor which rotates in steps because we require control and precision of 1 mm during a diametric change in pipelines. Thus we used a stepper motor coupled with a lead screw to convert rotary motion into linear displacement.

Motor Efficiency

$$\%Efficiency = \frac{Tan\ (helix\ angle)}{Tan\ [helix\ angle + arcTan\ (f)]}\ x\ 100$$

When,

Helix angle = 3.1^{0}

f (coefficient of friction) = 0.2

$$\%Efficiency = \frac{Tan\ (3.1)}{Tan\ [3.1 + arcTan\ (0.2)]}\ x\ 100 = \mathbf{21}\%$$

Motor Torque:

$$Torque\ (N.cm) = \frac{Load(N)\ x\ Lead(cm)}{2\pi\ x\ efficiency}$$

When

Load = 50 N (Based on the Scissor Actuation Force)

Lead = 0.125 cm

Efficiency = 0.21

$$Torque = \frac{50\ x\ 0.125}{2\pi\ x\ 0.21} = \mathbf{4.74\ N.cm}$$

3.2 Scissor Mechanism

3.2.1 Comparison Between Scissor Mechanism & Parallelogram Linkage

Before going into the details of calculations pertaining to the scissor mechanism, it is imperative that the need of this mechanism is highlighted. This mechanism is used here to create the wheel pressed action of the robot. Once the Y-Element moves linearly, it opens the scissor mechanism and allows to increase the Normal force on the wheels hence help generate traction.

It is the first time in the history of ILI robots with ability to change their diameter that this mechanism is being used for this purpose. Prior to this mechanism various other mechanism have been used for this purpose including them Three-Bar Mechanism and the Four-Bar Mechanism.

For an In-Line inspection robot adaptability to diametric changes is an integral feature. Any modern pipeline inspection robot should be able to adapt to changes in the internal diameter of the pipeline. Adaption to pipeline diameter changes is classified into two broad ways namely Active and Passive adaptability. In active pipeline diametric adaptability, robot controls the extension and compression of its legs to remain in contact with the inside periphery of the pipeline whereas in passive diametric adaption, robot does not exercise any control on the adaptive abilities of the robot. In passive mode, springs or any other elastic mechanism produces constant force that allows the robot to continuously remain in touch with the walls of the pipe. The usage of these springs limits the radial adjustable range of robots and fail to provide the desired traction in most cases.

Scissor mechanism is a mechanical mechanism which consists of variable number of links connected to one another by pin joints. This is a one degree of freedom mechanism. We proposed this mechanism for our robot but in order to justify this mechanism we compared it with the other existing mechanisms to prove its feasibility in our given circumstances.

During its operation, a wall pressed wheel type robot should always be in contact with the inner periphery of pipeline through its wheel as the traction force required for propulsion is achieved by this wall pressed contact between the wheels and the pipeline. So, whenever the diameter of a pipeline changes, the robot should sense that and expand or contract its legs in accordance with the change in the pipeline's diameter for smooth propulsion and maintenance of the center line which is a pre-requisite for NDT activities that the robot will ultimately perform.

Methodology for Modelling & Comparison

While propelling in the pipeline, the robot should be able to negotiate the standard elbows, T and Y branches. This brings a constraint to the robot's maximum length. If a robot is supposed to pass through a particular elbow then its length cannot exceed a particular limit. The length of the robot interns adds constraint to the base length of the mechanism used for adaption to diametric changes. Hence, to achieve our desired diametric range we can't allow the base length of the mechanism to increase indefinitely.

In our study we designed two mechanisms. One scissor and the other parallelogram linkage. Both mechanisms had same base length. As base length of any mechanism is an integral factor in defining the range of its operation so we have given both the mechanisms same base length and same minimum diameter range.

3.2.2 Design of Scissor Mechanism

The scissor mechanism used had a base length of L. The minimum diameter that the scissor mechanism can measure is given as **D**. The relationship between the length of the other links and the base length is given by

$$L= \frac{D}{2*\sin\theta}$$

Where θ is the angle between the link and the base.

While θ can have any value in theory but in practical approach this θ can only have values with a certain range. We have selected the range of the theta to be 20-70 degrees.

If θ=0°, then an infinite amount of horizontal force will be required to raise the scissor mechanism from its initial state. As the value of the θ is increased the required force decreases and force transmitted increases that is the mechanical advantage starts increasing. In other words

Mechanical Advantage $\propto$ **θ**

Actuation force = F = $\frac{\boldsymbol{W}}{\boldsymbol{Tan}(\boldsymbol{\theta})}$

But here again as the angle increases it starts giving unrealistic values. For θ=90°, Force required for actuation becomes zero and Mechanical advantage becomes indefinite. Hence we have limited the maximum angle value to 70 degrees.

Now when the angle transverses from 20-70 degrees the scissor mechanism starts expanding and the maximum height is achieved at 70°.

3.2.3 Design of Parallelogram Linkage

In the design of the parallelogram linkage, same constraints were considered as used in the design of the parallelogram linkage. Since this mechanism needs an actuator which essentially protrudes out from the space occupied by the base link of the mechanism hence the total space occupied by the actuator link and the base link is considered as a base.

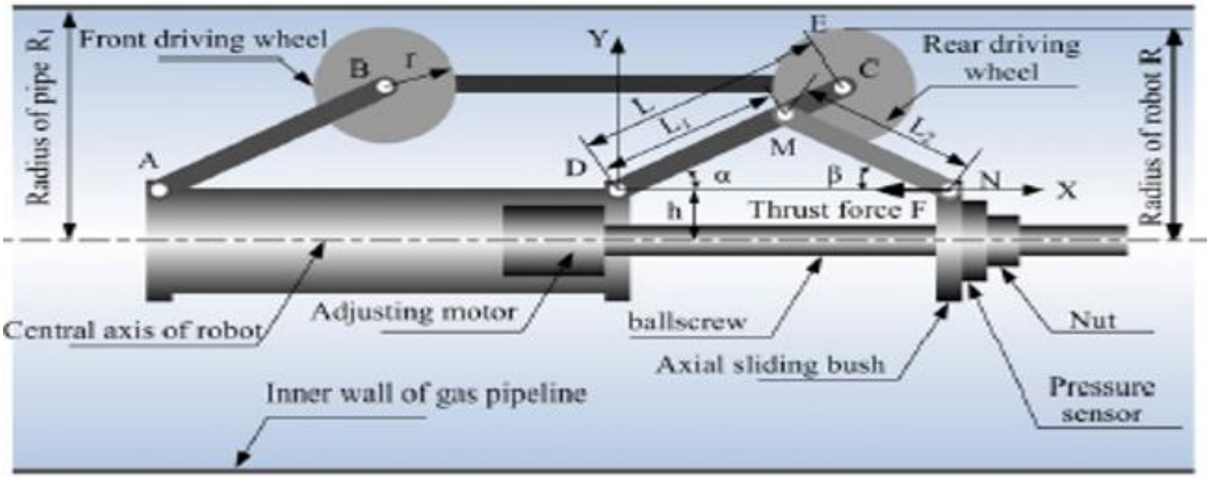


Figure 3. 12: A parallelogram wheeled leg of pipe diameter adaptive mechanism

Assumptions

L1=L2 & α=β and θ=20-70

Force for Actuation=F= $\frac{\boldsymbol{W}.(\boldsymbol{L}).(\cos\boldsymbol{\theta}+\sin\boldsymbol{\theta})}{2.(\boldsymbol{L1}).(\sin\boldsymbol{\theta}+\tan\boldsymbol{\theta}.\cos\boldsymbol{\theta})}$

3.2.4 Results

Extension achieved for same Base Length & Minimum Range of Diameter

SCISSOR MECHANISM

Minimum Height achieved by Scissor Mechanism = **D**

Maximum Height achieved by Scissor Mechanism = **2.73D**

PARALLELOGRAM LINKAGE

Minimum Height Achieved by Parallelogram Linkage = **D**

Maximum Height Achieved by Parallelogram = **2.33D**

So for same base length and minimum diameter, scissor mechanism offers more extension.

<u>**Mechanical Advantage Comparison for same Base Length & Minimum Diameter**</u>

Using F= $\frac{W}{Tan(\theta)}$ scissor mechanism & F= $\frac{W.(L).(\cos\theta+\sin\theta)}{2.(L1).(\sin\theta+\tan\theta.\cos\theta)}$ for Parallelogram Linkage, mechanical advantage for different values of θ was calculated. In linkages, mechanical advantage changes with angle. The results are in Fig.1 .From the graph it is apparent that the mechanical advantage offered by the scissor mechanism is more than the Mechanical Advantage offered by the Parallelogram Linkage when both are moved in the same angle range.

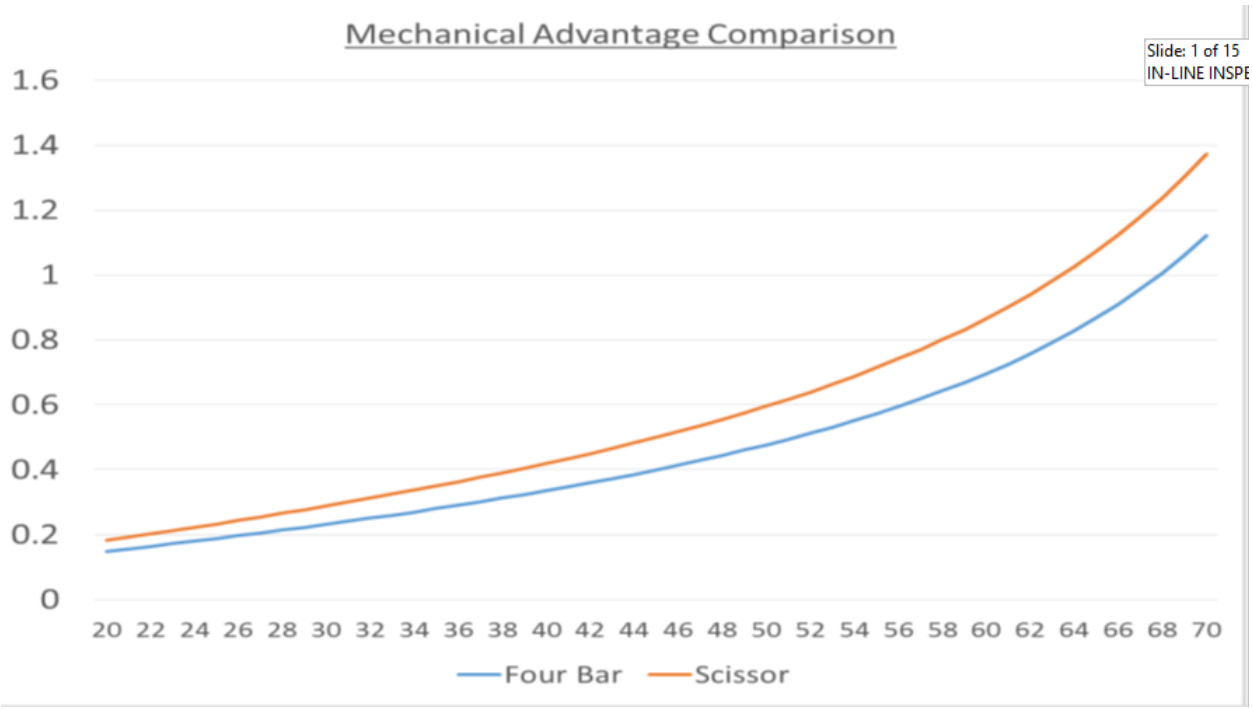


Figure 3. 13: Comparison of Mechanical Advantages

The results of this comparison clearly show that scissor mechanism is a better choice for our system.

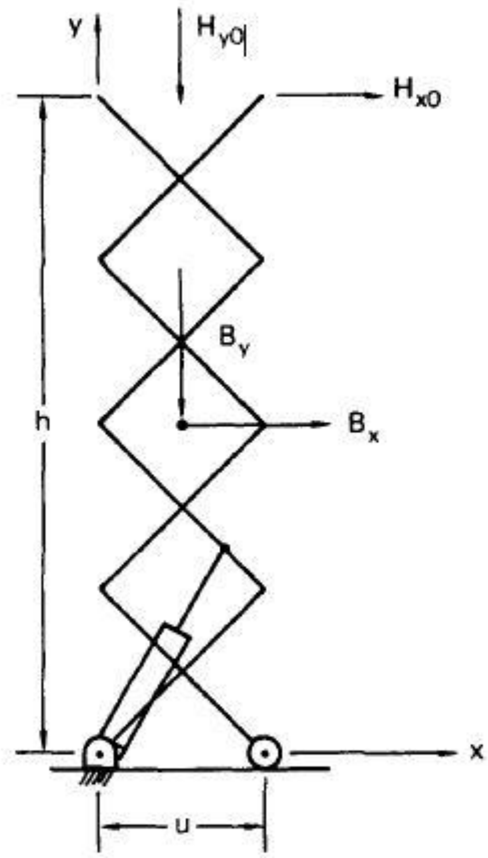
3.2.5 Mathematical Calculations for Scissor Mechanism

Principle of conservation of energy:

In this method friction forces are assumed to be zero, requiring that work in equals work out. This assumption makes it possible to calculate the actuator forces directly, simplifying the analysis of the scissor levels containing the actuator.

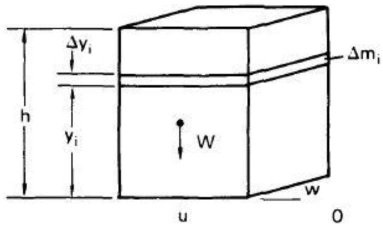
Derivation:

The distributed weight of the lift is accounted for by B_X and B_Y, acting at the center of the lift.



Four level lift loaded in the x and **y** directions.

Consider the uniform mass shown. The total potential energy stored



$$E = \lim_{\Delta m_i \to 0} \Sigma g \Delta m_i \, y_i$$

where g = acceleration due to gravity.

in the mass is given by

$$E = \lim_{\Delta y_i \to 0} \Sigma g(\rho u w \Delta y_i) \, y_i$$

$$= \int_0^h \rho g u w y \, dy \, .$$

If the weight is evenly distributed, then $\rho g u w = \frac{W}{h}$, and

$$E = \frac{W}{h} \int_0^h y \, dy \, .$$

$$= \frac{W}{h} \frac{y^2}{2} \Big|_0^h \, .$$

$$= \frac{Wh}{2} \, .$$

Now if the block height increases but the total weight stays the same, then

$$\text{Work} = E_2 \quad E_1$$

$$= \frac{W(h_2 \quad h_1)}{2} \, .$$

But $du/d\ell$ can be expressed in terms of $dh/d\ell$ as follows.

$$h = n(d^2 - u^2)^{1/2} ,$$

$$\frac{dh}{d\ell} = \frac{1}{2} n(d^2 - u^2)^{-1/2} (-2u) \frac{du}{d\ell} .$$

$$= \frac{-nu}{(d^2 - u^2)^{1/2}} \frac{du}{d\ell} .$$

$$= \frac{-n}{\tan\theta} \frac{du}{d\ell} .$$

$$\frac{du}{d\ell} = - \frac{\tan\theta}{n} \frac{dh}{d\ell} .$$

Making the appropriate substitution gives

$$-\left[\left(H_{y0} + \frac{B_y}{2}\right) + \left(H_{x0} + \frac{B_x}{2}\right) \frac{\tan\theta}{n}\right] \frac{dh}{d\ell} + F = 0 .$$

$$F = K \frac{dh}{d\ell} .$$

$$\text{where } K = \left(H_{y0} + \frac{B_y}{2}\right) + \left(H_{x0} + \frac{B_x}{2}\right) \frac{\tan\theta}{n} .$$

ℓ_0 .

where F = force exerted by the actuator

ℓ = length of the actuator

r = dummy variable.

Taking the derivative with respect to ℓ gives

$$\left(H_{y0} + \frac{B_y}{2}\right) \frac{dh}{d\ell} + \left(H_{x0} + \frac{B_x}{2}\right) \frac{du}{d\ell} + F = 0$$

In order to use this equation, an expression of *h* as a function of ***l*** must be derived. The derivative of the expression is then taken to give *dh/dl.* These functions are designated by f(*l*) and g(*l*) as shown below.

$$h = f(\ell)\ ,$$

$$\frac{dh}{d\ell} = g(\ell)\ .$$

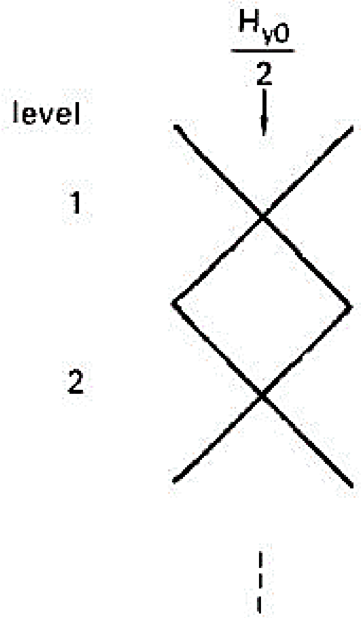
As an example of this method, the actuator forces on an n-level lift with two actuators attached to the bottom of the lift will be analyzed. The lift is assumed to be on a horizontal surface so that the weight of the lift has only the y component, B_Y. The only load that is applied at the top of the lift is H_O.

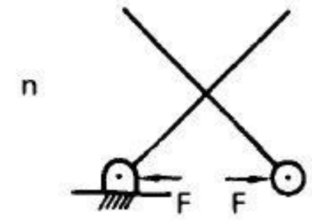
The formulas for f(*l*) and g(*l*) are derived as follows.

$$h = n\sqrt{d^2 - \ell^2}\ ,$$

$$\frac{dh}{d\ell} = n\,\frac{1}{2}\,(d^2 - \ell^2)^{1/2}(-2\ell)\ ,$$

$$= \frac{-n\ell}{(d^2 - \ell^2)^{1/2}}\ .$$





n-level lift with actuators
attached between the bottom joints.

The last equation can be expressed in terms of θ by noting that,

$$\frac{\ell}{(d^2 - \ell^2)^{1/2}} = \frac{1}{\tan\theta},$$

$$\frac{dh}{d\ell} = \frac{-n}{\tan\theta}.$$

Substituting this equation into equation gives

$$F = -\frac{1}{2}\left(H_{y0} + \frac{B_y}{2}\right)\frac{n}{\tan\theta},$$

$$= -\frac{1}{2}\left(H_{y0} + \frac{nb_y}{2}\right)\frac{n}{\tan\theta}.$$

Calculations:

$$F = \frac{1}{2}\left(H_{yo} + \frac{nb_y}{2}\right)\frac{n}{Tan(\Theta)}$$

Where

Normal Force on the wheels = H_{yo} = 23 N

Number of stages = 1

Weight of single platform = 2 N

Maximum Force is required at $\Theta = 30^0$

$$F_a = \frac{1}{2}\left(23 + \frac{1x2}{2}\right)\frac{1}{Tan(30)} = 20.8\ N$$

For a larger diametric range, this Θ becomes as low as 15^0. Using this value of Θ,

$$F_a = \frac{1}{2}\left(23 + \frac{1x2}{2}\right)\frac{1}{Tan(15)} = \mathbf{44.8\ N}$$

This F_a is used to calculate the Torque of the Lead Screw Motor.

3.3 Platform

The platform is designed to hold one link from the scissor mechanism stationary while allowing the other one to move horizontally for a length of 80 mm (8 cm). This horizontal motion of the link through a pin passing through a slot allows the robot to access pipelines ranging from diameter of 12 inch to 18 inch effectively. Three platforms are mounted on what can be termed as three legs of the robot. Each leg is supported at 120 degrees from the leg next to it. These legs provide the robot enough stability and traction for motion in our desired environment.

3.4 Suspension System

The suspension system is chiefly designed of “Compression Springs”. A careful comparison of different types of springs including extension, compression springs and their types was conducted and compression springs with the height of 2.5 cm were deemed suitable for our design.

Spring Design

Free Length =	3.05	cm
Initial Compressed length =	2.45	cm
Initial deflection =	0.6	cm
Initial Normal Force =	6	N
Spring Constant (k) =	1	N/mm

To handle 1 in diametric change, the springs need to be compressed a further 0.635 cm (2.54/4).

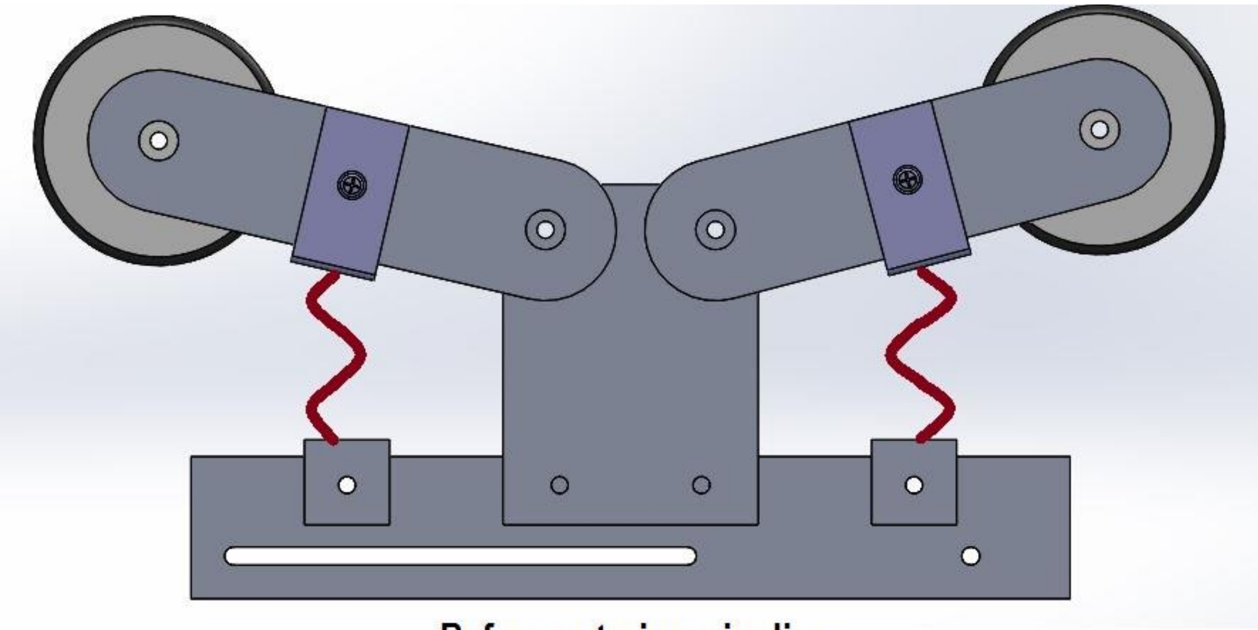
D = Max Dia (cm) =	1.5
Slenderness Ratio (free length/max Dia) =	2.0333333
Spring Index (Mean dia/Wire dia) =	12
d = Wire Dia (Mean dia/S.I) (cm) =	0.125

$$K = \frac{G\,d^4}{8\,n_a\,D^3}$$

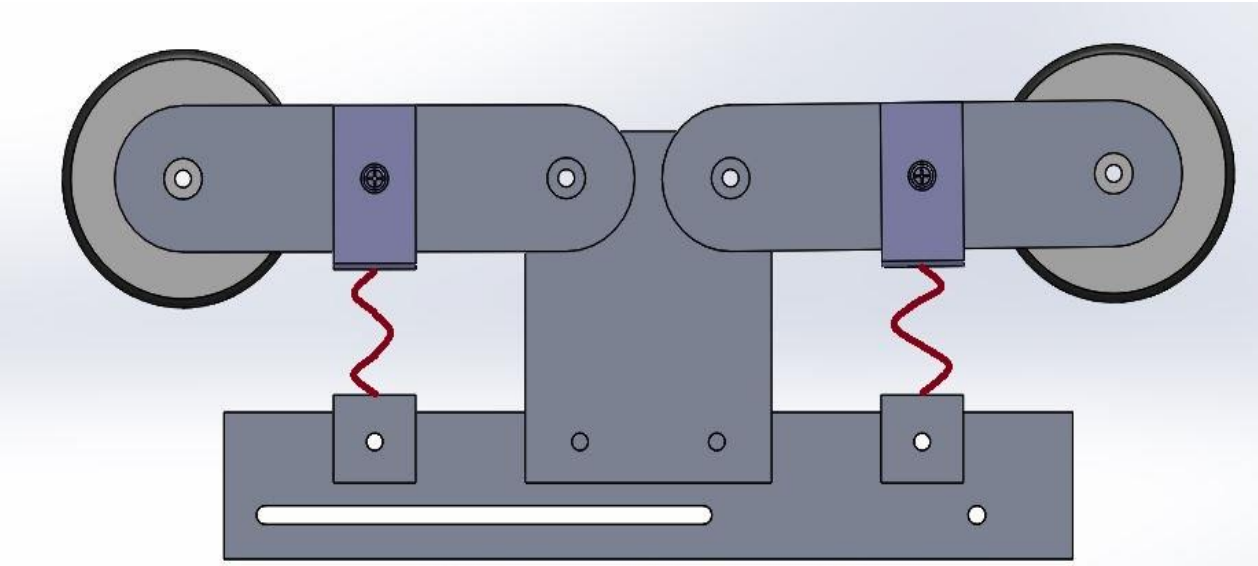
k =	0.994647	N/mm
G =	77	GPA
n_a =	6.9625289	7

Figure 3. 14: Spring design calculations

3.5 Illustrative Functioning of Platform & Suspension System for Handling Diameter Changes & Irregularities



Before entering pipeline



During propulsion in pipelines

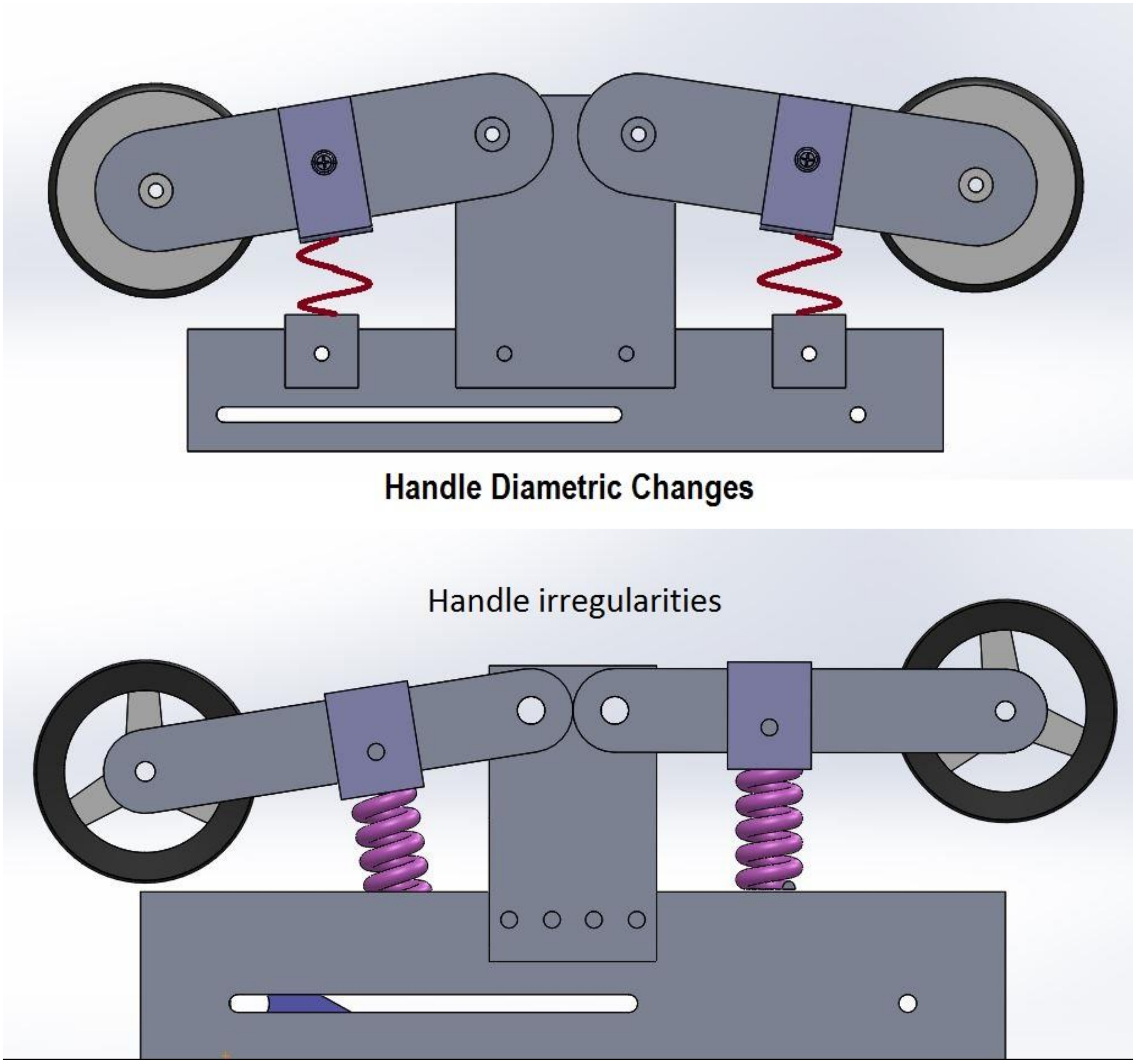


Figure 3. 15: Illustrative Functioning of Platform & Suspension System for Handling Diameter Changes & Irregularities

This sea- saw mechanism of platform is also novel design for In-Line Inspection Robots. This design along with the springs help the robot with passive diameter adaptation. For active pipeline diameter adaption, scissor mechanism can be opened and closed but for small changes and for handling any irregularities in the pipeline's internal periphery the platform and the suspension system are of great help.

3.6 Wheels & Traction Control System

For rapid propulsion of ATOM in a pipeline a propulsion system consisting of wheels and servo motors has been designed. Each leg of the robot is equipped with one servo motor and two wheels (1 Active and 1 Idol). The robot is essentially a rear wheel drive vehicle. The motion is controlled by servo motors which are user controlled through an Arduino based micro controller.

3.6.1 Drive Wheel Motor Torque Calculations

<u>Robot Specifications:</u>

Gross vehicle weight (GVW) = 50 N

Weight on each drive wheel (WW) = 25 N

Radius of wheel/tire (Rw) = 2.35 cm

Desired top speed (Vmax) = 5 cm/sec

Desired acceleration time (ta) = 5 sec

Maximum incline angle (α) = 20 degrees

Worst working surface = Greased Steel surface

To choose motors capable of producing enough torque to propel the robot, it is necessary to determine the total tractive effort (TTE) requirement for the robot:

TTE = RR + GR + FA

Where:

TTE = total tractive effort

RR = force necessary to overcome rolling resistance

GR = force required to climb a grade

FA = force required to accelerate to final velocity

The components of this equation will be determined in the following steps:

Step One: Determine Rolling Resistance

Rolling Resistance (RR) is the force necessary to propel a vehicle over a particular surface. The worst possible surface type to be encountered by the vehicle should be factored into the equation.

RR = GVW x Crr

Where:

RR = rolling resistance

GVW = gross vehicle weight = 50 N

Crr = surface friction = 0.01

Using the above values,

RR = 50 x 0.01 = **0.5 N**

Table 3.1: Rolling Resistance

Contact Surface	Crr
Concrete (good / fair / poor)	.010 / .015 /.020
Asphalt (good / fair / poor)	.012 / .017 / .022
Macadam (good/fair/poor)	.015 / .022 / .037
Snow (2 inch / 4 inch)	.025 / .037
Dirt (smooth / sandy)	.025 / .037
Steel (Greased)	0.01

Table 3. 1: Rolling Resistance

Step Two: Determine Grade Resistance

Grade Resistance (GR) is the amount of force necessary to move a vehicle up a slope or "grade". This calculation must be made using the maximum angle or grade the vehicle will be expected to climb in normal operation.

To convert incline angle, α, to grade resistance:

GR = GVW x sin (α)

Where:

GR = grade resistance

GVW = gross vehicle weight = 50 N

α = maximum incline angle [degrees] = 20^0

Using the above values,

GR = 50 x sin (20) = **17.1 N**

Step Three: Determine Acceleration Force

Acceleration Force (FA) is the force necessary to accelerate from a stop to maximum speed in a desired time.

FA = GVW x Vmax / (981 x ta)

Where:

FA = acceleration force

GVW = gross vehicle weight = 50 N

Vmax = maximum speed = 5 cm/s

ta = time required to achieve maximum speed = 5 s

Using the above values,

FA = 50 x 5 / (981 x 5) = **0.05 N**

Step Four: Determine Total Tractive Effort

The Total Tractive Effort (TTE) is the sum of the forces calculated in steps 1, 2, and 3. (On higher speed vehicles friction in drive components may warrant the addition of 10%-15% to the total tractive effort to ensure acceptable vehicle performance.)

TTE = RR + GR + FA

Using the above values,

TTE = 0.5 + 17.1 + 0.05 = **17.65 N**

Step Five: Determine Wheel Motor Torque

To verify the vehicle will perform as designed in regards to tractive effort and acceleration, it is necessary to calculate the required wheel torque (Tw) based on the tractive effort.

Tw = TTE x Rw x RF

Where:

Tw = wheel torque

TTE = total tractive effort = 17.65 N

Rw = radius of the tire = 2.35 cm

RF = “resistance” factor = 1.1

The “resistance factor” accounts for the frictional losses between the caster wheels and their axles and the drag on the motor bearings. Typical values range between 1.1 and 1.15 (or 10 to 15%).

Using the above values,

Tw = 17.65 x 2.35 x 1.1 = **0.456 N-m**

Step Six: Reality Check

The final step is to verify the vehicle can transmit the required torque from the drive wheel(s) to the ground. The maximum tractive torque (MTT) a wheel can transmit is equal to the normal load times the friction coefficient between the wheel and the ground times the radius of the drive wheel.

MTT = Ww x μ x Rw

Where:

Ww = weight (normal load) on drive wheel = 25 N

μ = friction coefficient between the wheel and the ground = 0.01

Rw = radius of drive tire = 2.35 cm

Using the above values,

MTT = 25 x 0.01 x 2.35 = **0.5875 N-m**

Interpreting Results:

- Total Tractive Effort is the net horizontal force applied by the drive wheels to the ground. If the design has two drive wheels, the force applied per drive wheel (for straight travel) is half of the calculated TTE.

- The Wheel Torque calculated in Step Five is the total wheel torque. This quantity does not change with the number of drive wheels. The sum of the individual drive motor torques must be greater than or equal to the computed Wheel Torque.
- The Maximum Tractive Torque represents the maximum amount of torque that can be applied before slipping occurs for each drive wheel.

- The total wheel torque calculated in Step Five must be less than the sum of the Maximum Tractive Torques for all drive wheels or slipping will occur.

In our case, the robot is primarily supported by TWO Drive Motors.

TTE (per Wheel) = 17.65 / 2 = **8.825 N**

Tw = TTE x Rw x RF

Where:

Tw = wheel torque

TTE = total tractive effort = 8.825 N

Rw = radius of the tire = 2.35 cm

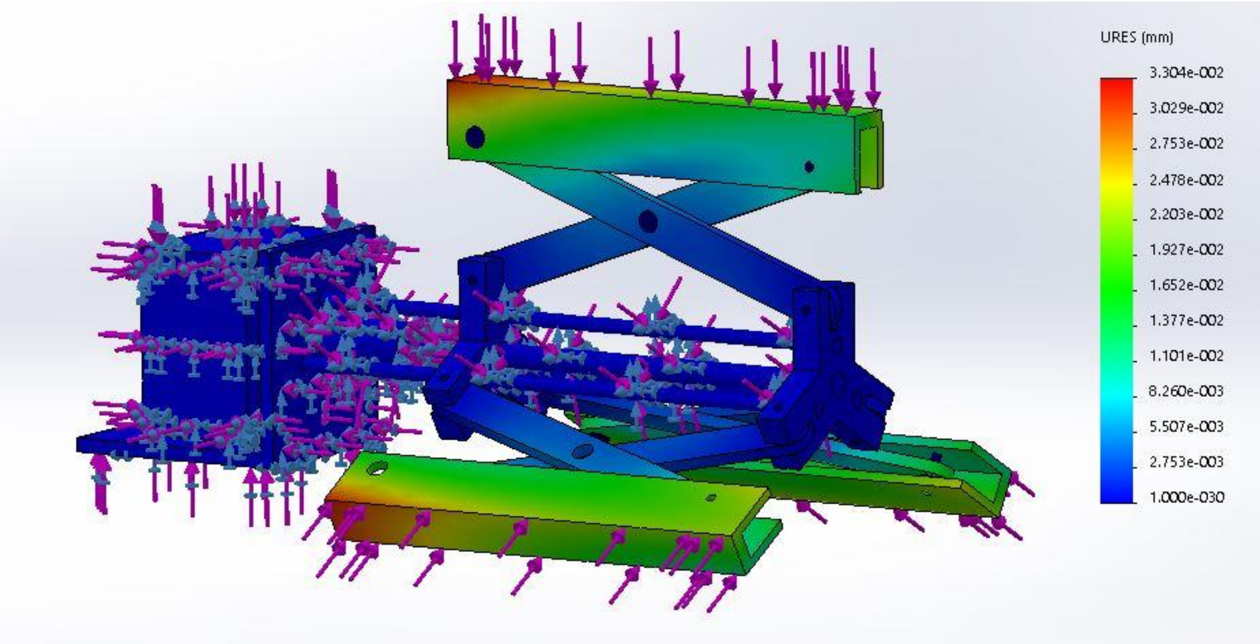
RF = “resistance” factor = 1.1

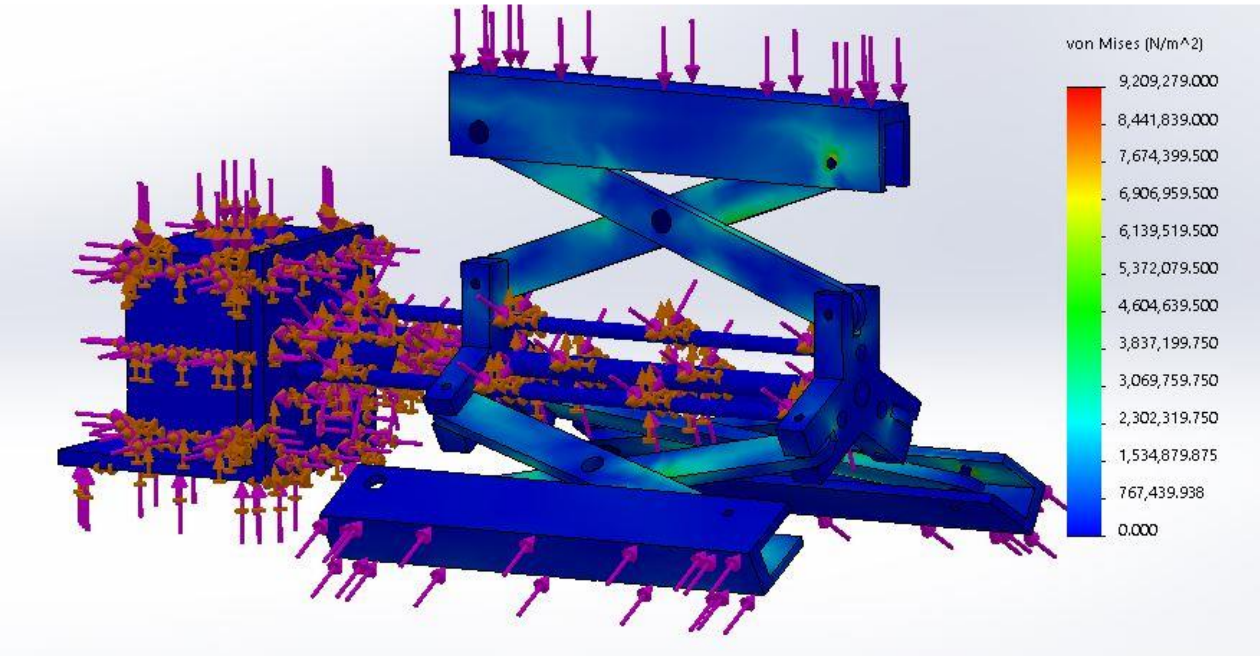
Tw (Single Wheel) = 8.825 x 2.35 x 1.1 = **0.228 N-m**

Chapter 4

4.1 ANALYSIS (FEM)

Stress analysis performed with different loadings is depicted in the illustrations below





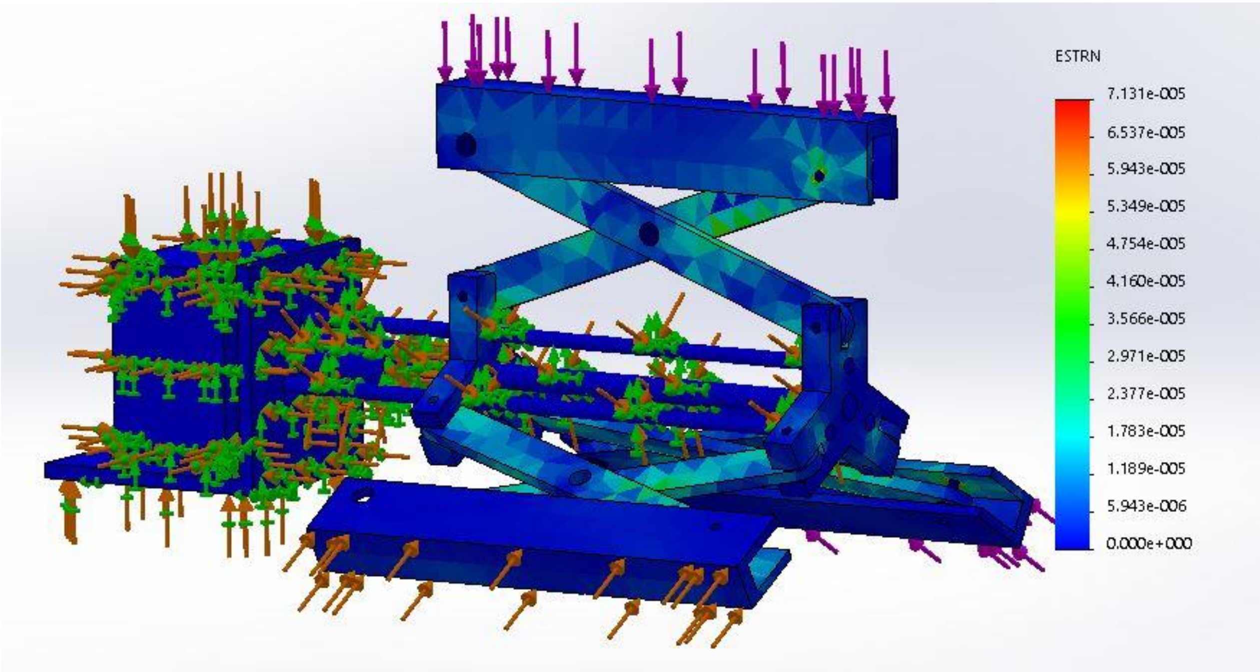


Figure 3. 16: Stress analysis performed with different loadings

Chapter 5

5.1 Fabrication

Aluminum was selected as the material which ATOM would be chiefly made of. For any In-Line Inspection Robot, strength, ability to survive in corrosively harsh environment and light weight are of paramount importance. Though these characteristics are exhibited by number of materials as well like composites but after considering the market availability, cost impacts and strength to wait ratio, we decided to use Aluminum for ATOM's manufacturing.

Following Manufacturing operations have been performed during ATOM's manufacturing

1. Turning
2. Drilling
3. Tapping
4. Vertical Milling
5. Broaching
6. Shearing
7. Press fitting
8. Bench Fitting
9. CNC Operations

All these operations were performed at one stage or another, separately or simultaneously for effective and accurate manufacturing of ATOM. The wheels of ATOM are made of hard Nylon. Generally for Links the sheet thickness has been 4 mm but in some links sheets of 3mm thick Aluminum have also been used depending upon their position in the mechanism.

Chapter 6

6.1 Conclusion & Future Considerations

A mechanical model of an In-Line Inspection Robot is now fully functional with abilities to

1. Travel linearly in Pipelines ranging from 12 inches to 18 inches in diameter
2. Handle standard inclinations of 45 degrees
3. Conduct visual inspection

Now in the future this robot needs a lot more to be done it before it can be termed as a final product. Not only on the inspection part. There is a lot to be done on improving its mechanical functioning yet. Teams can work on steering control of this robot which will be a research opportunity for them, right now this robot is only conducting linear motion so how it will tackle standard Y- Joints, T-Joints and elbows will also be another important study.

To make this robot fire proof and follow all the safety standards as required by the Oil & Gas sector will also be a new challenge since there is a lot of circuitry present in this machine which is potentially dangerous for spark ignition. Wireless control of this machine for long distances while underground is also something which will require work on communication techniques being employed for such products.

Once we are done with the creation of a sound vehicle having no mechanical trouble, we need to ensure that this vehicle is mounted with gadgetry required to inspect the pipelines. For corrosion inspection and crack detection, state of the art inspection technologies will be needed and for mounting them on this robot, its design should be made accordingly.

All in all there is a lot of work which needs to be done to convert this project into a commercialized product. This can be achieved by consistent work on this project.

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