Mechanical Design and Dynamic Analysis of Pipe Crawling Robot for 6” to 10” diameter Internal Gas Pipeline Inspection

by

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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In partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

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May 2012

CERTIFICATION OF ORIGANALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgement, and that the original work contained herein have not have been undertaken or done unspecified sources or person.

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(MOHD AMIRUL BIN CHE HUSSAIN)

ABSTRACT

With the world moving forward, robot has been considered as an attractive and innovative alternative to help human in their work. For oil and gas industry, pipelines have been an important asset that needs to be maintained always. For many centuries, it has been integrals part of our constructions. However, with the cost of maintenance continue to increase, a new approach needed to accomplishing them.
Many different types of pipelines robot have been proposed in the past. Unfortunately, many of the robot work under very restricted area or environments such as customized pipes sometimes have no vertical movement or can traverse through only a simple pipeline structure. This project is targeted to build and design a functional robot where the application can be tailored to internal pipelines inspection and maintenance. With overcome the existing problem from the past pipeline inspection robot, a new and improved design will help in constructing the robot. The scope of this project is focused on mechanical and structural design of the pipe crawling robot. The methodology of this project will be involving research and identification, conceptual and system design including analysis, construction of the prototype, simulation testing and analysis and completing the final report. In the end of this project will be able to develop a simulation model of pipe crawling robot for internal pipeline inspection. The related mechanical model and analyzing of the mechanical design and active adaption to pipe diameter, tractive force adjusting, control system structure are discussed. As a pipe crawling robot for visual inspection, this project can become the fundamental for other inspection robot.

ACKNOWLEDGEMENTS

First and for most, I want to express my deepest gratitude to my project supervisor, Pn. Rosmawati Binti Mat Zain who had support, guide and encourage me to successfully completed this project. He always expects for high quality work and this project is no exceptions. He continuously challenges me to learn new thing and come out with new ideas in order to produce a high quality project.

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CHAPTER 1
INTRODUCTION

1.1 Background of the study

1.1.1 Gas Pipelines

Gas pipelines network which are tools for transporting oils, gases and other fluids such as chemicals was like any other structure, are vulnerable to damage from many source. Most of them are caused by aging, corrosion, cracks, and mechanical damages (H.Choi, 2005). Smaller fluid systems such as those serving residences may be repaired with easy, low-cost methods and in many cases it may be best to simply replace the pipes. But with complex pipelines system such as gas pipelines, however, frequently need some better way of dealing with plumbing failures. Buried pipes for example, commonly used for gas conduits, cannot be inspected as efficiently as above-ground pipes. This is because of the excavation and backfilling work involved (Y.Kawaguchi, L.yoshida, H. Kurumatani, T.Kikuta and Y.Yamada, 1995). All this work takes amount of time to be finish beyond the time required for the actual inspection job.

Interior surface inspection technology is possible such as the remote field eddy current inspection (T. Kikuta, K. Tomita, and K. Yasui, 1986) or ultrasonic sensors to detect cracks or corrosion thinning in pipes has been established. However this required the access to the external surface of pipes which is difficult and costly in many situation due to long and buried length. Furthermore, this does not address the problem of clogging or fouling. In many such applications, an internal inspection solution may be the best preferred ways.

1.1.2 Pipe Crawling Robot

Robots can be thought of as computers equipped with sensors, instrumentation, and mobility to interact with the environment. Robot also had evolved rapidly and adapted several technologies as advance happen in computer systems, electronics and motion controls. Many of today's robots are used for inspection, surveillance and monitoring a tasks in utility work area (H.T.Roman, B. A. Pellegrino, and W.R Sigrist, Sept 1993). A research about the existing pipe-inspection has been conduct to access the feasibility of the project and to determine what the best approach to design and build the robot (H.T.Roman, B. A. Pellegrino, and W.R Sigrist, Sept 1993). It was found that there were several mechanisms have been developed like as wheel-type, inchworm type, legged mobile-type, screw type, crawler-type, PIG-type and passive type. Among them, the most popular one were wheel-type pipeline inspection robot (Young-Sik Kwon, Oct 18-22,2010). It was found also that several pipe-inspection robots have been constructed experimentally; some are even commercially available products. But, the simplest design which is platform resting on wheels and tractors treads underneath is the numerous design in the market. Such robot suffers from the inability to climb vertical section of pipe. Also, many of them have limited steering abilities which is one of the important things and may be too long to pass through even horizontal elbows.

Mainly, inspection robots have had such limitations as their mobility to turn in a T-shaped pipe or moved in a plug valve. But, researcher by W.Neubauner has developed more advanced pipe inspectors which are capable of travelling through vertical pipes (Neubauer, 1994). It is capable of traveling through complex pipe network by using hierarchical control architecture with reflective and reactive behavior (Neubauer, 1994). Besides that, there are more research projects, have been constructed of this type, using tracks or wheels. Furthermore, more complex robots are use serpentine motions or "inch-worm" mechanisms for propulsion. Even though they advanced in motion and shown promising but they remain experimental.

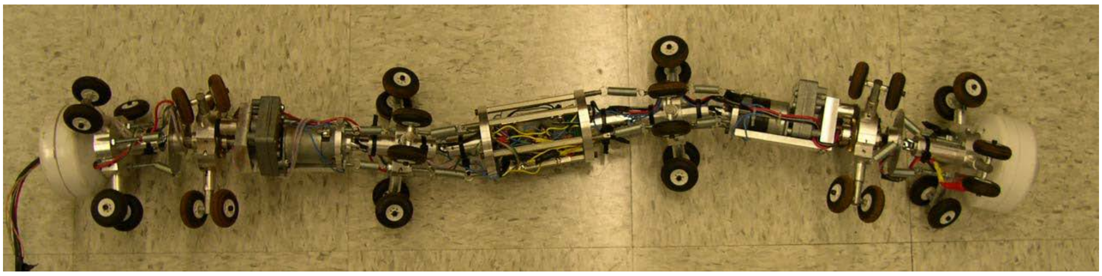

Figure 1.1: Snake-Like Pipe Crawling Robot

1.2 Problem Statement

Recently natural gas became the most demanding thing in the world and its impact on the development is getting larger. Pipelines which are most important thing in export the natural gas must always be maintained. Some of gas pipelines are composed of those with small diameter which makes it impossible to carry the inspection equipment inside the pipelines. How the inspection can be done?

1.3 Objectives

The main objectives of this project are to design and develop a Pipe Crawling Robot capable autonomously inspecting pipelines with different diameter of pipe ranging from 6 inches to 10 inches for internal pipelines inspection.

1.4 Scope of Study

The scope of the project is focused on mechanical and structural design of the pipe crawling robot. The significant of the mechanism design is discussed. The proposed system has the following features:

- It remains operational with pipeline in service as testing requirement.
- It has very simple structure which means the minimum number of moving part/ actuators and minimum number degree of freedom to moving.
- It is stable enough throughout its motion in order to maximize the performance of the inspection sensors and reduce vibration.
- It can be suit pipes with inside diameters ranging from 6 to 10 inches

Mechanical and structural design of the pipe is important in order for the robot to be able to withstand the pressure.

CHAPTER 2
LITERATURE REVIEW

2.1 Driving Mechanism

There are several driving mechanism or manoeuvre for pipe inspection robot. The type of In-pipe robot can be classified using it driving mechanism, as shown in Fig 2.1.

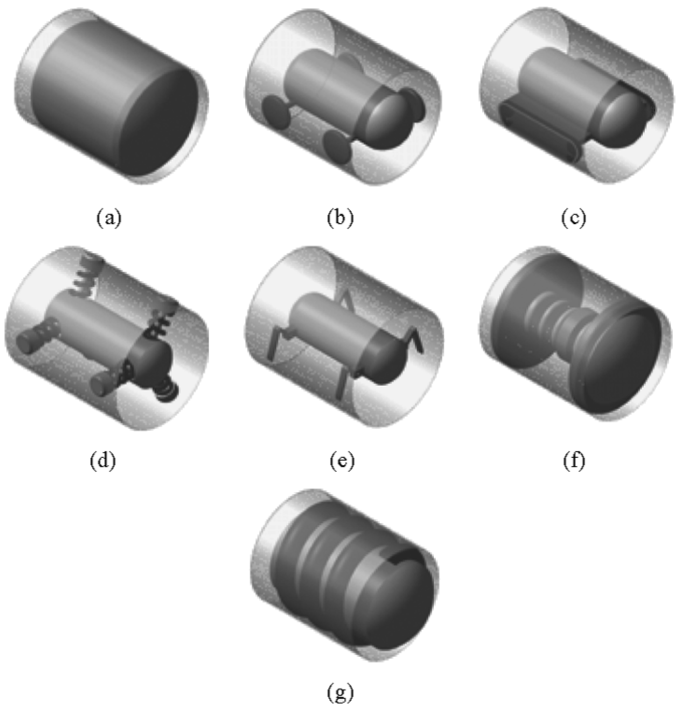

Figure 2.1 : Classification of in-pipe robots (a) Pig type (b) Wheel type (c) Caterpillar type (d) Wall-press type (e) Walking type (f) Inchworm type (g) Screw type

As shown in Fig. 2.1, for example, the pig type is one of the most well-known commercial ones, which is passively driven by the fluids pressure. Mostly it been implemented on with large diameters pipelines (J. Okamoto, 1999). Besides that, there is wheel type which is the most popular one that used by inspection robot. (S. Hirose, 2000) (Kanade, 1987). Fig 2.4 (c) shows the caterpillars type and Fig 2.4 (d) which use the wall-press mechanism that pressing the wall. This type is suitable to climb the verticals pipelines. (S. Hirose, 2000), (Kanade, 1987). This type also is suitable to move faster in the horizontal pipe. Existing type of robot can travel along horizontal pipe smoothly but stuck in vertical pipelines, elbow (sometimes refer as Lshaped pipelines). For successful navigation, the ability to travel along in complex pipelines is strongly demand. For all the types of driving mechanism, there are advantages and disadvantages for each type. This can be simplified by the table below.

Table 2.1 Advantages and disadvantages of driving mechanism

Driving Mechanism	Advantages	Disadvantages
Pig Type	• Driving though shape of pipe. • Suitable for long distance	• Can be used only for large diameter.
Wheel Type	• Faster in horizontal pipes	• Cannot travel through vertical type pipes.
Caterpillar Type	• Can distribute weight well • Can moves through horizontal and vertical pipes.	• Reduce speed
Wall-Press Type	• Suitable for vertical pipes(climbing pipes)	• Not suitable for higher diameter
Walking Type		• Very slow • Only can travel through vertical pipes when have some tweak in its foot.
Inchworm Type	• Suitable for small diameter	• Cannot travel trough vertical types pipes
Screw Type	• Suitable for small diameter • Very fast in horizontal pipe	• Cannot travel in vertical pipes.

The features of the design used the caterpillar tracks that enable to move horizontal and vertical, but in this project we just focus more on horizontal movement. Based on the research, the caterpillar tracks used can help distributed inspection robot evenly over a larger surface of the track when compared to the wheel based type robot. This ability of the caterpillar track can helps the robot to handle the uneven surface more efficiently. The roller at the front and back of the continuous track robot which aid in the movement will take up the additional load. The complete movement smoothly help the robot in loose area. But, with using this type of driving mechanism is track have lower top speed due to friction. But, the caterpillar track can cause lesser damage to internal surface of the pipeline because their smooth rolling surface, than the wheel-based robot. Besides that, it can move vertical depends on the design.

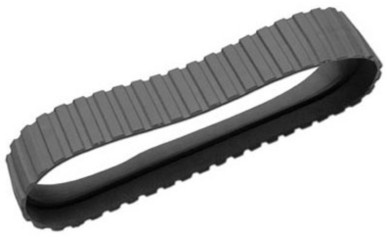

Figure 2.2 Example of Caterpillar Continuous Track

Besides that, the wall press type also is suitable for this project as it will give the robot more sufficient tractive force. The ability to give more force to the robot is one of the important factors that needed to be focus. But, it has disadvantages where it can not be used to bigger diameter of the pipelines as the force will reduce along the leg.

2.2 Tractive Effort and Traction Force

Tractive effort is in the contact area between the tires of the driven wheels and the road surface that propel the vehicle forward. It is produced by the power plant torque and transferred through transmission and to drive wheels. When the tractive effort is more than resistance efforts, the vehicle is moving forward. In the design of wheel or tracked vehicles, high traction between wheel and ground is more desirable than low traction, as it allows for more energetic acceleration without wheel slippage. With using the continuous track or caterpillar track, the traction can be increased because dramatically increase surface area of track compare to the wheel. Besides that, the choosing of the material also important to increase the traction force. For example, soft rubbers often provide better traction but also wear faster and higher losses when flexed. The acceleration of the robot can be shown in below equation where Ft is tractive force, Fr is resistance force and dM is mass.

Equation 2.1

$$\frac{dV}{dt} = \frac{\sum F_t - \sum F_r}{\delta M}$$

2.3 Pipelines

Natural resources like oil and natural gas which is the raw material for energy consumes mainly was found in vastly different part of location in the world. With many forms of transportation are used to move this product to marketplaces, pipelines remain the safest, most efficient and economical way to move this natural resource (The oil pipeline industry and the members of the American Petroleum Institute (API) and the Association of Oil Pipe Lines (AOPL), 2007).

Gas pipelines where most of it is buried under the ground are prone to external corrosion usually derived by moisture and chemical agent in soil. This will cause the material losses of the pipe wall (H.Choi, 2005). Besides that, damage from construction, electricity, sewage works are considered as one of the major reasons for pipelines failure (H.Choi, 2005). Also, the buried pipes are vulnerable to permanent ground deformation and wave propagation (shaking). Pipe damages mechanism include: compression/ wrinkling, joint weld cracking/ separation, bending/ shear resulting from localized and tension (The Shake out Scenario, U.S Geoclinal Survey Open File Report, 2008)

Figure 2.3: Corrosion happen external side of the pipelines

Figure 2.4: Corrosion inside of the pipe

From the statistic, The United States has the largest network of energy pipelines for both oil and natural gas in any nation in the world (Operation Map Domestic Pipeline System, 2011). Malaysia is the number 10 biggest gas network in Asia (Asean Plan of action for Energy cooperation (APAEC), 2004-2009). For natural gas, pipelines are usually constructed from carbon steel and its size is very from 2 to 60 inches in diameter, depending on type of pipeline. For this project, one of the criteria of the robot is it is suitable for 4 to 10 inches. Besides that, gas pipelines are pressurized up to 1450 psig. Piping systems consist mainly of straight pipe. Besides that, there is T-junction pipe, Y-junction and elbow. This is shown by picture below.

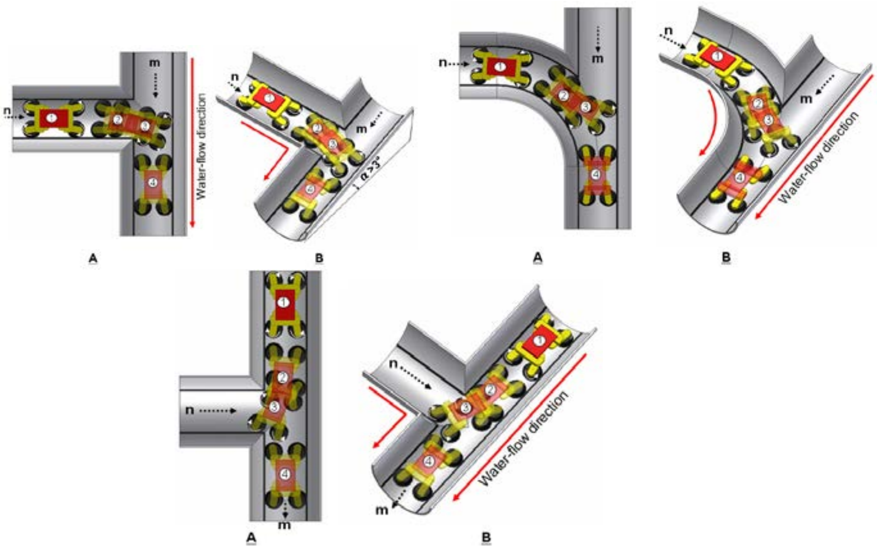

Figure 2.5: Type of the pipelines

2.4 Pipe Adaptive Mechanism

There are quite few of research in inventing the inspection robot that can moving in varying diameter. There are mechanisms that use to move the rotating part (C. Choi, 2006). There are mechanism that used a worm gear system as figure below (Huk-Ok Lim, 2009).

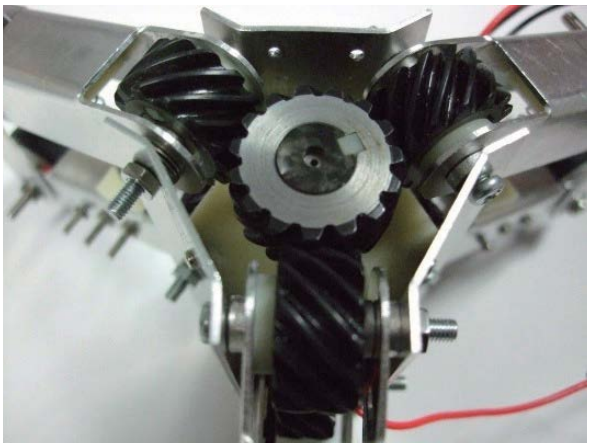

Figure 2.6: Worm Gear Mechanism

When the middle gear is moving, the worm gear will move to move the linkage of the wheels. Thus, it makes the wheel contact the surface by pressing it. The middle gear also control the force applies to the wall with receive some command from the circuit. Besides that, there is spring-linkage with some degree of freedom (DOF) (Kim, 2008).

Figure 2.7: Example of Spring -Linkage

The spring is used as a force to push the linkage to the wall. The distance between the central body and the track can be determined based on the movement of flexible link, the elastic restoration force of the spring at the link and reaction force from the wall. The stiffness of the spring determines the force that exert to the wall.

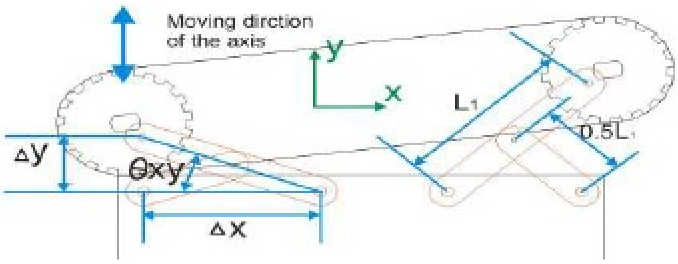

Figure 2.8: Vertical force in Spring-Linkage Mechanism

The vertical force that pushes the wall can be calculated by below equation based on

Equation 2.2

$$\tan(\theta) = \frac{\Delta y}{\Delta x}$$

and by Pythagoreans' theorem

$$L1^2 = \Delta y^2 + \Delta x^2$$

$$=> \Delta y^2 = \Delta L1^2 - \Delta x^2$$

$$=> \Delta y = \sqrt{L1^2 - \Delta x^2}$$

and also

$$\Delta y = \Delta x \tan(\theta xy)$$

Besides that, there are robots that use ball screw as a mechanism to change the diameter. This project made by (Yan Y. Z., 2006) used a ball screw as active pipe-diameter adaptability but the robot it uses is big in size and not fits to moving inside small diameter size pipe. But, the research made from him made the designer to use this method for robot that can change diameter.

Besides that, ball screw also is a mechanical linear actuator that translate rotational motion into linear motion with little fraction. It also can withstand high thrust loads with minimum internal friction. This made them suitable to use for automation industry. The calculation needed to use the ball screw as the torque need to rotate the motor is using the equation

$$T = \frac{Fl}{2\pi\mu}$$

Where T is torque applied to screw, F is linear force applied, l is ball screw lead and nu is ball efficiency. This equation can be a platform for designing the adaptive pipe diameter to moving in 6 inches to 10 inches pipe.

2.5 Summary

As conclusion, there is no ‘ideal’ drive configuration that simultaneously maximizes stability, manoeuvrability and controllability. Each inspection robot applications will determine the unique constraint on the robot design problem. And, it up to the designer to choose the most appropriate drive configuration possible from among other configuration. As for this project, the wall press mechanism with caterpillar tracks will be selected as a locomotive mechanism.

For pipe adaptive mechanism, ball screw has been selected for this project because the advantages of this ball screw. Also, it is suitable to use in small place and easy to construct the mechanism for changing diameter.

CHAPTER 3
METHODOLOGY

Mechanical engineering design is mainly a creative activity which involves a rational decision making. Generally speaking, it tends to directed at the satisfaction of a particular needs by means of a mechanical system, where general configuration, performance specifications and detailed definition conform the task of the design activity. There is no identified approach or methodology to actually design a system. Given a particular needs or criteria, the designer would probably design something different. However, there are some common guidelines which can be useful in designing a system in general way. These guidelines are variations of so called 'design process' which is a stepwise description of the main tasks typically develop in a comprehensive design exercise. In any case, one of the main tasks in any design situation is called 'definition of the problem' or 'problem statement'. The details of the methodology will be discussed below.

3.1 Project Activity

At the initial stage of the project, it is important to find the information and literature review that are related with the project which regarding the design of the inspection pipeline robot. This literature review is essential for designing the concept design for the robot. Furthermore, previous project or research can be set as an initial datum or benchmark to improve and to set the specific requirement.

With the specific requirement and objective is set, the design concept is generated. In addition, the generate concept must be realistic and can be fabricate. The most suitable design concept is selected to make the detail design. The evaluation of concept design must be based on the scope of study and objective of the project. After that, the model of the selected concept is produce.

Then, the simulation of the model is conduct to be able to testing and analysis the model. The result data which regards to performance of the design is analyses and improvement can be made. Finally, the project will be documented into a formal report. The project process flow can be seen in detail in the figure below.

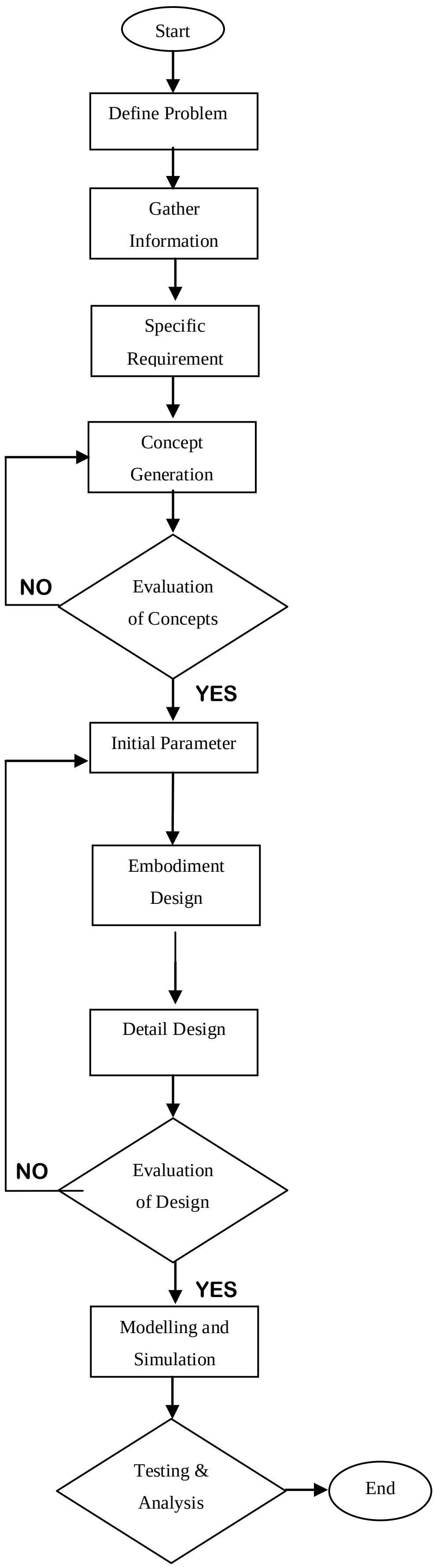

Figure 3.1: Process flow for Designing Pipe Crawling Robot

3.2 Gantt Chart

These Gantt chart show the activities that will be done during the research period. All the activities have been given specific time frame in order to show the research is more manageable and to avoid any delay activities in the research.

	Task/Activities	26-Jan	30-Jan	6-Feb	13-Feb	20-Feb	27-Feb	5-Mar	12-Mar	19-Mar	26-Mar	2-Apr	9-Apr	16-Apr	23-Apr
NO	**DETAIL/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Project topic Selection	■	■												
2	Literature Review			■	■	■	■								
3	Design Concept Generation							■							
4	Proof - Working Concept								■						
5	Evaluation of Concept									■	■				
6	Detail Design Concept											■	■		
7	CAD Model Design													■	■

	Milestone	26-Jan	30-Jan	6-Feb	13-Feb	20-Feb	27-Feb	5-Mar	12-Mar	19-Mar	26-Mar	2-Apr	9-Apr	16-Apr	23-Apr
NO	**DETAIL/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Preliminary Report						●								
2	Proposal Defence									●					
3	Submission of Interim Draft Report													●	
4	Submission of Interim Report														●

● **-Milestones** ■ **- Progress**

Table 3.2: Gantt chart for Final Year Project 2

	Task/Activities														
NO	**DETAIL/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	CAD Model Design	■	■	■											
2	Simulation			■	■	■									
3	Testing					■	■	■							
4	Analysis					■	■	■							
5	Progress Report Submission								○						
6	Prepare final report									■					
7	Pre-EDX										○				
8	Draft Report Submission											○			
9	Dissertation submission												○		
10	Technical paper submission												○		
11	Oral Presentation													○	
12	Project Dissertation														○

○ **-Milestones** ■ **- Progress**

3.3 Tools

The main software used is Autodesk Inventor to develop a model and also mainly use for the analysis. Besides that, MATLAB program which contain Simulink also been used to verify some mathematical model and dynamic analysis of the inspection robot.

CHAPTER 4
RESULT AND DISCUSSION

4.1 Design and Development

With the given problem statement in introduction part, how can the inspection robot can be develop? What are the requirements? This is the main question to solve before designing a mechanism. Wanted here is the inspection robot that can move autonomously in varying pipe diameter. For this project, it is 6 inches to 10 inches. So, for this project, the most important specifications at this point are:

- Maximum and minimum dimensions: there is not specific length, but the width has to be between 152.4 mm (6 inches) and 254 mm (10 inches).
- Drive: Only electrical power is authorized, so no combustion engines may be used.
- Locomotion: All robot needs to used caterpillar tracks with wall press mechanism. These tracks stable enough to carry inspection equipments thus will maximize the performance of the inspections sensors.
- Inspection: The robot must have several inspections equipment besides camera inspection. For examples; Eddy-Current sensor and Ultrasonic Sensor.

In order to construct an inspection robot, some design decisions have to be made.

4.1.1 Concept

The concept generation comes from the brainstorming process. The systematic design methods for designing can be implemented in the robot design. It is because they involve a structured process for generating design solution. But, before designing and developing a new robot platform, the limitation or specific requirement must be remembered. Before presented on more details of concepts generation, the shape of the robot has been decided. It is because we want to use it in a pipe. So, the shape of the robot is tending to follow the shape of pipe as represent by the figure below. In the first stage of the process, the content of this shape is unknown. It is just to fulfil its task. And, step by step, the process to refine the design and work out each of different modules in this cylinder shape. The final design is also shown in Fig 4.1

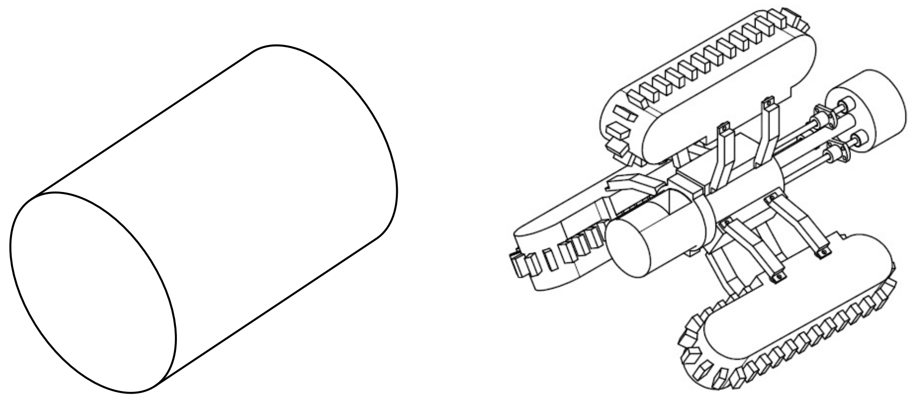

Fig 4.1: Analogy of the robot design and the final design

4.1.2General dimension and Robot shape

The requirement set before is a guideline to build this robot. The main limitations are the dimensions. For this project, cost of the robot is not the problem. The maximum and minimum dimensions set before is as per below:

- The maximum length Lmax is not determine
- The maximum width Wmax is 254 mm
- The minimum width Wmin is 152.4 mm
- The maximum height Hmax 254mm
- The minimum height Hmin 152.4mm

The shape of this robot is a great importance and can have an impact on the robot performance. If refer to Fig 4.1, the shape of the pipe will have more effects on the design of the robot. For instance, a pipe with cylindrical space for robot with identical width is limit to moving left and right. Since the robot is used for inspection, a shape of the design is very important for stability and performance. Also, environments in pipe where there are high pressure and some other substance will affect the shape of this robot. Figure below show some analogy considering general dimension and general shape. The body of the robot is design based on the minimum requirement and can be expended to maximum dimensions.

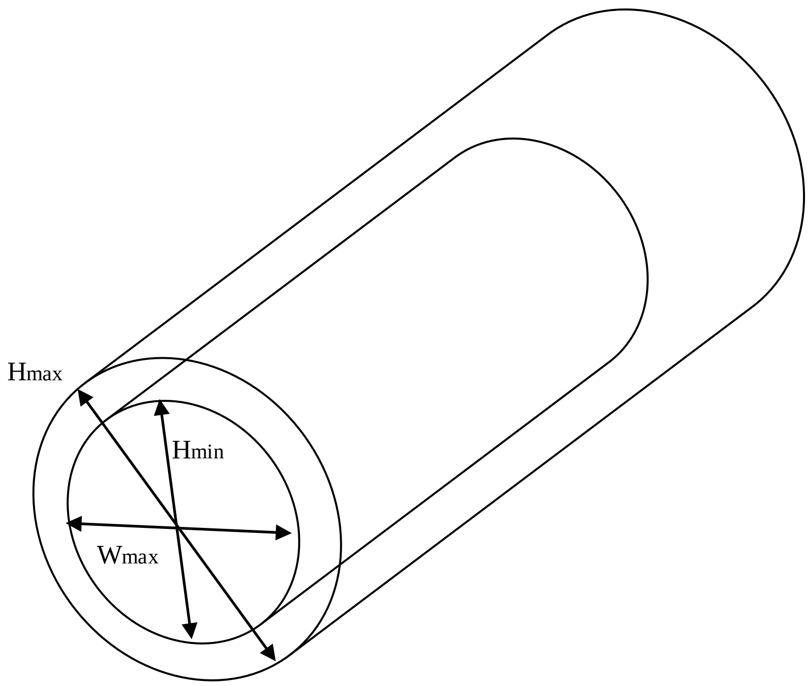

Fig 4.2 General Dimension and Shape

4.1.3 Driving Mechanism

The next step in the design process is the choice of a driving configuration. In chapter 2, an overview of a possible configuration is given and all configurations depend on the objectives and it's functional.

Based on the discussion above, the caterpillar track with wall press mechanism has been selected. Wall press mechanism will give additional tractive force. In this project, it has been decided to use the caterpillar type manufactured by Inuktun Company. This type of driving mechanism has some benefits with respect to others type. The main benefits:

- Can help distribute its weight evenly over a larger surface of the track, when compared to the wheel-based robot.
- The caterpillar track also helps the robot to handle an uneven surface much efficiently.
- The caterpillar tracks give more grips because of segment in its surface.
- The track based robot will have better mobility than the regular wheel-based robot.

Even it had many benefits, it also has disadvantage. For example;

- The tracks will have lower top speed due to friction but this friction is necessary to vertical movement. But, in this project, it only deals with horizontal movement in pipeline.
- Caterpillar track are mechanically challenge when compared to wheel-based robots.

The characteristic of the Inuktun Microtrac Caterpillar tracks as per below(refer **appendix I**):

This caterpillar tracks are made from stainless steel which it weight is 2kg. It operating environment is as per below

- Temp : 0-50 degree Celsius
- Power : Voltage 24VDC
- Depth rating : 0-30m/0-100ft

For it transporter units is as below:

- Speed : 0-9m/0-30ft per minute
- Pull Rating : 6.5kg/15 lbs per track
- Payload Capacity : 10.8kg/24lbs per track

From this specification, it is suitable for this project because it can handle the high pressure environment and high temperature. It also can handle weight of the robot successfully. For it to be able to move the robot, two set of parallelogram leg is attached to it. The technical drawing of this mechanism is shown in **Appendix II**.

4.1.4 Dimension Changing Mechanism Selection

As for this project, it focuses more on robot that can vary diameter from 6-10 inches, a driving mechanism for changing the diameter must selected. Based on the discussion on the chapter 2, many type of changing mechanism is available. In this project it has been decided to use the ball screw as the mechanism for changing diameter for the robot with some modification to fits into the robot.

The main advantage of ball screw:

- Has high efficiency which is over 90%
- No tendency for slip-stick
- Minimum thermal effects
- Smoother movement over full travel range
- Smaller size even for high load

The main disadvantage:

- Requires higher levels of lubrication

The dimension changing mechanism is called as adaptive pipe diameter. Further explanations about this mechanism will be discussed below.

4.1.5 Modularity

To easy manage in designing the robot, it has been decided that the general shape of the robot which is cylinder as indicated by Fig 4.1 will be divided to three platforms which is head, body, and rear part. This is shown with figure below. Head part will be a part where inspection camera will be attached. This camera will be connected with the computer and sending to the computer in real-time. Meanwhile, the body parts will consist of driving mechanism and changing diameter mechanism. This part is very important to make the robot to fulfil a desired robot task. Besides that, the motor also will be put in here to control the dimensions changing. Last part will be platform to hold the brain of robot, circuit, sensor and specific electronics device. In this way modularity is introduced in the design phase.

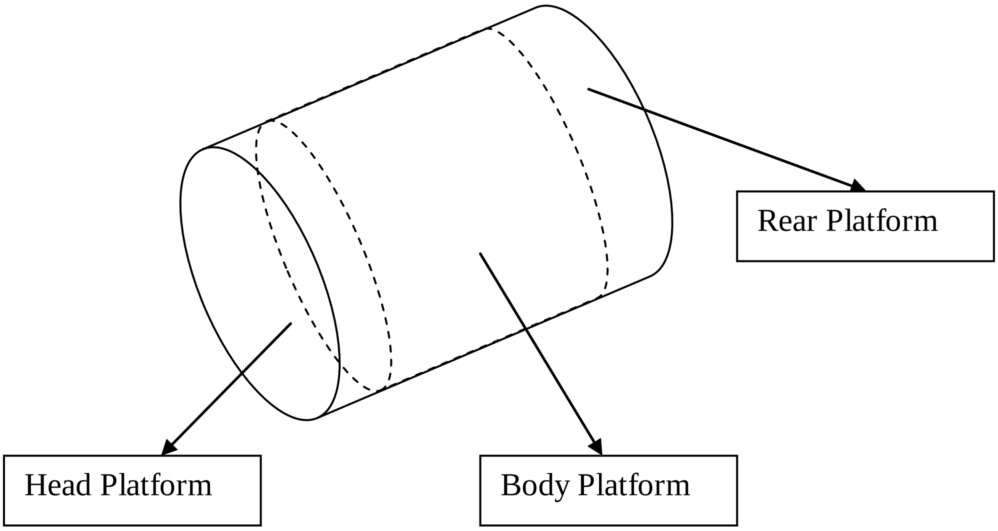

Fig 4.3 Platform divided

4.2 Mechanical Design (Embodiment Design)

4.2.1 Head Platform

The design process starts with focusing in head platform. All parts of the head platform are designed in 'Autodesk Inventor' a computer aided design (CAD) program. In head platform consist of camera inspection or also known as pan–and-tilt camera that are bought in specialised stores because of their complexity. Besides that, it also consists of clipper to hold the camera inspection. The technical drawings for camera clipper parts are appended in **APPENDIX III**.

The proposed concept is design based on the centre point of the cylindrical. So, it leads to a symmetric design which will increase the robot's stability. Based on the manufacturer design for the camera inspection, the dimension for it to be able to moving 360 degree and 180 degree is about 2 inch from 4.1 inch long. So, the clipper design must not block the inspection camera to moving freely. The clipper part will be attached with the body of the robot. The analogy for the design can be shown below.

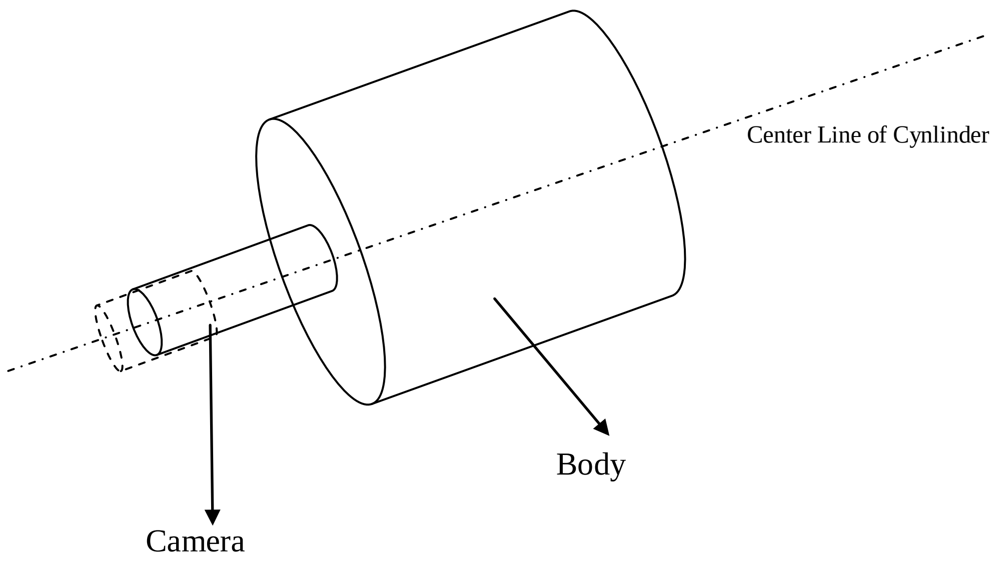

Fig 4.4 Camera position in robot

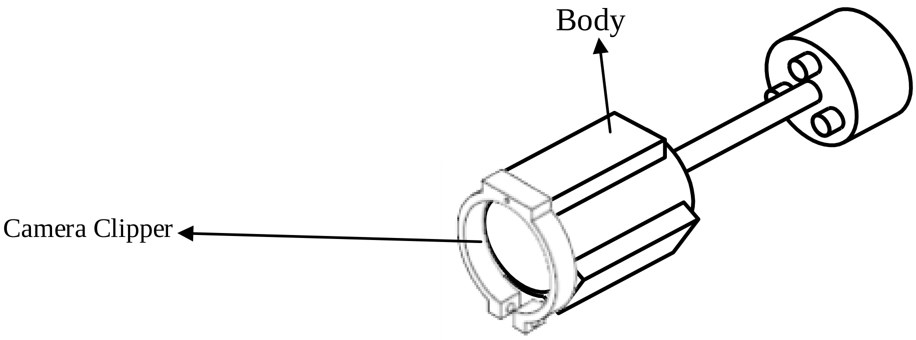

Fig 4.5: Position of camera clipper to hold the camera.

The clipper part is used to hold the camera to desire point where it can hold the camera while camera moving. The figure above has shown how inspection camera is attached to the body part.

4.2.2 Body Platform

The body platform consists of 2 important parts where the driving mechanism and active adaption pipe diameter mechanism is attach here. This part is very complex because it is deal with the motor and small parts like proximity sensor. The illustration of the final design for body is shown below. This body is design from the cylinder shape to fits the components.

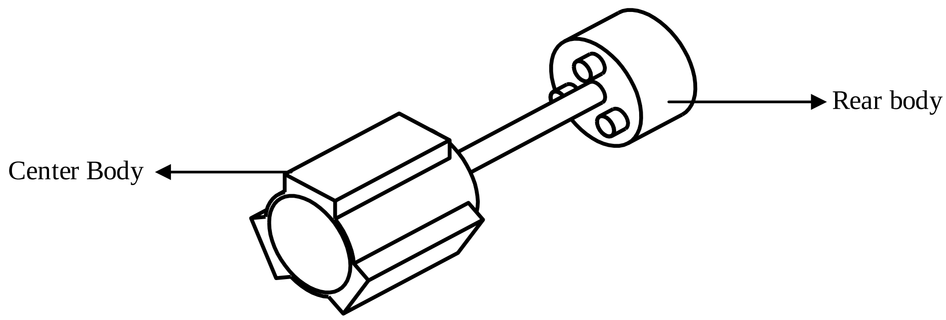

Fig 4.6: The body part of the robot (include the rear part of the robot)

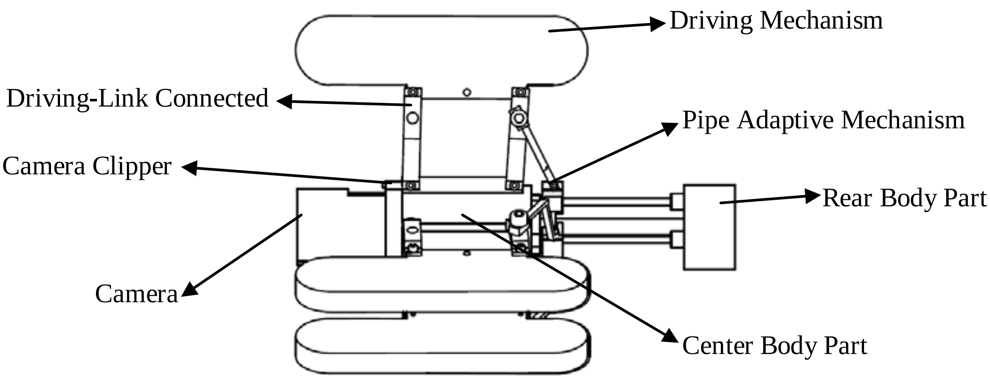

Fig 4.7: Details of how mechanism is connected to body

4.2.2.1 Driving Mechanism

The driving mechanism here refer as caterpillar type is the leg for this robot are the most important assemblies of the mechanical platform and in this robot, there are three legs use to make this robot moving in the pipe. First of all the pipe wall contact must be ensured. The three caterpillar type legs must be able to hold the entire weight of the robot. Secondly the legs are stable enough to maximize the sensor performance. And finally the track for caterpillar type has to be driven to produce the motion. Fig 4.5 show drawing of the leg made in ‘Autodesk Inventor’ (The actual item maybe be different from the drawing). In this project, the caterpillar track has been selected and bought in specialize shop because of it complexity. The material use for this type is stainless steel as it also can handle various chemical in the pipe. The driving mechanism is attached to parallelogram leg and attached to the body as shown in Fig 4.7**.** The detail of this product has been discussed above.

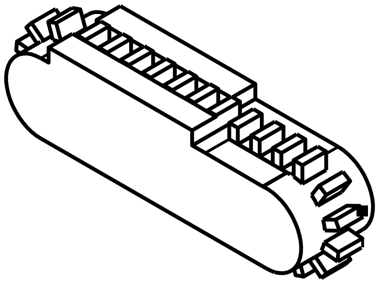

Fig 4.8 Caterpillar-Type Tracks

4.2.2.2 Active Adaptation to Pipe Diameter Mechanism

For design the changing diameter mechanism, the ball screw has been selected. This mechanism is usually been used in automation and manufacturing. Ball screw has been selected because it can withstand high thrust loads with minimum internal friction. The technical drawing of the ball screw is in **appendix IV**. This ball screw needs some modification to fit it to the body of the robot. The nut of the ball screw is the part that needs the modification. It can be shown in figure 4.9 below. For this pipe crawling robot, 4 mm ball screw has been selected based on the loads that we use and size of the robot.

The specification of the ball screw is in table below.

Nut type	Lead	Diameter	Stroke	Thread Length	Overall Length	No of circ.	Ball Diameter	Max Dyn. Load (N)	Max Static Load (N)
Cylindrical	0,5	4	70	95	135	3	0,6	170	240

Table 4.1Specification of the screw ball

The key part of this design robot is the link between the driving mechanism and changing diameter mechanism which is ball screw. The link to connect this thing will drive the two parts simultaneously when the motor of the ball screw is moving, affect changing diameter of the robot. The illustration of the link connects the ball screw and the caterpillar leg is shown in figure 4.11 below.

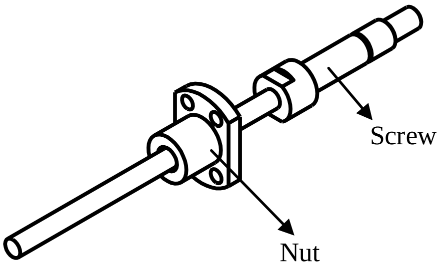

Fig 4.9 Ball Screw Design

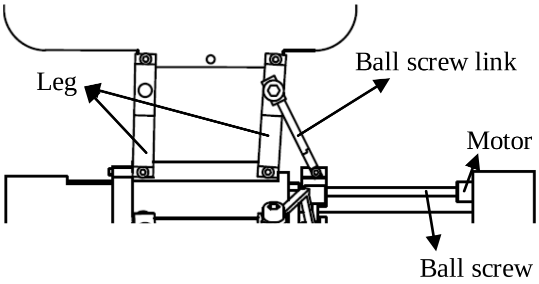

Fig 4.10 Illustrations for link connect ball screw and caterpillar track

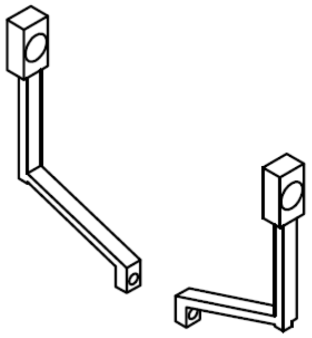

Figure 4.11: Ball Screw Link

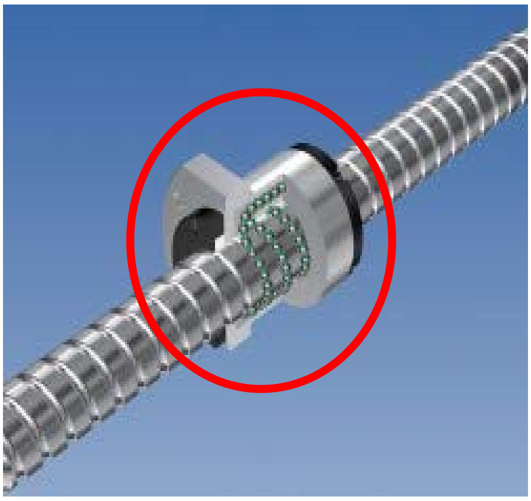

Figure 4.12: Part that needs to be modified

Some modification to the nut of the ball screw need to be make for it to be able to link the driving mechanism and pipe adaptation diameter. The nut that has been modified is shown in figure 4.13. Also some sensor is put in here to control the movement of the ball screw.

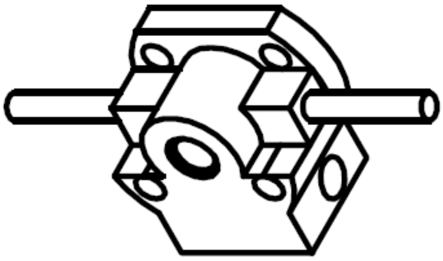

Fig 4.13: Modified Nut

Besides that, because this project deal with narrow space, we decided to design a new holder where the end part of ball screw does not needs to attach to the body of the robot, instead it will be attached to a ring that can hold the end part screw. In the small ring, there will have a bearing that will help screw rotate. The ring is shows in figure below.

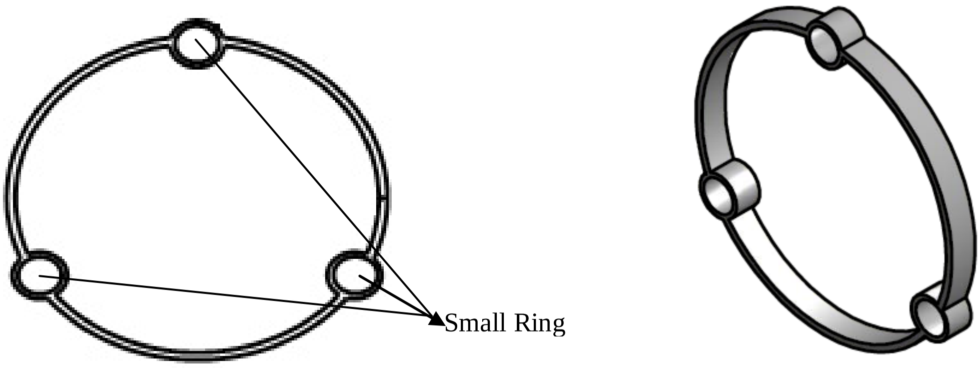

Fig 4.14 Ball Screw Holder

This ball screw holder will be attached to the body of the robot. The small ring is dividing to 3 where it is 120 degree between each small ring.

4.2.3 Rear Platform

The rear platform is the brain for this robot where is consist a circuit to control the motor and sensor for inspection. For this project, it has been decided that the robot will have two circuit board; one for the driving mechanism and another one is pipe diameter adaptation changing. With this, it will be easy to handle the circuit of this robot. And, here also have the power source to supply the power to equipment. The control system strategy for the active pipe diameter changing will be discussed in the discussion below.

4.3 Kinematics Analysis

4.3.1 Pipe Diameter Adaptive Mechanism

Kinematic is the study of the mathematics of motion without considering the forces that affect the motion. Robot kinematic describes robot movements. Kinematic study deals with the geometric relationships that influence the system, and with the relationship between control parameter and the behaviour of a system in state space. In order to design the mobile robot for desired tasks and to create control system for the robot, the mechanical behaviour of the robot must be understand. Based on study by (Yan Y. Z., 2006)as a reference, the analysis for this inspection robot is done.

This robot has a pipe diameter adaptive mechanism where it is active to change to adapt to pipe diameter and adjust it tractive force. This robot composed of three set of parallelogram caterpillar leg that has been circumferentially spaced out 120° apart symmetrically. Each of the leg has a caterpillar track that been tide to it. Fig 4.11 illustrates the one of the three sets. The operation of the adaptive diameter mechanism is driven by a step motor with convenience to be controlled. This motor is called as adjusting motor. With this motor, it can drive rotation of the ball screw then can push parallelogram caterpillar leg to make the caterpillar track contact to inner wall of pipe, or adjust the pressure between driving caterpillar tracks and pipe wall. With this structural design, it is possible to realize this adaptive mechanism to adjust in wide range pipeline. The nut of ballscrew and pressure sensor is connected together by screw bolts. The pressure sensor is used to test all the pressure between all driving leg and pipe wall directly. This is useful to control the pressing of the driving mechanism. With this sufficient and stable tractive force can be obtain and can provide overload protection to prevent the mechanism overloading that can damage the parallelogram leg.

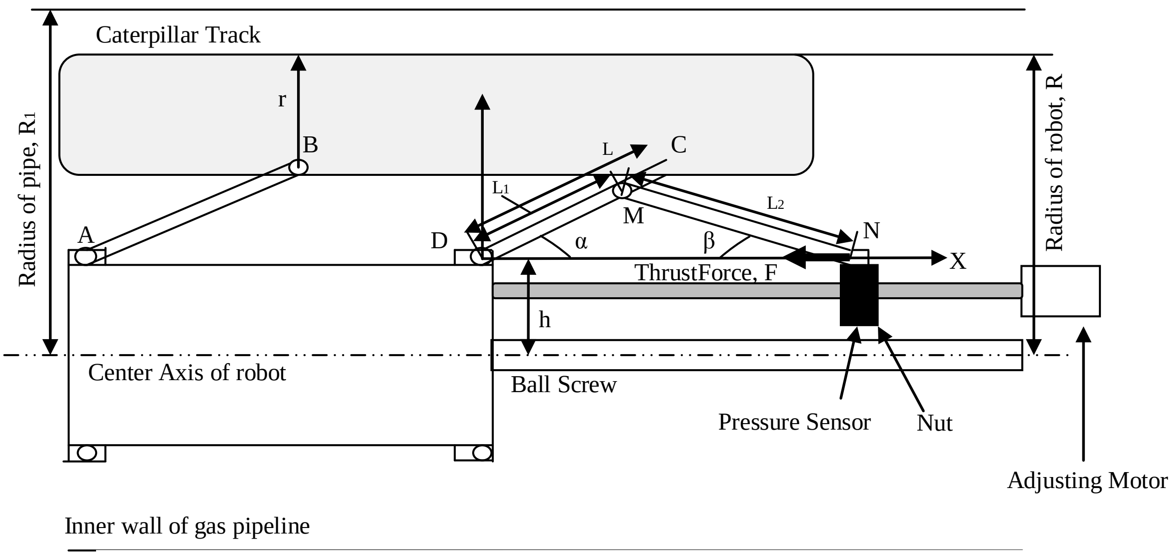

Figure 4.15: A parallelogram wheeled leg of pipe diameter adaptive mechanism

As in Fig 4.11, R is the radius of the robot, R1 is the radius of a pipe, h is denotes the height from the central axis of the inspection robot to supporting point D, r is the radius of a driving caterpillar track, L is the length of link CD, L1 is the distance between point D and point M, L2 is the length of link MN, α is the included angles between link CD and axis X, β is the included angles between link MN and axis X, and F denotes the thrust force of mechanism motion, which can caused by rotation of the ball screw and which can be measure by the pressure sensor.

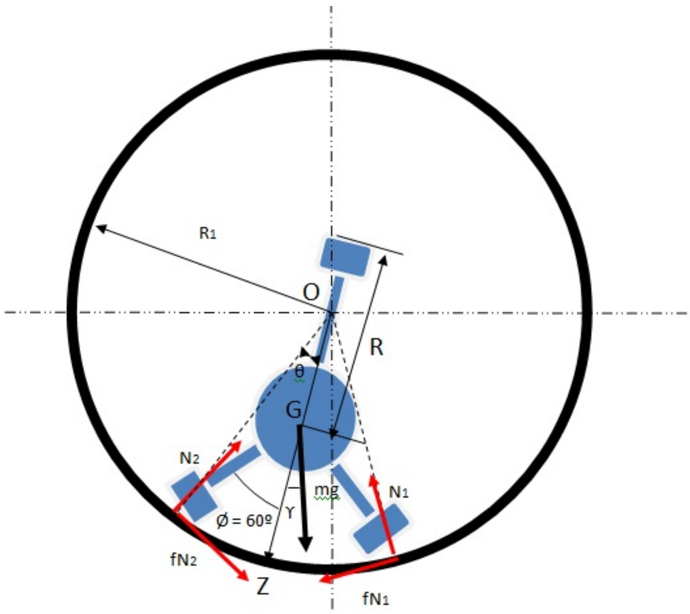

Figure 4.16: Force diagram

The inspection robot need to change it body size actively, to be able to do it, the adjusting motor must drives rotation to the ball screw with an output torque T and then produce thrust force F which can drive the translation of parallel linkage ABCD to change the radial size of the robot. When link ABCD moving, the others two set of leg will also perform same action synchronously.

Based on figure 4.12, the central axis of the robot doest not overlap the central axis of the pipe. Thus, an addition torque is required to overcome the opposition caused by the transverse friction between surface of pipe wall and the caterpillar tracks supporting the gravity. Since the structure of the robot is symmetric, its centre of gravity is denoted by symbol G can be assume at it central axis of the robot. In figure 4.12, symbol γ denotes the attitude angle of the robot which can be reflecting its rotation round the pipe. Meanwhile, N1 and N2 respectively denotes the supporting force acting on the two set of leg of driving mechanism by the gravity robot, θ is the included angle between axis OZ and the line from supporting point of the driving tracks to the pipe center, s is the arc length of θ, z is the coordination of G at axis OZ and f denotes the coefficient of transverse friction between driving wheels and pipe walls. From figure 4.11 and figure 4.12, we can conclude that the geometric relationship for this inspection robot is

$$\begin{aligned}
&R = r + h + L\sin \propto \\
&x = L_1 \cos\alpha + L_2 \cos\beta \\
&L_1 \sin \propto = L_2 \sin\beta \qquad (1) \\
&s = R_1\theta \\
&R\sin\emptyset = R_1 \sin\theta \\
&z\sin\emptyset = R_1\sin(\emptyset - \theta)
\end{aligned}$$

Where x is the coordinate of point N at axis X. Differentiating both sides of Equation (1) yields

$$\mathrm{dx} = -\frac{L^1(R-r-h)}{L}\left(\frac{1}{\sqrt{L^2-(R-r-h)^2}} + \frac{1}{\sqrt{L_2L^2- {L^1}^2(R-r-h)^2}}\right.$$

$$ds = \frac{R_{\ 1} sin^2 \phi}{\sqrt{R_1^2 - R^2 sin^2 \sin\phi}}\, dR \tag{2}$$

$$dz = -(\cos\phi + \frac{R\ sin^2 \phi}{\sqrt{R_1^2 - R^2 sin^2 \sin\phi}})$$

We assume there is no frictional heating. By considering a slope angle ø of pipe, we can obtain below formula by considering to equilibrium equation of forces and conservation energy.

$$\begin{cases} \Sigma N = N_1 + N_2 = \frac{mg\cos\varphi\cos\gamma}{\cos\theta} = \frac{mg\cos\varphi\cos\gamma}{\sqrt{R_1^2 - R^2 sin^2 \sin\phi}} \\ F\, dx + f\, \Sigma \mathrm{N}\ \mathrm{ds} = \mathrm{mg}\ \mathrm{dz}\cos\varphi\cos\gamma \end{cases} \tag{3}$$

where $\sum$N is the sum of all supporting force.

If we define

$$\begin{cases} k_1 = -\frac{L_1(R-r-h)}{L}\left(\frac{1}{\sqrt{L^2-(R-r-h)^2}} + \frac{1}{\sqrt{L_2L^2- {L^1}^2(R-r-h)^2}}\right. \\ k_2 = \frac{R_1\ sin^2 \phi}{\sqrt{R_1^2 - R^2 sin^2 \sin\phi}} \\ k_3 = \cos\phi + \frac{R\ sin^2 \phi}{\sqrt{R_1^2 - R^2 sin^2 \sin\phi}} \\ k_4 = \frac{R_1}{\sqrt{R_1^2 - R^2 sin^2 \phi}} \end{cases} \tag{4}$$

And substituting Equation (2) into Equation (3), we can have

$$F = \frac{mg\cos\varphi\cos\gamma}{k_1}\ (k_2 k_4 f + k_3) \tag{5}$$

Then, the output torque of the adjusting motor can be written as

$$T = \frac{P_h}{2\pi\eta} F \tag{6}$$

Where η denotes the efficiency of the ball screw, meanwhile *Ph* is the leads of the ball screw.

4.3.2 Mechanism of Tractive force adjusting

For the inspection robot to be able to moving in a pipeline by pull its tether cable from the camera and other equipments while travelling inside a gas pipeline to complete it maintenance, it must have sufficient tractive force. As been discuss early in literature review, for an object to moving forward it must have enough driving force. This tractive force is determined by adhesion force which depends on the normal pressure and adhesion coefficient between caterpillar tracks and pipe wall. Thus, this robot that have the ability to adaptive changing it diameter is capable to adjust its tractive force also.

When the robot is moving along a distance pipe, more tractive force is demanded to overcome increasing friction resistance of the tether cable and another resistance caused by the pipe. As when the robot produce more driving force to moving, the adhesion force maybe become insufficient and may make the driving tracks slip on the surface of the pipe wall. Therefore, additional pressure enhancing the adhesion force can be produced by the pipe diameter adaptive mechanism to increase the tractive capacity of the robot.

The mechanical model of the robot needs to be analysis. This can be establish by define the sum of all pressures applied to driving tracks as a supporting force denoted by $\sum N$ and sum of pressure produced by pipe changing mechanism as additional pressure denoted by symbol $\sum P$. As shown in figure 4.13, the central axis of the robot is nearly overlaps the central axis of the pipe during the adjustment of tractive force. Therefore, there will be one or two parallelogram legs will support the gravity of the robot depends on any attitude angle of the robot. In the figure 4.13, the supporting force applied to three set of leg is denotes by symbol N_1, N_2 and N_3. We can define that attitude angle along counter-clockwise is positive and vice versa.

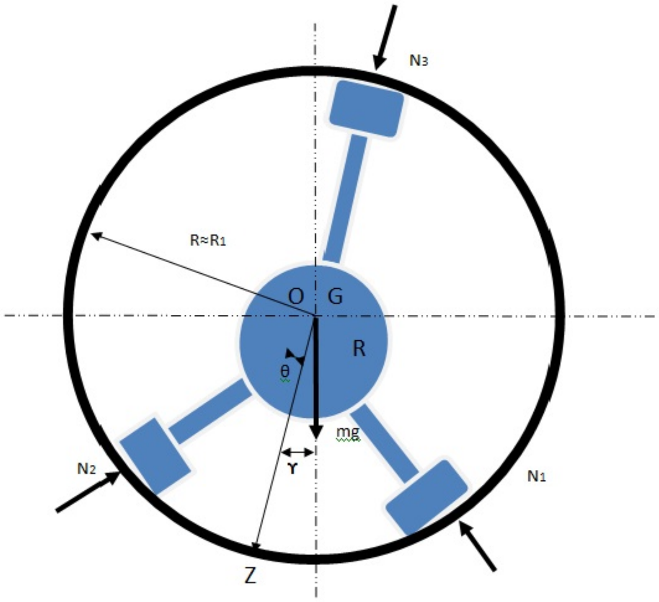

Figure 4.17: Supporting force distribution

$$N_3 = 0 \quad -60° \le \gamma \le 60°$$
$$N_1 = 0 \quad 60° \le \gamma \le 180° \qquad (7)$$
$$N_3 = 0 \quad 180° \le \gamma \le 180°$$

We can obtain equation according to equilibrium of forces

$$\begin{cases} N_1 \cos(\gamma + 60°) + N_2 \cos(60° - \gamma) = mg \\ N_1 \sin(\gamma + 60°) - N_2 \sin(60° - \gamma) = 0 \end{cases} \quad -60° \le \gamma \le 60°$$
$$\begin{cases} N_2 \cos(\gamma - 60°) + N_3 \cos \gamma = mg \\ N_2 \sin(\gamma - 60°) - N_3 \sin \gamma = 0 \end{cases} \quad 60° \le \gamma \le 180° \qquad (8)$$
$$\begin{cases} -N_3 \cos(\gamma) + N_1 \cos(60° + \gamma) = mg \\ -N_3 \sin(\gamma) - N_1 \sin(60° + \gamma) = 0 \end{cases} \quad 180° \le \gamma \le 300°$$

By solving equation (8) and considering the slope angle ø, we can have

$$\Sigma N = \begin{cases} 2mg \cos\gamma \cos\varphi & -60° \le \gamma \le 60° \\ 2mg \cos(\gamma - 120°) \cos\varphi & 60° \le \gamma \le 180° \\ 2mg \cos(\gamma - 240°) \cos\varphi & 180° \le \gamma \le 300° \end{cases} \qquad (9)$$

The tractive force of the robot can de determine if the driving force of the motion motor is sufficient

$$\mathrm{F_T} = (\Sigma \mathrm{N} + \Sigma \mathrm{P})\mu \qquad (10)$$

where μ denotes the adhesion coefficient. Based on geometric relationship on equation (1), we have geometric relationship that depends on the X and Y axis where x is the coordinate of point N at axis X, meanwhile y is the coordinate of point E at axis Y. The equation is

$$R = r + h + L \sin \propto$$
$$y = R - h$$
$$x = L_1 \cos \alpha + L_2 \cos \beta \quad (11)$$
$$L_1 \sin \propto = L_2 \sin \beta$$

If we differentiate both sides of above equation, we can yields

$$\delta y = \delta R \quad (12)$$
$$\delta x = -k_1 \delta R$$

By applying principle of virtual displacement yields

$$(\Sigma N + \Sigma P)\, \delta y + F \delta x = 0 \quad (13)$$

Substitute Equation (12) and Equation (13), we can obtain

$$F = \frac{1}{k_1} (\Sigma N + \Sigma P) = \frac{1}{k_1 \mu} F_T \quad (14)$$

By that, the required output torque of adjusting motor obtain is

$$T = \frac{P_h}{2\pi\eta} F \quad (15)$$

The variation of the thrust force F, output torque T of the adjusting motor, additional pressure $\sum P$, and tractive force F_T was a combination of equation from equation (9),(10),(14) and (15) to make the tractive force adjusting possible.

4.5 Discussion

4.5.1 Active adaptation to pipe diameter

Based on the mechanical model of active adaptive diameter above, both the required thrust force, F and output torque, T change with respect to diameter change behaviour, R_1 and R. Both F and T have different variation as different pipe diameter as for this project is 6 inches to 10 inches. This can be shown in figure 4.18, 4.19 and 4.20 below where the pipe diameter is D=2R and $D_1=2R_1$. The required F and T are more in pipelines with small diameter than in pipelines with large diameter.

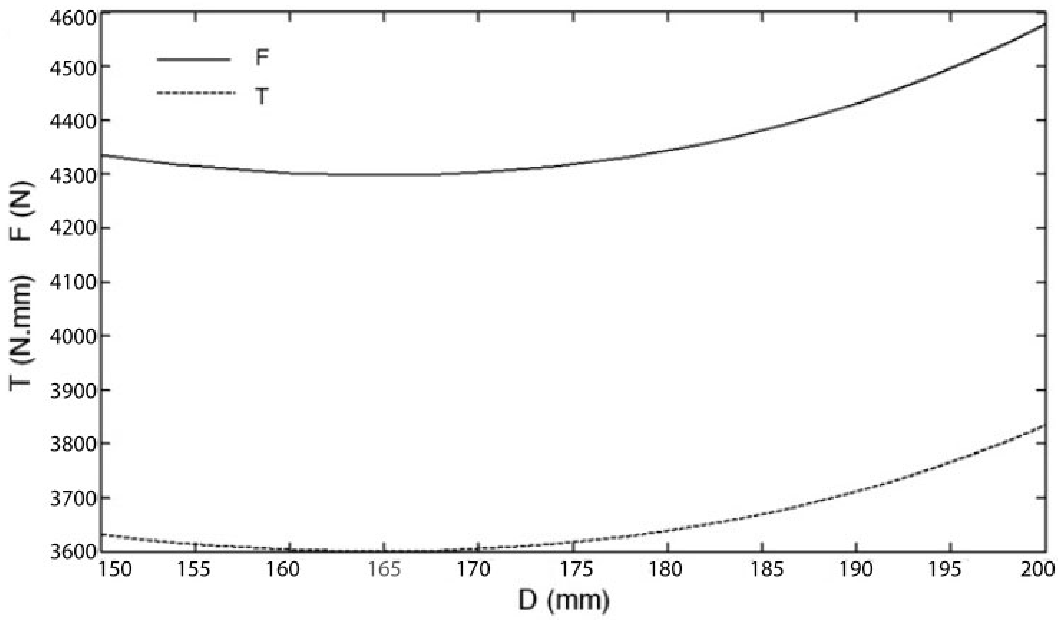

Figure 3.18: Variation of F and T versus robot radial size in different pipe diameter ,D1 = 200mm

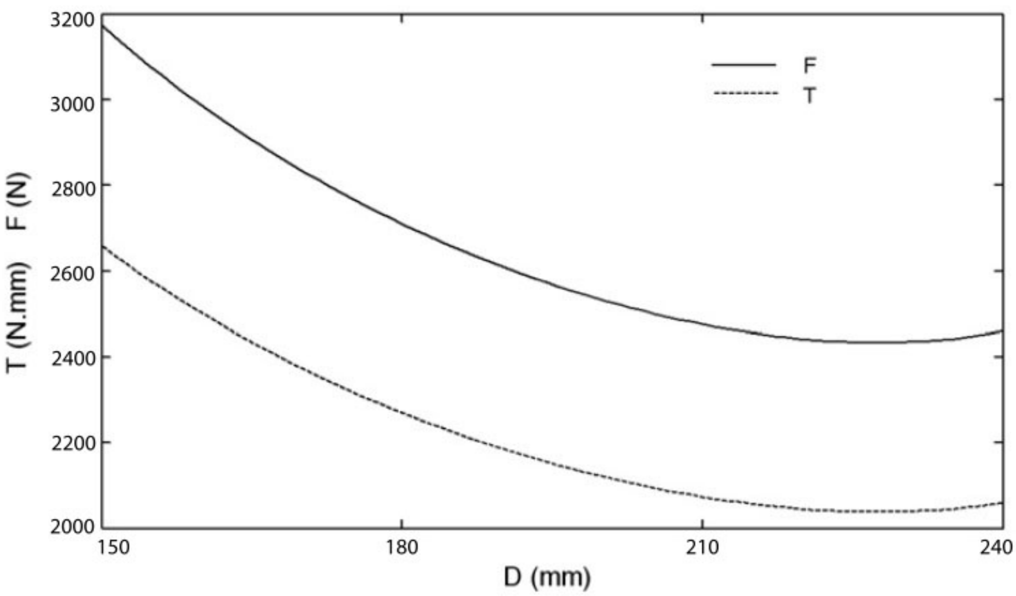

Figure 4.19: Variation of F and T versus robot radial size in different pipe diameter, D1 = 240 mm

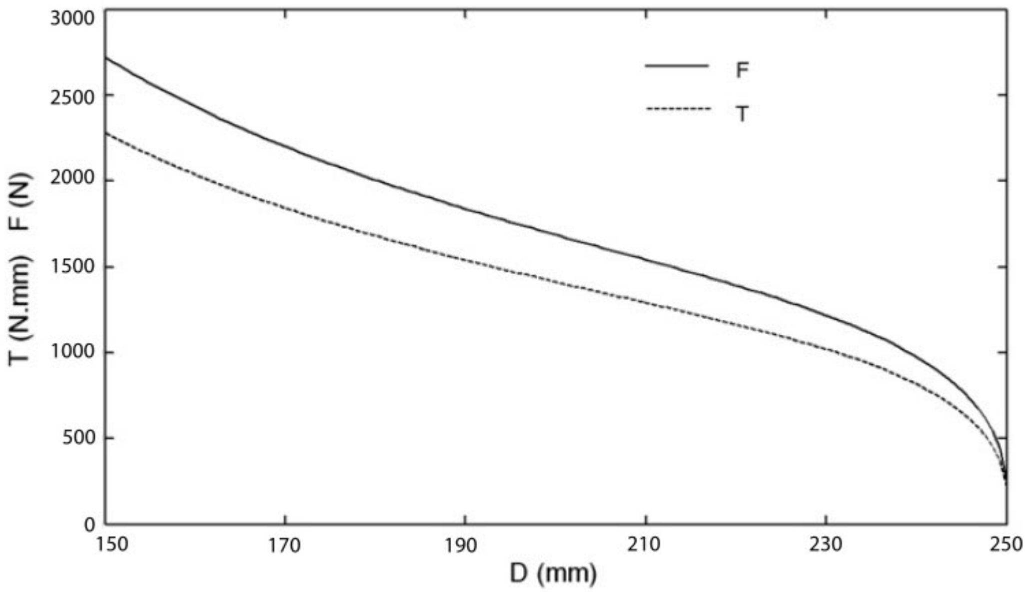

Figure 4.20: Variation of F and T versus robot radial size in different pipe diameter, D1 = 250 mm

In order to prevent the adjusting motor from overloading, speed reducer can be placed between the adjusting motor and ball screw. The strength and rigidity of related component bearing load need to verify. This can be seen in figure 4.21 below where the related component is link between the body and driving mechanism which is the parallelogram leg. This figure show that the loads from the changing diameter can affects the leg at the screw hole. Besides that, the material that be used also can be reduced as the figure show that the stress at the body is low.

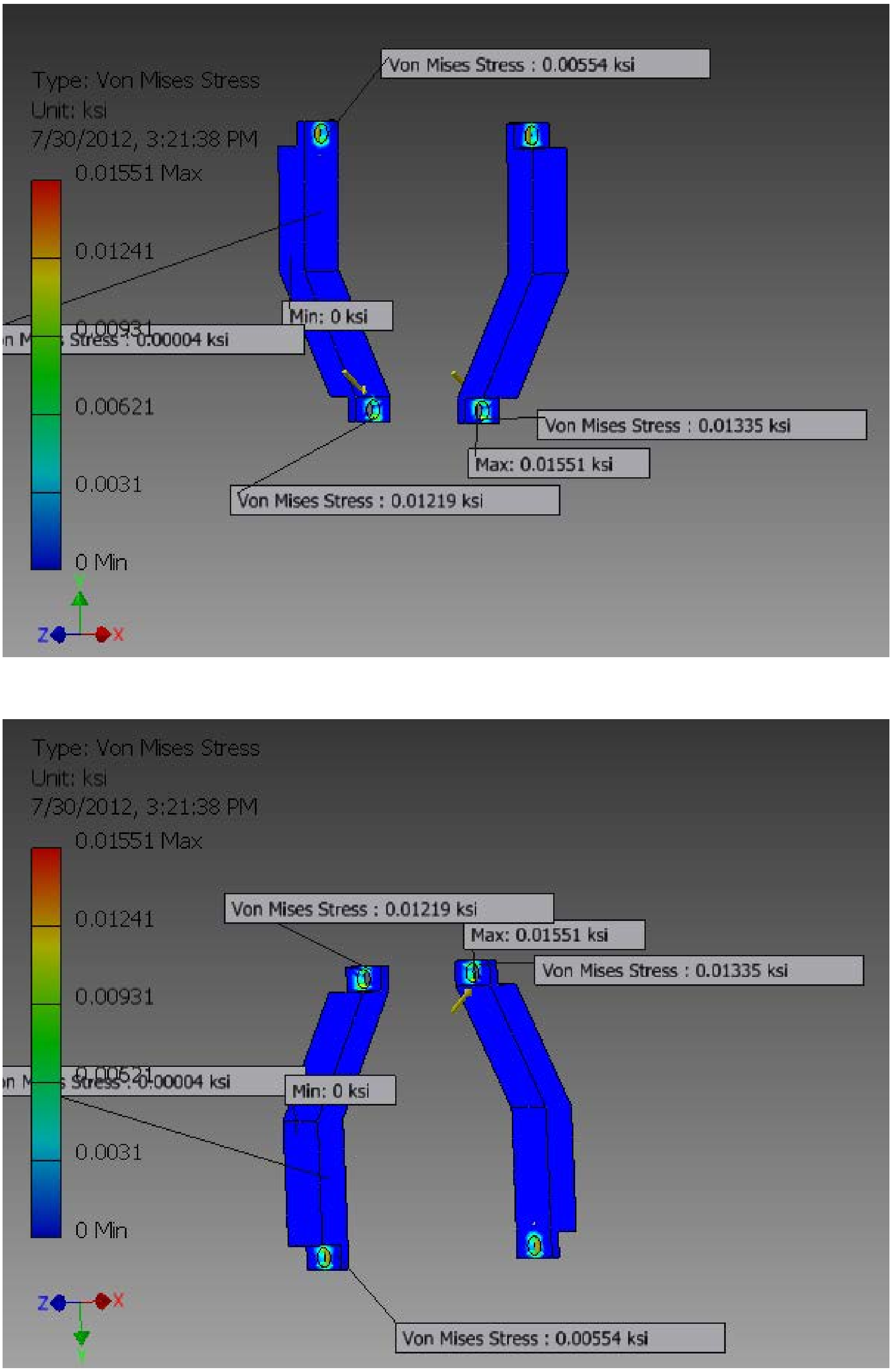

Figure 4.21: The von Misses Stress on loading that affect from the ball screw movement.

4.5.2 Tractive Force Adjusting

From equation (4), the first derivative of it respect to the R can equals

$$\frac{dk_1}{dR} = \frac{L_1}{L}\left(\frac{1}{\sqrt{L^2-(R-r-h)^2}} + \frac{L_1}{L^2L_2^2-L_1^2(R-r-h)^2}\right) + \frac{L_1(R-r-h)}{L}\left(\frac{R-r-h}{L^2-(R-r-h)^2} + \frac{L_1(R-r-h)}{L^2L_2^2-L_1^2(R-r-h)^2}\right) > 0 \qquad (16)$$

By substituting equation (16) into the first derivative of equation (14) with respect to R yields

$$\begin{cases} \frac{dF}{dR} = \frac{dF}{dk_1}\frac{dk_1}{dR} = -\frac{(\Sigma N+\Sigma P)}{k_1^2}\frac{dk_1}{dR} < 0 \\ \frac{dT}{dR} = \frac{P_h}{2\pi\mu}\frac{dF}{dR} < 0 \end{cases} \qquad (17)$$

as we can see, in the process of tractive force adjusting, R ≈ R1. Equation (17) shows that both F and T decrease as the pipe diameter increase. It also show that to produce a same tractive force needs a different thrust force, F and output torque, T of the adjusting motor in case of changing diameter.

The changing diameter mechanism can adjust robot diameter and adjust it tractive force through additional pressure. Increase the tractive capacity of the robot will need improvement of the additional pressure. But, as the additional pressure increase, the loads distributed to the part of the robot and it related components will also increase. Therefore, it is necessary to restrict this adjusting in a reasonable range according to the limit that has been set in the design.

4.5.3 Optimal Attitude angle

The weight of the robot is one of the factors that contribute to the tractive capacity for the robot. As this robot is mainly made from the stainless steel, the weight is quite heavy. Weight of the robot became factor contribute to the tractive force and we define it as the ration of the total supporting force ∑N to the weight of the robot, mg as the weight use factor I_g. This ratio is used as references how much weight of the robot contributes to its tractive force. This is show in equation (18)

$$I_g = \frac{\Sigma N}{mg} = \begin{cases} 2\cos\gamma\cos\varphi & -60° \le \gamma \le 60° \\ 2\cos(\gamma - 120°)\cos\varphi & 60° \le \gamma \le 180° \\ 2\cos(\gamma - 240)\cos\varphi & 180° \le \gamma \le 300° \end{cases} \tag{18}$$

This equation is illustrates in figure 4.15. From this figure, it shows that the travelling attitude of the robot inside the pipe may affect it tractive capacity. This effect depends on the weight of the robot. Therefore, the inspection robot must be keep one optimal attitude angle of γ =0º, γ = 120º and γ = 240º to efficiently utilizes its weight to improve its tractive capacity.

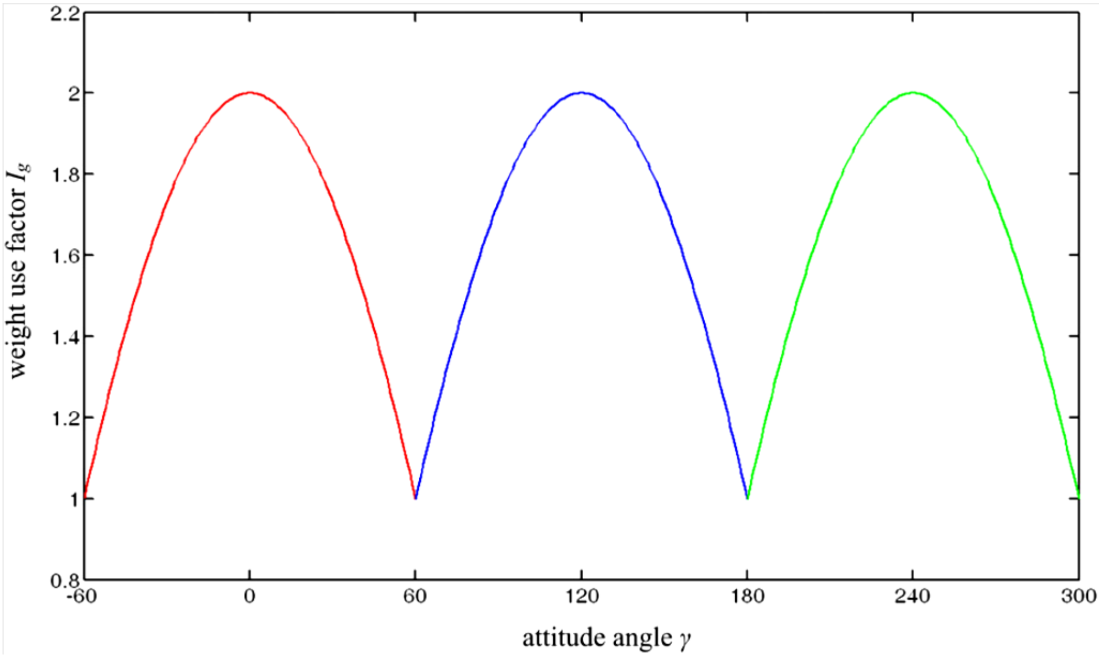

Figure 4.22: Variation weight use factor versus attitude angle

4.5.4 Control System Strategy

Control system is important in make the inspection robot can be tested as a working system. The control system of this inspection robot is illustrated in figure 4.16 where F_{Td} denotes the desired tractive force and F_d denotes as the desired thrust force.

The control system proposed here is mainly for the active pipe diameter changing. It involves two aspects. Firstly, the inspection robot will adjust it radial size to press against wall pipe. When pipe radius R1 changes, it will be captured by a pipe diameter sensor. Then, the control system compares current R1 with current radials size of inspection robot R. If the difference between R1 and R is more than a desired value Δ, the PD controller operates the pipe diameter adaptive mechanism to change it radial size of the robot until the difference is less than Δ. Second aspect is the control system adjust it actual tractive force Ft of the inspection robot to track the desired tractive force F_{Td}. The desired value of the thrust force Fd can be calculated by using the mechanical model if given desired tractive force F_{Td}.

Therefore, the input from real-time feedback comparison between actual thrust force, F and the desired thrust force, Fd is use to actuate the PID controller for adjusting motor. By implement this control system in the inspection robot system, it can automatically adjust itself to a desired diameter by giving sufficient tractive force.

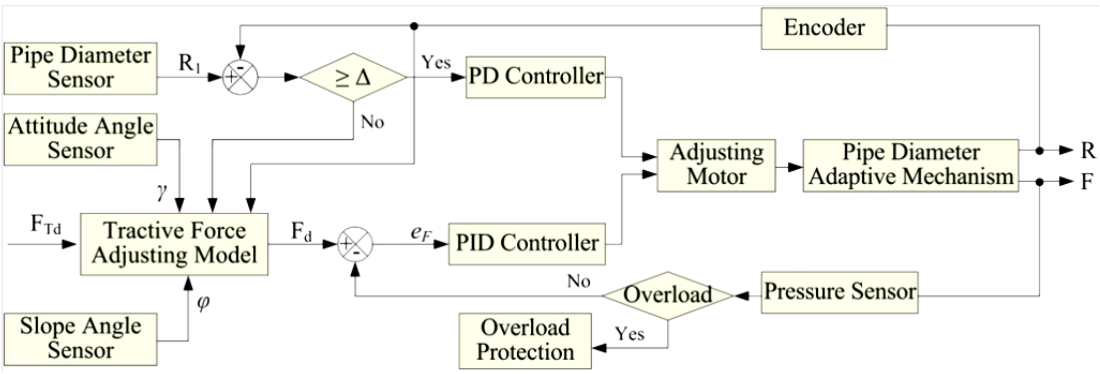

Figure 4.23: Block Diagram of Control System

CHAPTER 5
CONCLUSION

5.1 Conclusion

I can conclude that designing and develop the pipe crawling robot can help the gas industry and other in doing the maintenance job more efficient. Further study must be conducted in order to confirmed that all methodology in this proposal is relevant in the process of acquire the wanted data. This project is still in planning stage and hopefully that this project will run smoothly according to the time and source allocated to achieve the objective.

However, this progress just concentrate on the paperwork of the project which given detail idea to construct the project flow. Based on the previous research paper that related with the project, this project is feasible to be performed since the mechanical design of the robot quite same for the entire previous project. The part of the mechanism is same. Thus, it proofs that the project is relevant to be proceed and the results just depends on the implementation of it.

5.2 Recommendation for Future Works

Some improvement need to be done before be able to build the prototype. And some more analysis need to done, so the cost and performance of the robot is in optimum level. More feasibility study needs to be done on the performance of the inspection sensor.

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Appendix I

The **Evolution** of Pipe Inspection

Inuktun technology lets you… see it for yourself.

INUKTUN
CRAFTSMANSHIP IN HIGH TECHNOLOGY

see it for yourself.

MICROTRACS

Able to operate in confined spaces within hazardous environments, submerged or on land, our modular Microtrac™ crawler units give you control and maneuverability in even the most inaccessible pipes and duct work. Available in brass, stainless steel or aluminum construction, our precision machined Microtrac™ units can be adapted to upgrade your existing inspection vehicle or built into a complete system tailored to the specific needs of your industry.

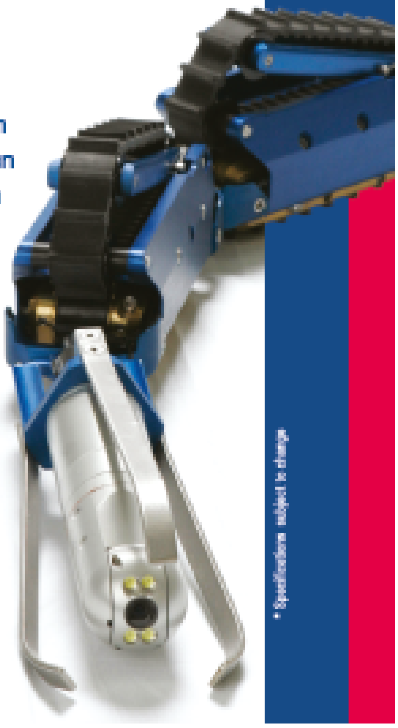
OPERATING ENVIRONMENT

Temp 0-50°C (32-122°F)
Power Voltage 24VDC
Current 2A@24VDC (max load)
Depth Rating 0-30m/0-100ft

TRANSPORTER UNITS

Speed 0 to 9 m/0 to 30 ft per minute
Pull Rating 6.5kg/15lbs per track
Payload Capacity 10.8kg/24lbs per track
Dimensions 6cm (H) X 5cm (W) X 17cm (L)
2.25" (H) X 2" (W) X 7" (L)
Weight (ea) Aluminium - 1.4kg/3lbs
Brass - 2kg/5lbs
Stainless Steel - 2kg/5lbs

For more information on advanced pipe inspection systems contact Inuktun today.



CALL 1 877 468 588
E-MAIL sales@inuktun.com
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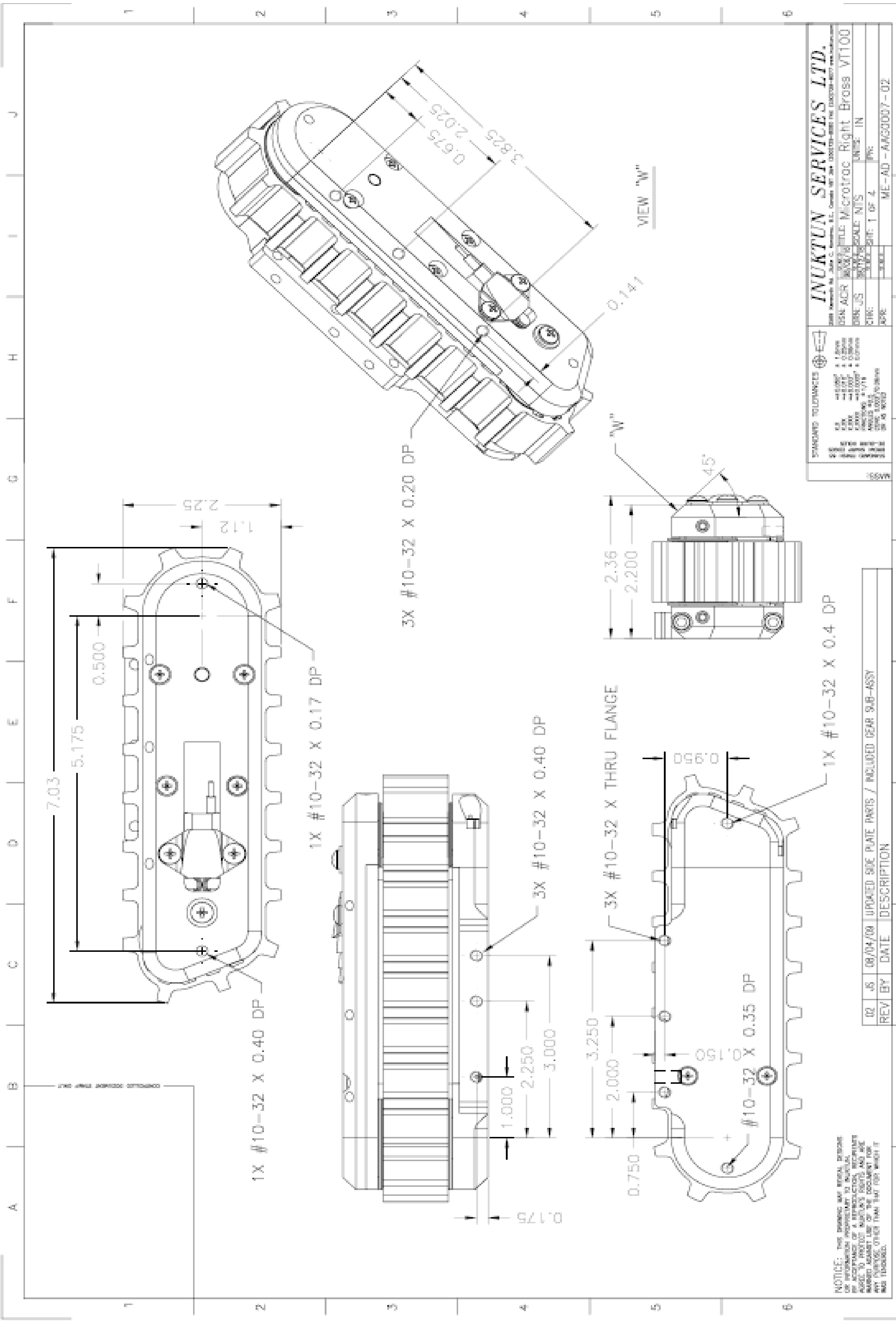
* Specifications subject to change

Appendix II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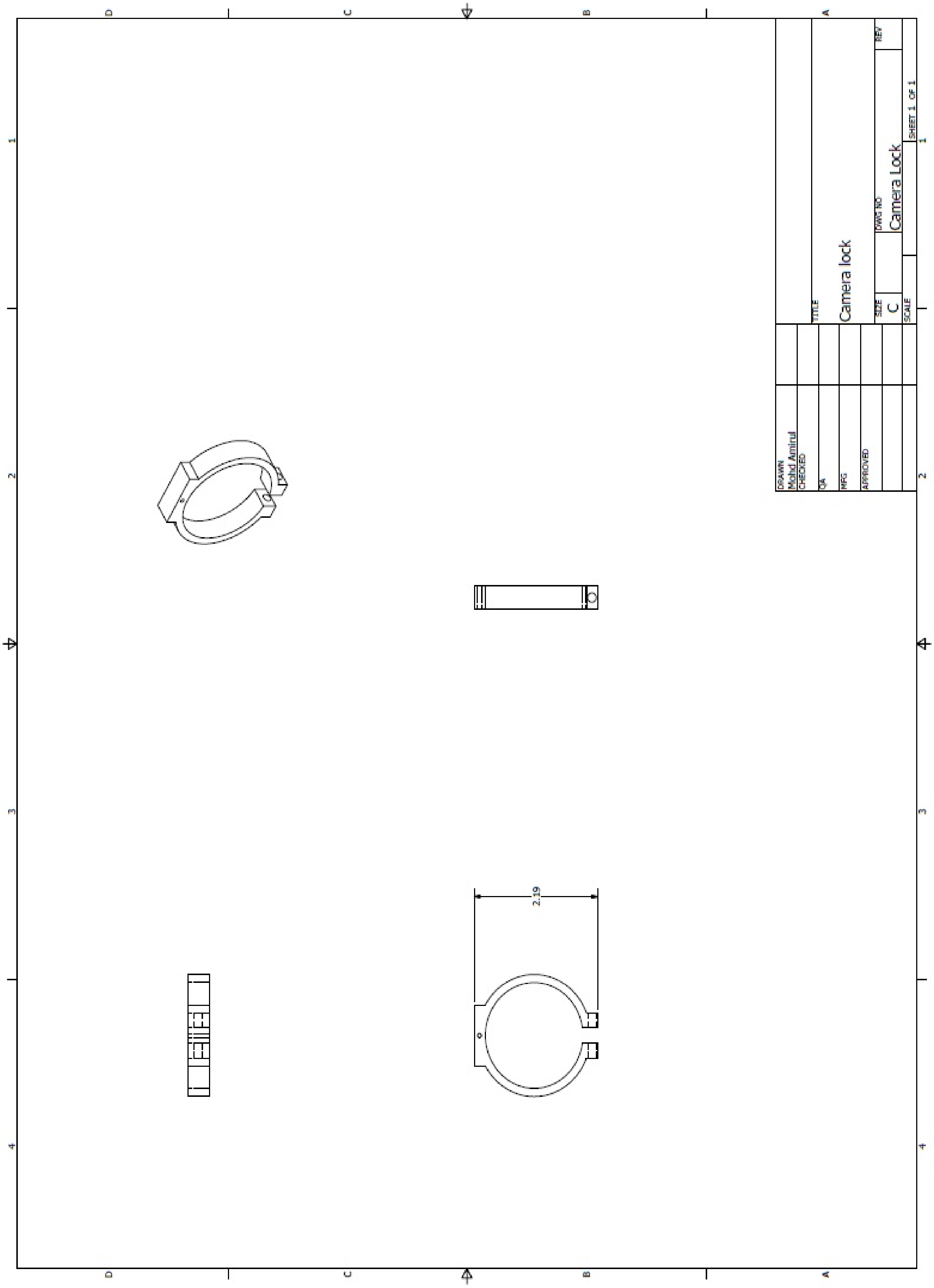
5.175
0.500
2.25
1.12
1X #10-32 X 0.40 DP
1X #10-32 X 0.17 DP
3X #10-32 X 0.20 DP
0.675
2.025
3.825
0.141
VIEW "W"
"W"
45°
1.000
2.250
3.000
0.175
3X #10-32 X 0.40 DP
3.250
2.000
0.750
3X #10-32 X THRU FLANGE
0.950
0.150
#10-32 X 0.35 DP
1X #10-32 X 0.4 DP
2.36
2.200
02 | JS | 08/04/09 | UPDATED SIDE PLATE PARTS / INCLUDED GEAR SUB-ASSY
REV | BY | DATE | DESCRIPTION
INUKTUN SERVICES LTD.
TITLE: Microtrac Right Bross VT100
DSN: ACR
DRN: JS
SCALE: NTS
UNITS: IN
SHT: 1 OF 4
ME-AD-AAG0007-02

Appendix III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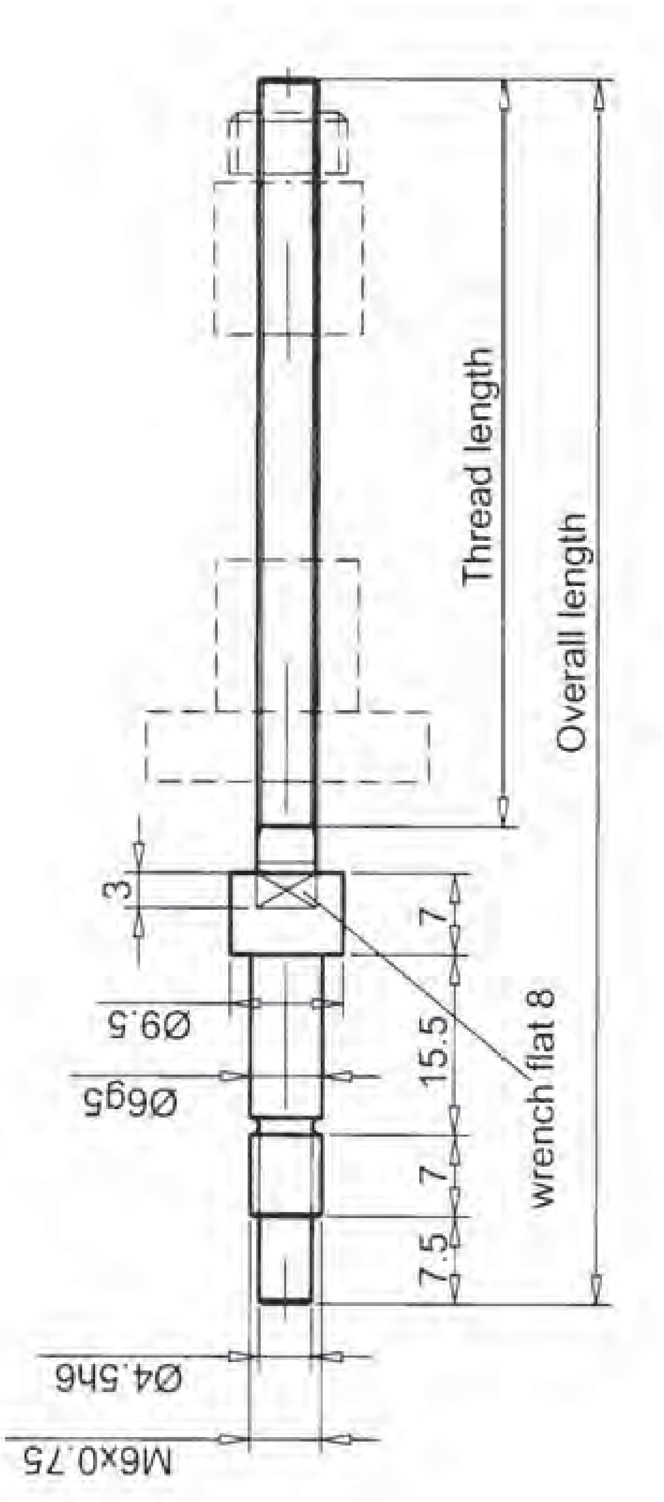
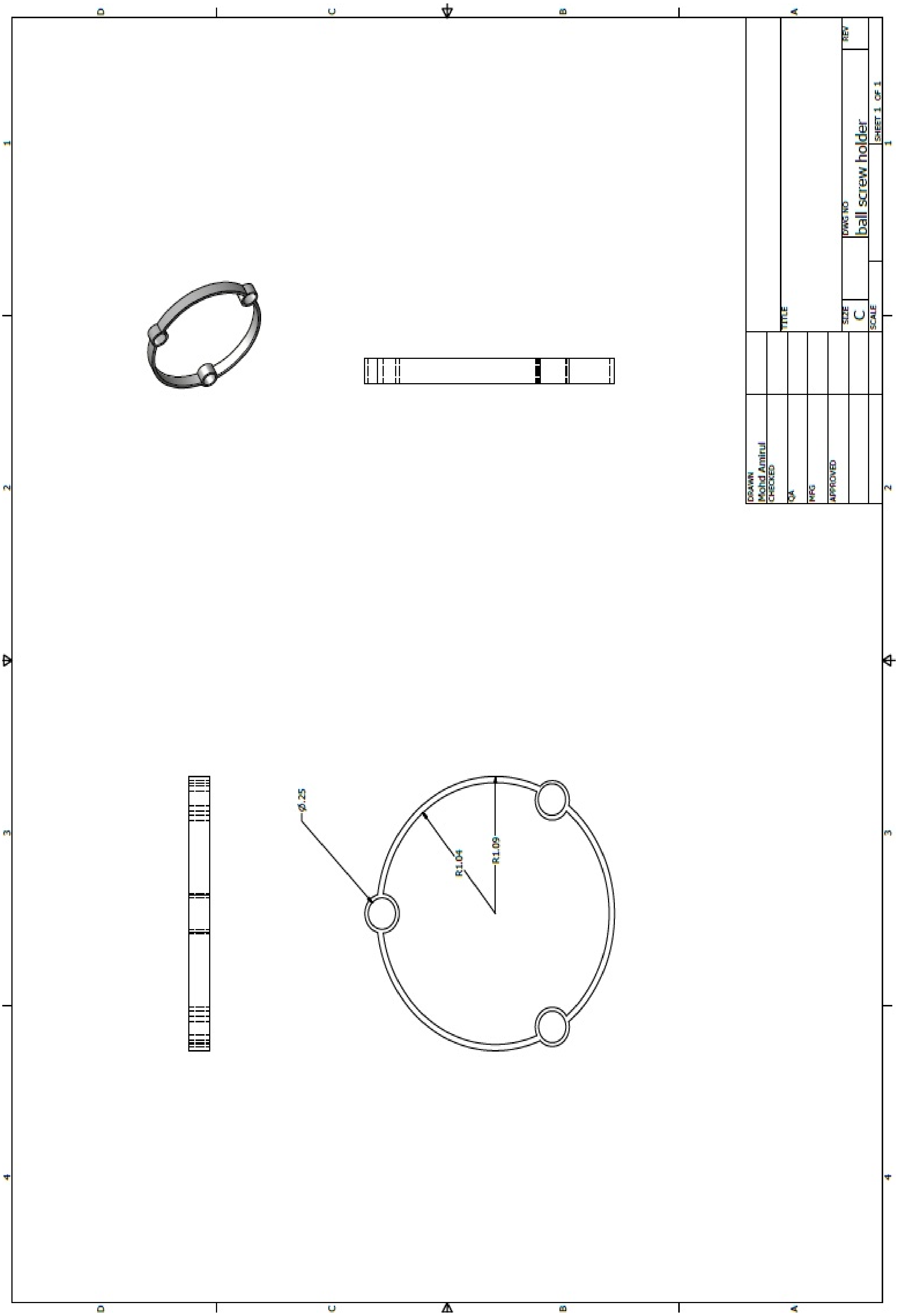
Camera lock
SIZE
C
DWG NO
Camera Lock
REV
SCALE
SHEET 1 OF 1
DRAWN
Mohd Amirul
CHECKED
QA
MFG
APPROVED
2.19

Appendix IV



Thread length
Overall length
wrench flat 8
3
7
15.5
7
7.5
Ø9.5
Ø6g5
Ø4.5h6
M6x0.75

Appendix V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R1.04
R1.09
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Mohd Amirul
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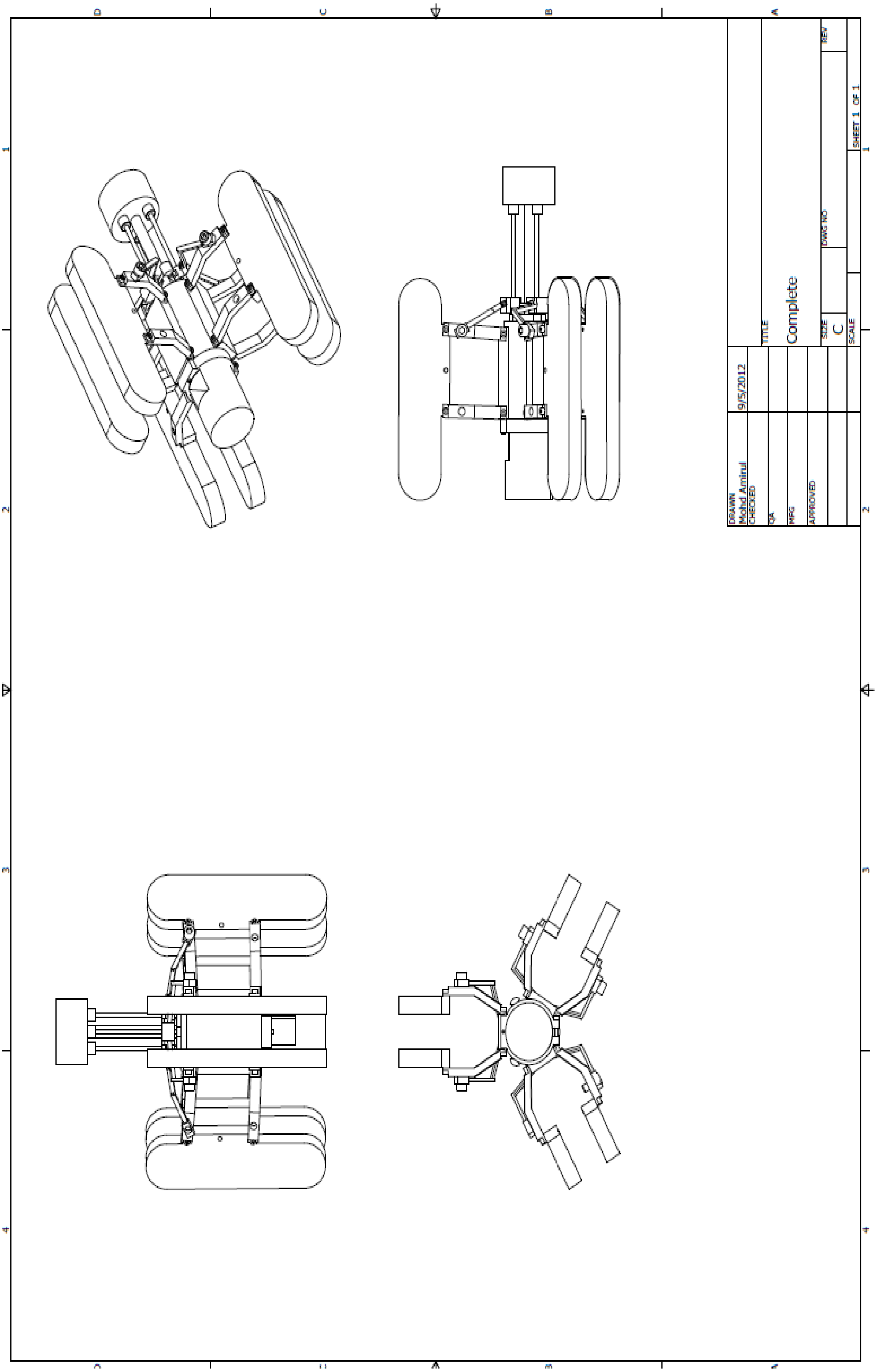
ball screw holder
REV
SCALE
SHEET 1 OF 1

Appendix VI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Mohd Amirul
9/5/2012
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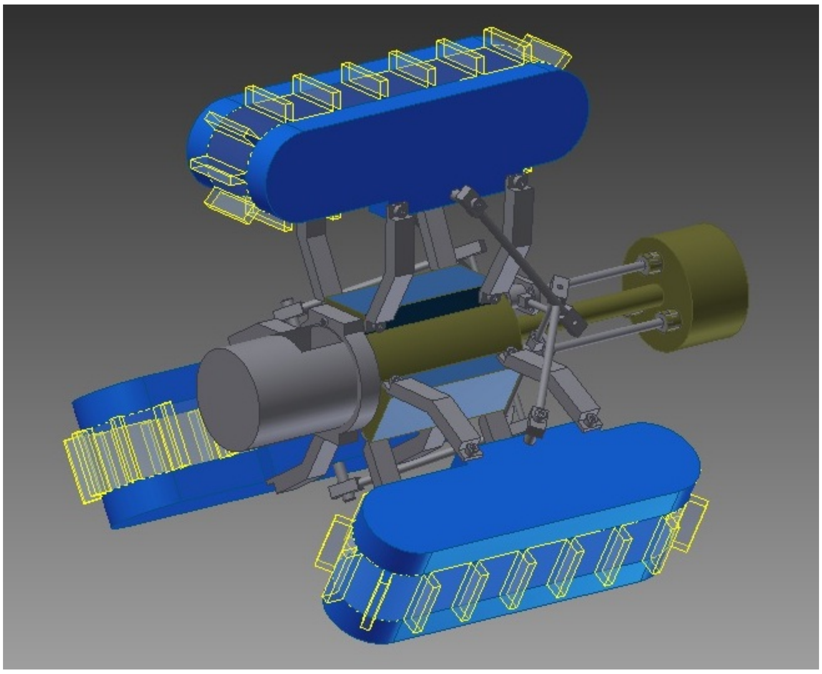
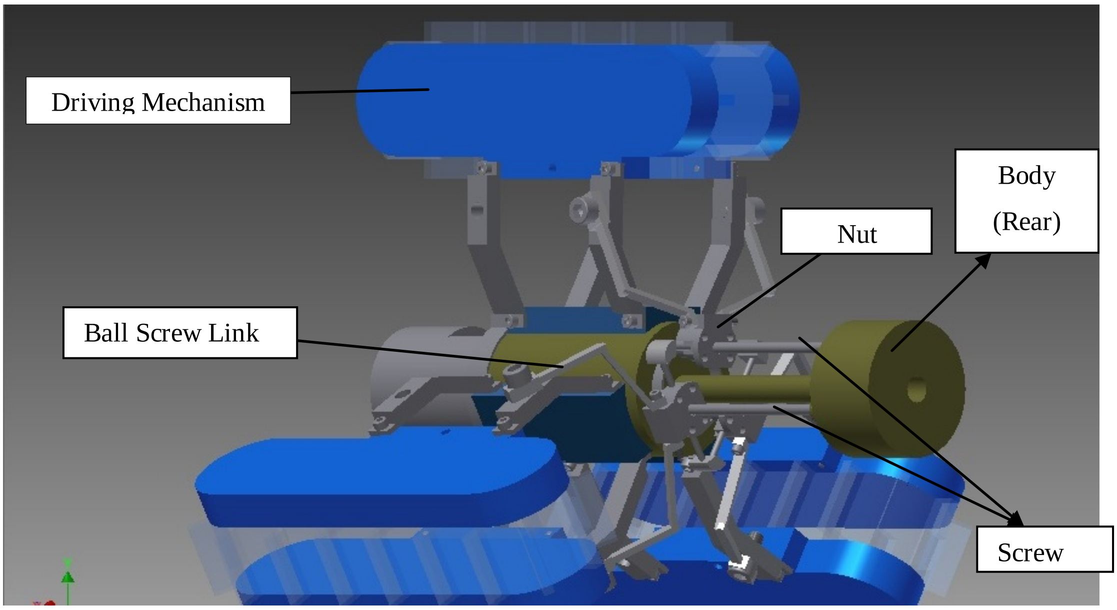
SHEET 1 OF 1

Appendix VII





Front and Back of the robot