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HYDRAULICS DESIGN AND SIMULATION OF NEW KIND OF LEG

Master of Science Thesis

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ABSTRACT

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Rolking leg is the phenomena which represent those legs which has the capability of rolling as well as walking. The importance of this kind of leg is that it removes the drawbacks which are present in both rolling and walking kinds of leg phenomena. Rolking leg is not only smooth but also can move with some good speed from different kind of terrain. Rolking leg with electric actuators is already been researched in Helsinki, but they are not for carrying load. That is the one goal given by General Intelligent Machines (GIM) to Department of Intelligent Hydraulics and Automation (IHA) to have such hydraulic actuated leg which can carry heavy load.

In this master thesis goal is to choose the hydraulic components which are necessary for the rolking leg. Implementation of hydraulic system in order to carry the heavy load cannot be denied, because the electrical actuator can work upto some extent but they are not long term solution. Selection of hydraulic cylinders and valves came into existence according to the need of leg and the weight it has to carry. After selection of components, simulation of designed rolking leg has been made and control system to lift and lower the leg in Matlab.

A rough terrain has been given to leg through which it has to pass and leg frame stability has been monitored as well behavior of hydraulic system to gain the stability. All the results shown with having quite reasonable behavior of selected hydraulic components as well as the stability of rolking leg frame.

PREFACE

The research work in the master thesis is a part of the project by General Intelligent Machines (GIM) in Department of Intelligent Hydraulics and Automation (IHA) at Tampere University of Technology (TUT).

I would like to thank Prof. Kalevi Huhtala that he gave me the chance to work in this project than my whole heartedly thanks to my supervisor Janne uusi-Heikkila for his guidance, patience, support, advice and gave me the precious time from his busy schedule. I would also like to thank my project partner Jari Jaatinen for such nice behavior throughout this time and I learned a lot from him. I would like to mention my thanks to Mika Hyvonen and Mikko Myllymaki whose previous work on this project has been studied, researched and used where necessary in initial phase of the project.

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I would like to thanks my family and would like to dedicate my thesis to my mother for her love and support.

Tampere, February, 2013

Faisal Mehmood

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ACRONYMS AND NOTATION

RL	Rolking Leg
IHA	Department of Intelligent Hydraulics and Automation
TUT	Tampere University of Technology
GIM	General Intelligent Machine Research Group
DARGA	Defense Advanced Research Group Agency
ALDURO	Anthropomorphically Legged or Wheeled Duisburg Robot
PI	Proportional integral

P	Hydraulic pump
T	Hydraulic tank
A	Cylinder piston port
B	Cylinder rod port
G	Centre mass of gravity
F_{rear}	Force at rear wheel
F_{front}	Force at front wheel
D_{s1}	Cylinder 1 and joint distance
D_{s2}	Cylinder 2 and joint distance
L1	Length of main link
L2	Length of tilt link
α	Joint 1 angle
β	Joint 2 angle
A_p	Piston area
A_r	Rod area
d_p	Piston diameter
d_r	Rod diameter
V_p	Piston Side Volume
F_p	Piston force
F_r	Rod force
L/min	Litre/min
R_e	Reynold's number
ρ	Density of fluid
v	Flow velocity
d	Hydraulic diameter
μ	Dynamic viscosity

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1. INTRODUCTION

1.1. Background

From an ordinary robot to high load capacity machines, many parts they are been researched in different laboratories to make these robots works better and more precise. The part which also really affects the final results and precision of robot is leg mechanism of robots. As the demand is increasing of having smooth movement of heavy load machines like in the forestry machines, more research work is being carried out on the legs. The legs which are studied previously are the mammal's legs and the wheel legged. Both legs have their own advantages and disadvantage the reason to use in different robots. In mobile machines mostly the mammals leg phenomena is used because these legs they are good in rough and extreme terrain but they lack high speed, while the wheeled legged mechanism is good in having the high speed on smooth terrain but they are not favorable in case of rough terrain. Almost half of the earth is not accessible with wheeled vehicles because in heavy machineries have to undergo different kinds of terrains.

In order to sum up advantage of both kind of legs it is been researched to make the leg which should be the combination of mammal and wheel legged mechanism. The word rolking is been used for such kind of legs i.e. rolling as well as walking. It means that mechanism is designed in such a way that it has the capability of walk as well as roll. Rolking leg mechanism is been under research study from very long time, because the idea about the rolking leg is to have machine carrying the heavy load or sensitive instruments and it is passing through the rough terrain, due to combine advantages of both these rolling and walking phenomena's in the leg, machine body remains the stable even after it moves from difficult terrain, and it even attain the high speed too. Aalto University of Technology has researched rolking leg successfully and result oriented but their research area was mainly focus on the electrical actuation of the leg, which makes the system unfit for the heavy loads and the load bearing capability of the rolking leg surely be affected when it is electrically actuated. To carry heavy loads up to approximately 4000 kg it was necessary to design hydraulic actuation system. So that's the idea which is been researched by IHA to design and simulate such hydraulic components for the rolking leg to make rolking leg capable of not only carrying heavy load but also capable of smoothing the frame position in the rough and variable terrain. Another phenomenon in Rolking leg which is under consideration is to make it energy efficient. The stability of the frame is the main issue on variable terrain.

The application of rolking leg can be seen that it is been used in heavy machinery like the forestry and rigging machines to very sensitive robots like Mars Curiosity.

1.2. Scope of work

The work which is carried out in this thesis work is to study the design model of the rolking leg which is two leg mechanisms, simulate the model of rolking leg, selection of suitable hydraulic components according to design consideration. The main emphasis of the thesis work is that we get the behavior the leg well before the test bench. So every single components justification has to be made by calculations and have foreseen by simulation too. From the simulation results the parameters of the hydraulic components has been decided.

A market survey has to be made in thesis work that these required parameter hydraulic components are they readily used in the commercial market or manufactured in the industry. So that a recommendations has been made to use them for the test bench.

The key feature of the rolking leg to design and simulate such hydraulic components which makes the frame of the leg stable. For that purpose control has to be designed which fulfill the requirement of frame stability.

2. THEORETICAL BACKGROUND

Worldwide different kinds of legs they are been used in different robots, and different approach has been researched and implemented to make them work. These legs phenomena's are given below

2.1. Different types of leg mechanism

Different types of the leg mechanism have been studied around the world in laboratories. In the leg types of walking robot important issue is of the number of legs. Because the number of the legs determined the speed of machines. Four leg robots are bit slower than the ones having six legs and also those can handle the balance of machine quite properly. When we are having six leg robots then it works on the principle of alternating tripods. That means that to support the robot or machine the two non adjacent legs of one side and middle leg of the other side alternate. [1]

The geometric model of the six leg robot is given in the Figure 2.1.

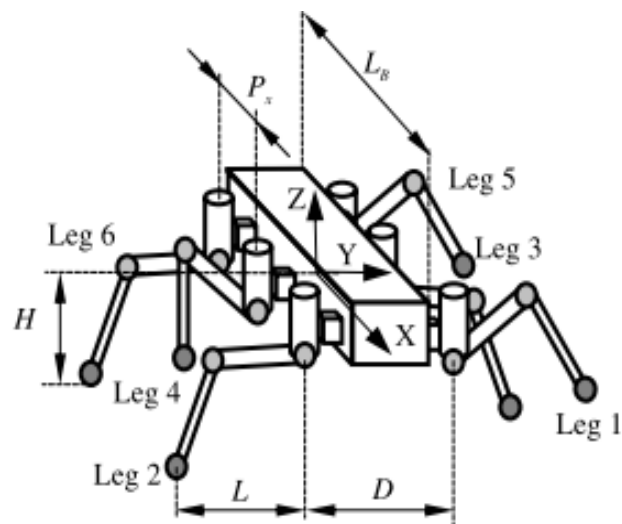


Figure 2.1. Six Leg Robot [1]

In a six leg walking kind of machines the weight distribution of the machine on the leg in case of tripod is that the central one is going to carry the half of the weight of the machine while the non adjacent same side legs are going to carry on the $1/4^{\text{th}}$ of the machine weight each [2].

BigDog robot is developed by Boston Dynamics also an example of four leg robot [3]. Robot is under the supervision of Defense Advanced Research Group Agency (DAR-GA), and is mainly been designed to be used in the military services. The whole design of the robot is to have unmanned robot that can move on the rough terrain. Some of the main characteristics which are been focused during the research of the BigDog robot is that it should run for many hours, can easily lift pay load and can negotiate the terrain problem and can adjust according to that terrain. BigDog has been implemented with system that provides power and all the required sensors and actuators are mounted on the robot. BigDog contain almost 50 sensors in which inertial sensor measures attitude and acceleration while the joint sensors monitor the joint movement. Some of the salient features of the robot are that it can run, troll and walk, means its speed can vary and is controllable with having maximum speed it can attain is 2 m/s. Detail explanation of the BigDog robot is given in the Figure 2.2. [3]

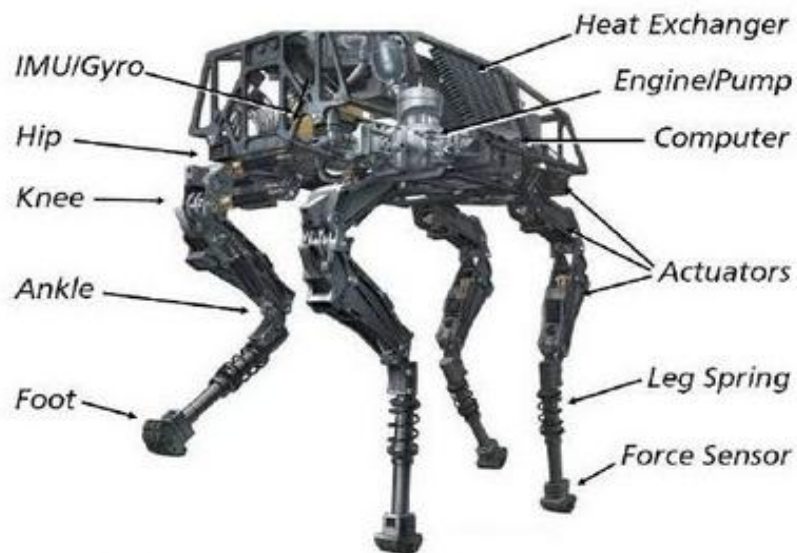


Figure 2.2. BigDog Robot [4]

Some of the specification of the BigDog robot is it weighs about 109 kg, and it is about 1 m tall, 1.1 m long and 0.3 m wide and it can also jump on the terrain around 1.1 m. There are springs in the legs of the BigDog which are used as dampers. Force sensors in the toe of the robot to determine the force robot leg exert as well as

Timberjack forest harvester shown in the Figure 2.3 has been researched on the walking concept and behavior of the machine [5]. It is six leg walking machine which is completely controlled automatically by a control system using the network of sensors. According to terrain condition, machine adopts its behavior and control system transfer the weight on the leg according to terrain. When an obstacle comes in front of the machine it steps up the barrier with the ability to walk forward, backward and even side-wise [5]. In Timberjack forest machine driver only controls the direction and speed while rest has been automated by the control system.



Figure 2.3. Timberjack Forest Harvester [6]

The leg phenomena which is firstly been developed used for the cranes and the excavators they are having the wheel is used for rolling and in case of obstacle as a stepping. Here leg is connected between the wheel and the body of cranes by having the parallelogram link [7]. In these kind of leg both link they are not interconnected directly with each other in leg makes it a power efficient and suitable for large working volume. That is the reason these legs were used in cranes and other heavy duty machines because of their load bearing capacity shown in the Figure 2.4.

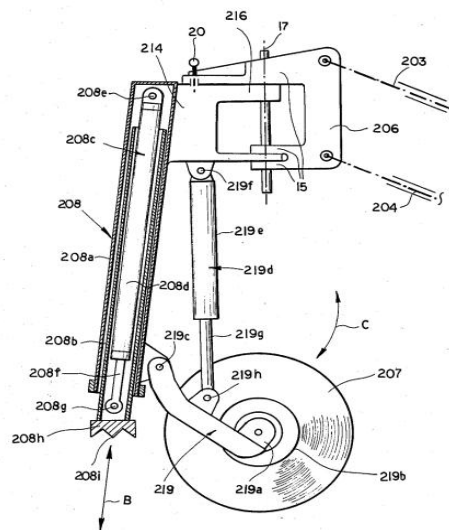


Figure 2.4. Leg Design for Crane's and Excavator's [7]

Anthropomorphically Legged or Wheeled Duisburg Robot (ALDURO) walking machine is also researched and find suitable for rough terrain. It is basically four leg machine and the main characteristics is it can be used as walking machine as well as rolling machine by replacing the feet by wheels. ALDURO is a multibody consist of many links which are connected by number of joints. Figure 1.5 shows the ALDURO machine models [8].

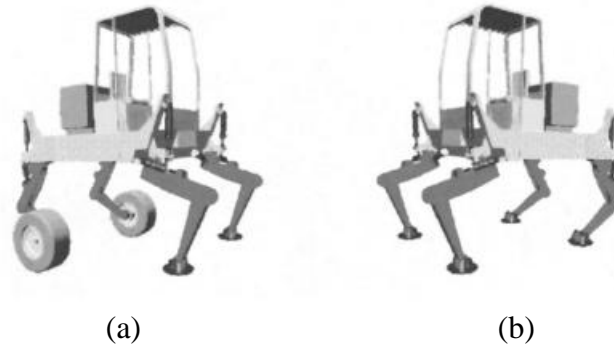


Figure 2.5. (a) Legged and Wheel Mechanism (b) Walking Mechanism [8]

ALDURO has many degrees of freedom and as well as hydraulic components, so important thing to research is the coupling between mechanical and hydraulic components. A block diagram in the Figure 2.6 shows the overall approach which is been adopted in order to carry on the coupling properly so that both system did not conflict with each other and leg mechanism work to give the desired motion to machine.

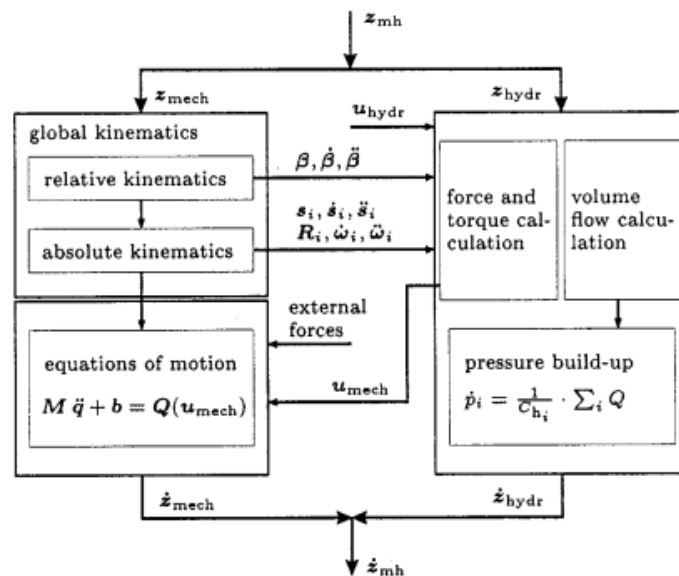


Figure 2.6. Coupling of Mechanical and Hydraulic System [8]

The block diagram shows how parallel both the mechanical and the hydraulic process works and how their coupling is been done. Process description is given as

- Relative Kinematics gives the joint coordinates and absolute kinematics gives the absolute coordinate system to hydraulic system for the calculation of forces
- Now the forces in hydraulic components is calculated and used in equation of motion in mechanical system while flow calculation is further used for the pressure calculation
- Now parallel we get the final result from the equation calculation by the equations of motions as well hydraulic system calculations, and by merging we get the final values/result

2.2. Hybrid leg

In the above mention leg phenomena either we have walking machines or the motion is dependent on the wheel. Both kinds of motions have their own advantages. When we have the legged locomotion it is good in case of rough terrain but they have less speed while in case of wheel locomotion they are good in speed but they are not as good when it comes to the case of variable terrain. So in order to obtain both the advantages the phenomena of hybrid leg has been introduced so that machine can negotiate rough terrain and can be able to attain some good speed. In hybrid kind of motion the force for moving the robot is created by the wheel and the leg together.

This hybrid leg motion phenomenon has been carried out in Mars rover because of so much advantages specially mobility in rough terrain [9]. Mars rover is shown in the Figure 2.7.



Figure 2.7. Mars Rover Leg Mechanism [9]

As mars rover has to carry the sensitive instruments, so leg design research has been carried out that frame should remain in stability. Mars rover is leg legged hybrid robot in which legs they are electrically actuated as they do not have to carry on the heavy load. This shows the importance of hybrid leg in rough terrain that it is been utilized in such sensitive project.

Aalto University in this regard works on the robot named Workpartner which work on the principle having the hybrid leg phenomena [10]. In this outdoor robot having two links in a leg connected to each other by a joint with weight of 21 kg which can produce 100 kg upward force. One end of tilt leg is been connected to wheel while the other support the frame of the machine. In this robot legs they are been actuated by the electric actuators. The structure of the wheeled leg is given in the Figure 2.8.

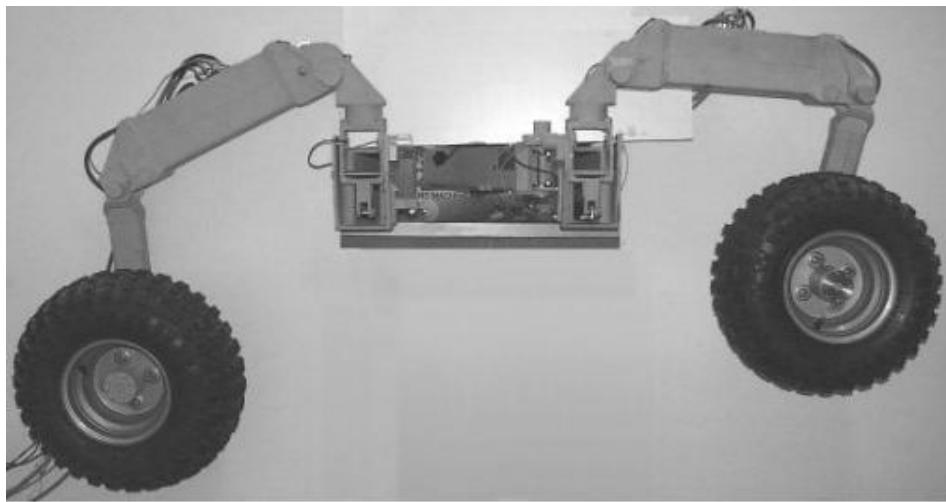


Figure 2.8. Design Model of Workpartner [10]

The actuation components for the Workpartner robot leg are the Maxon EC250W electric motor, gear by rover LTD and ball screw. All the joints of the legs they have to control all the time during the motion of the leg. With this hybrid leg it is possible also to form shape of the obstacle if we take into account the data of actuator current and the joint angles. Due to electrical actuation these kinds of legs they are unable to carry heavy load which makes them faulty for the heavy load. [10]

In order to remove all the present flaws in the Workpartner robot. The task has been assigned to IHA to make such kind of hybrid legs for the GIM machine which can bear not only load of approximately 4000 kg of machine but also suitable for the variable terrain without disturbing the stability of frame of machine.

3. ROLKING LEG

3.1. Design Objective

The main objective of the design to have such kind of leg which is capable of carrying heavy load as well as leg should be energy efficient. Keeping eye on these design objective, rolking leg is been modelled as two link mechanism. The Rolking leg is going to be actuated by hydraulic mechanism. So rolking leg has to be modelled with two link mechanism and two hydraulic cylinders. The factors to keep in mind are that parameters of hydraulic components should not conflict with the rolking leg. Because the hydraulic cylinders have to fit in both the links. So in the design objective factor which is to be considered that how much load leg has to carry. Links should be enough strong to carry it and hydraulic cylinders are enough to provide force to carry the frame of machine.

Having these rolking legs general intelligent machines can move from different terrain and frame movement of the machine remains smoothened by the wheel and the leg mechanism. Now we will see the detailed rolking design and the simulation of the rolking leg.

3.1.1. Rolking leg Model

Model of the leg is shown in the Figure 3.1 which is been designed in the Solidworks

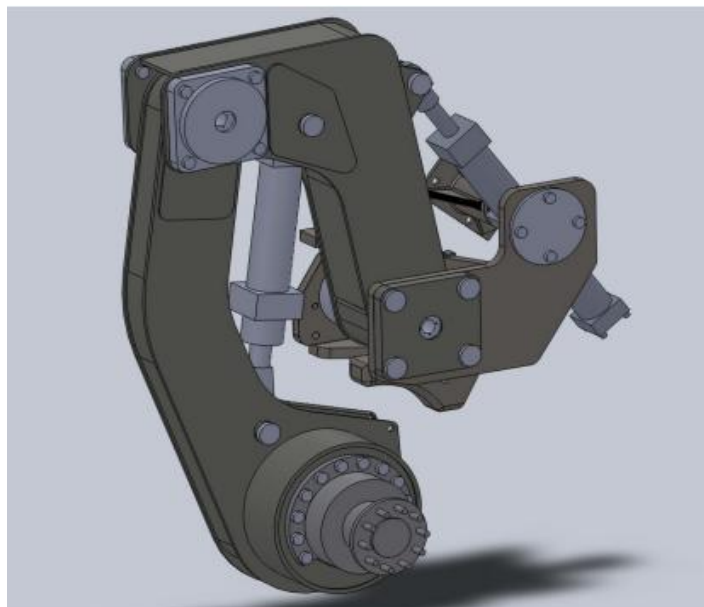


Figure 3.1. Design Model of Rolking Leg [11]

In the rolking leg we have two links they are been joined together. One is called main link which is joined with the frame which carry the weight of the machine. The other one is called tilt which is connected to tire/wheel. These legs as well as frame and main link they are been connected by hydraulic cylinders. The whole design is given in the Figure 3.2.



Figure 3.2. Overall Rolking Leg Design [11]

Rolking leg design is shown in the four leg machine. Frame of the machine will be supported by these legs. Another factor which has to keep in mind during designing the components of the leg that when machine experience the rough terrain, machine frame weight will vary on legs. The estimated weight machine has to carry on is 4000 kg and leg is been designed by considering if leg has to carry almost 2500 kg maximum.

3.2. Rolking Leg Mechanism

The whole rolking leg mechanism is been simulated. So that their behaviour can be seen before implementing practically on the test bench. Simulation model is been shown by the block diagram in the Figure 3.3. In the simulink model we have the frame which is connected to main link. The frame holds the body of the machine and is been connected to the main link. Frame and main link they are both connected by the revolute joint 1 and main hydraulic cylinder. Main link is connected to tilt link by revolute joint 2. Tilt hydraulic cylinder makes connection between main and tilt link of the rolking leg. The schematic diagram of the rolking mechanism is given in the Figure 3.3.

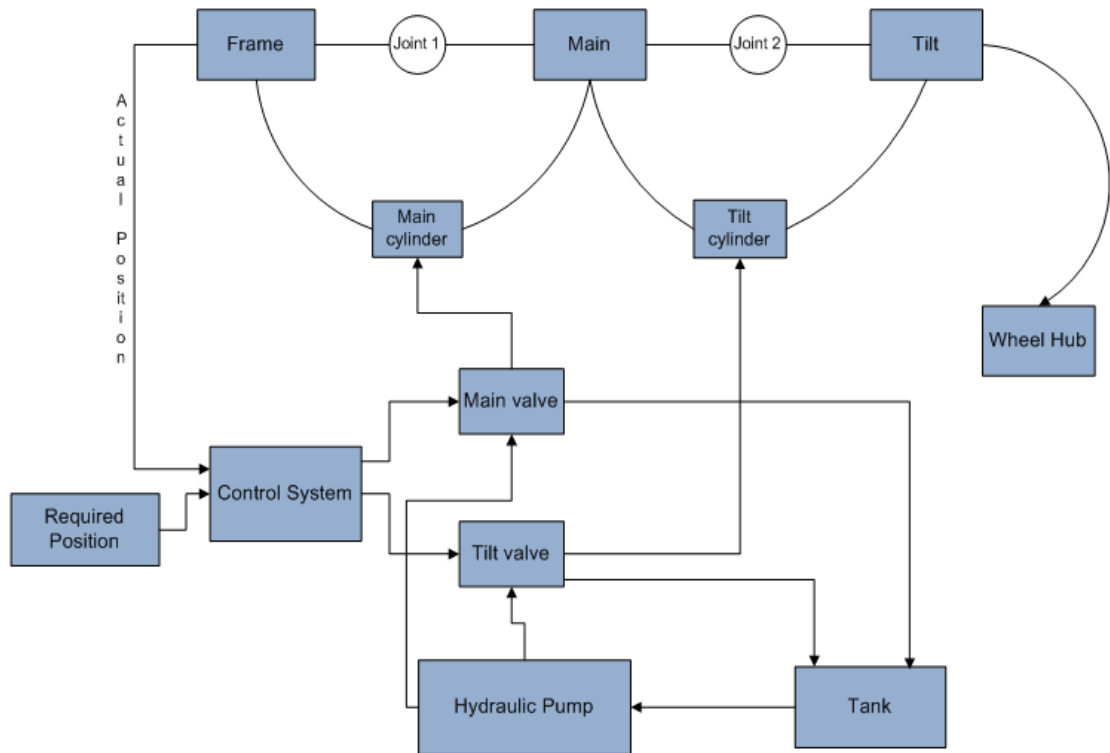


Figure 3.3. Block Diagram of Rolking Leg

Hydraulic cylinders provide the required power that is needed to move the tilt leg. Main hydraulic valve is connected to main cylinder while tilt hydraulic valve is connected to tilt cylinder. Both these hydraulic valves provide the required flow to hydraulic cylinders. Both these valves they have connection to hydraulic pump and the control system of rolking leg. From the hydraulic pump valves get the required flow which they direct toward the hydraulic cylinders while from the control system gives the signal according to leg movement and mainly which depends on the feedback system of the leg. Control system get the feedback from the position of frame and the tire and according to that control system gives the signal to hydraulic valves that open and gives flow to hydraulic cylinder and both valves are used to fulfil the requirement of the cylinders. Pump in the block diagram which is connected to hydraulic valve provides the required flow to the valves and also take the extra amount of fluid back from the valves.

3.2.1. Simulation of Hydraulic Valve

Hydraulic valves that regulate the flow of the fluid and its direction. Valves generate the required pressure for the Hydraulic cylinder piston movement. Valves for rolking leg are 4/3 hydraulic valves which means that three positions and four ports valve. One of the position describes the one when we don't have any flow. The symbol of these kinds of valves is given in the Figure 3.4

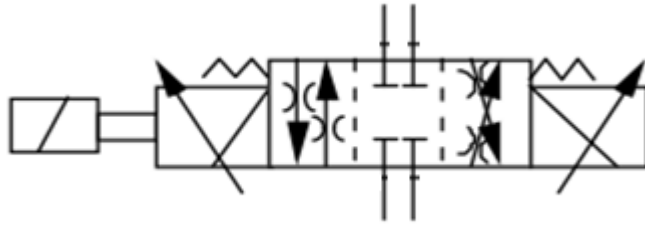


Figure 3.4. Hydraulic Valve

Here we have four ports, P represent pump connection, T represent tank while A and B are the two ports connected to hydraulic cylinder. While the two positions are well described in the valve symbol in the first flow of fluid is from pump to port of cylinder while fluid from the other side moves from port B back to tank similarly when fluid flows from pump to port B situation changes and now fluid from port A flows to the tank. Simulation model of hydraulic valve is shown in the Figure 3.5.

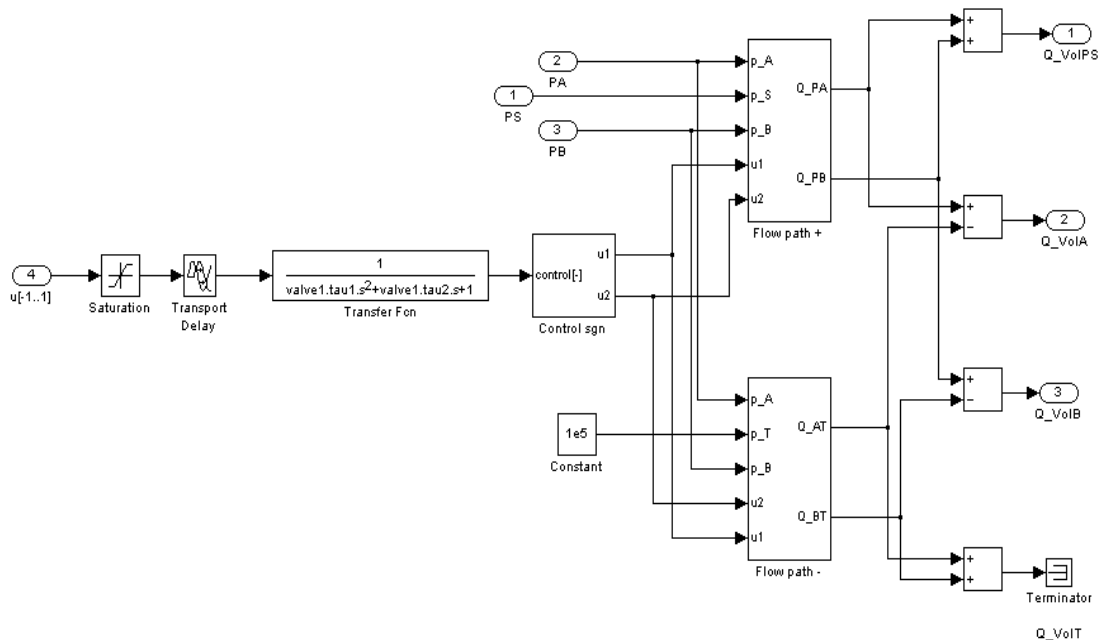


Figure 3.5. Simulation Model of Hydraulic Valve

Hydraulic valve is connected to pump and the control system. When control system gives the required signal to valve, it moves the position of spindle inside the hydraulic valve which causes the flow in the desired port. Simulation of how control signal works in valve is given in the Figure 3.6.

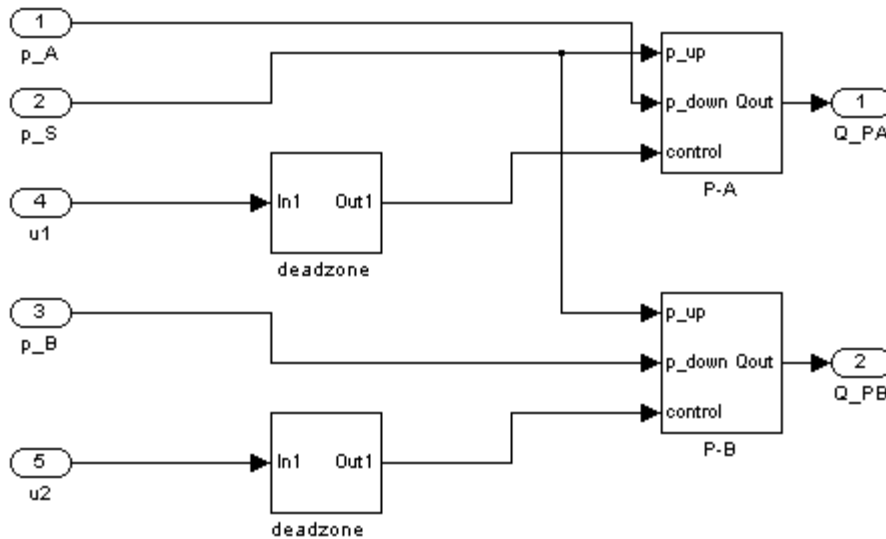


Figure 3.6. Control Signal Effect on Valve Ports

In the control signal two signals generates in a hydraulic valve u1 and u2. With u1 signal the connection has been made it because the flow happens from pump P to Port A of hydraulic pump as well as flow back from port B to tank T, because signal makes the connection open P-A and B-T. Similarly when control signal u2 is on it will make the port open P-B and A-T.

3.2.2. Simulation of Hydraulic Cylinder

Hydraulic cylinder is connected in between two bodies or links from their connection points to generate the force. Simulation of hydraulic cylinder is given in the Figure 3.7.

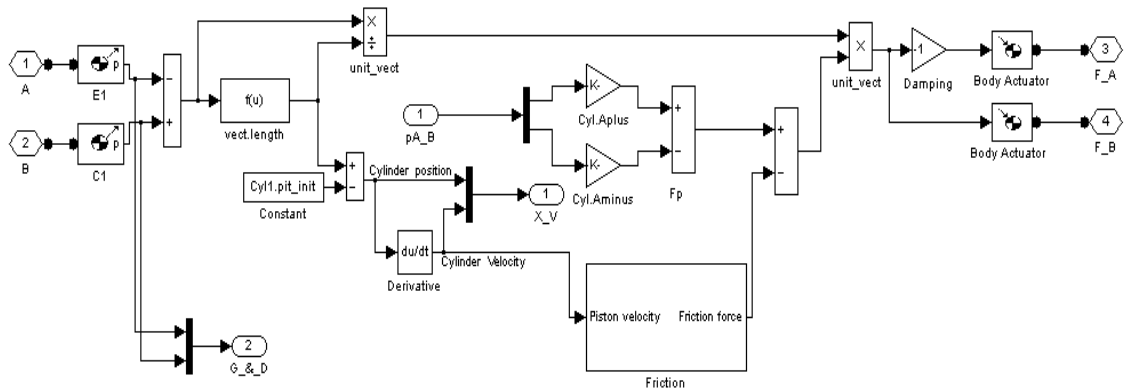


Figure 3.7. Simulation of Hydraulic Cylinder

Simulation of hydraulic cylinder starts off with two points A and B, these are the two points where hydraulic cylinder is connected. At these two points we have the position sensors which give the indication of actual position of hydraulic cylinder. Cylinder

speed is been calculated from the length of cylinder which then derivate to give cylinder velocity. Pressure is given from other port of simulated model to rod side and as well piston side. As pressure to cylinder generates the force and friction forces (coulomb and viscous friction) is subtracted from that force and that's the net force which cylinder exert on both the links. F_A and F_B are the forces which we get as output.

3.3. Major Working Area

The model of the rolking leg is been studied as well as the simulation of the rolking leg. Now we have to consider the most important issues in the major working area. So by working on these issues the rolking leg will be capable to give the desired results. First of all we have to see which are the suitable hydraulic cylinders for the rolking leg, which are enough to carry the heavy load. According to that we have to made selection of hydraulic valves for these cylinders, so these valves can be able to provide the required power to cylinders. Another important working area is to design controller for the hydraulic leg, because as the leg goes from the variable terrain despite of it controller should be intelligent enough that it can give satisfactory stable performance of the system. Second issue is that weight on the leg can vary according to the terrain. These are the factors which have to keep in consideration while doing the selection of hydraulic components.

4. HYDRAULIC COMPONENTS DESIGNING

The important task is to design the hydraulic system which includes the selection of hydraulic cylinders and hydraulic valves. During designing of these components all the important factors have to be considered that what kind of hydraulic cylinders are required. The factors which are important to consider are the suitable length of hydraulic cylinder, piston diameter, bore diameter and all other factors lead to the end result that how much force it going to exert, so that it can lift the weight of machine quite easily. We have to use two hydraulic cylinders in our design. Designing of both main and tilt hydraulic cylinders will be different as position of the cylinders different in the design and expected result from the cylinders also varies, that makes to choose different hydraulic cylinders.

Once suitable hydraulic cylinders have been chosen then next step is to choose hydraulic valves for them. Valves provide the required flow to the cylinders to carry out the desired operation.

4.1. Static force calculation on rolking leg

Before going to design selection of the hydraulic cylinder, calculation of static force which acts on the rolking leg of the machine. Important assumptions has been made that the whole mass of gravity of the machine is acting in the centre of the machine which has been denoted by G [11]. When machine is moving on the terrain the force acting on the front wheel as well as rear wheel in the upward direction. These forces are denoted by F_{front} and F_{rear} . All these values they are been mentioned in the Figure 4.1

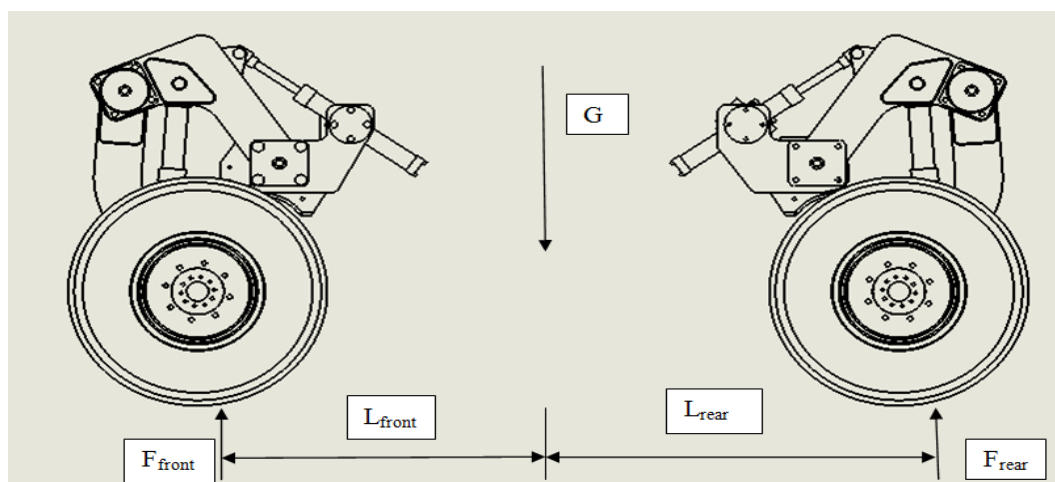


Figure 4.1. Static Forces on Rolking Leg

Now we start to calculate the force that exert in the upward direction to rolking leg. First take the front leg so all the formulation for the front wheel force

$$F_{front} = \frac{L_{front} * G}{L_{rear} + L_{front}}$$

Similarly the equation for the force on the rear wheel is given as

$$F_{rear} = \frac{L_{rear} * G}{L_{rear} + L_{front}}$$

This is the upward force that leg is going to experience when machine is moving on the ground. The important factor we are going to see is that how much force is going to exert on the hydraulic cylinders those have to drive the rolking leg. For that purpose we make some correlation of this upward force and the force generated by the hydraulic cylinder. We take simple model of the leg and make this correlation of the forces.

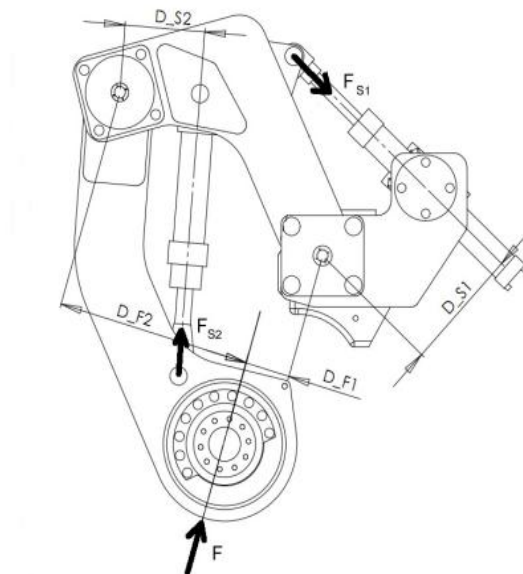


Figure 4.2. Comparison of Upward and Hydraulic Forces [11]

Here we can see the upward force acting on the rolking leg. Now first if we talk about the hydraulic cylinder 1. The force which acts on the cylinder is F_{S1} . D_{S1} is the distance from the centre of the hydraulic cylinder 1 to joint 1. D_{F1} is the distance of the upward force on the leg and the joint 1. We make all this force co relation from the joints because designing and control of the leg is dependent on the joint limitation. The equation is given as

$$F_{S1} = \frac{F \cdot D_{F1}}{D_{S1}}$$

Similarly the force which is exerted on the cylinder 2 is also been calculated mainly from the joint 2. Force calculation is given as

$$F_{S2} = \frac{F \cdot D_{F2}}{D_{S2}}$$

Now when we are going to calculate the static angles for the rolling leg. During the designing we have to see the limitation of the joints. Joint angle and how they are been calculated from the links are shown in the Figure 4.3

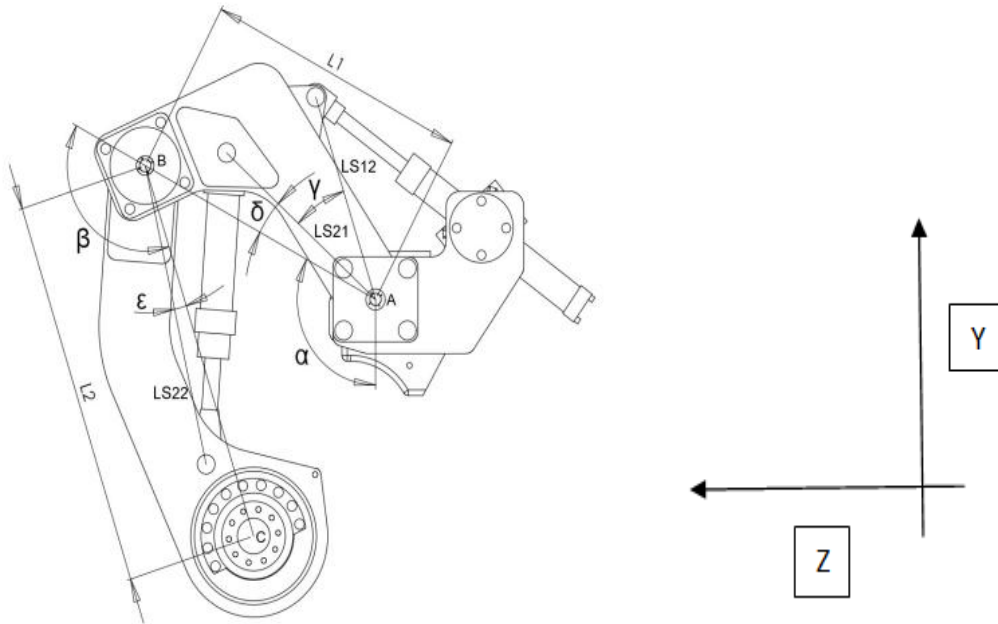


Figure 4.3. (a) Joint Angles Demonstration [11]

(b) Joint Coordinates

As this is two leg mammal leg phenomena so joint movement as well as their limitation plays an important role. As both the legs they are interconnected by the hydraulic cylinders to each other, so mainly the upward motion of the frame in Y coordinate is caused by joint 1. While in the motion in horizontal direction is been carried out by knee joint which is joint 2. Here the phenomena of consideration is that movement of knee also effect the thigh of the leg and they are connected, so the situation changes according to centre point of the wheel and its movement, so first take the components at the centre point of the wheel and C represent the centre point of wheel hub [12].

$$C_z = L_1 * \sin(\alpha) + L_2 * \sin(\beta)$$

$$C_y = L_1 * \cos(\alpha) + L_2 * \cos(\beta)$$

From these two components of the centre point of the wheel the angle calculation is been done by the following formulae for both joints [12].

$$\alpha = \arccos\left(\frac{x^2+y^2+L1^2-L2^2}{2*\sqrt{x^2+y^2}*L1}\right) - \arctan\left(\frac{x}{y}\right)$$

$$\beta = \arccos\left(\frac{x^2+y^2-L1^2-L2^2}{2*L1*L2}\right)$$

4.2. Selection of Hydraulic Cylinder

Before going to make some selection of the cylinders there are certain factors which need to be considered. The factors we have to see how much the upward force machine going to experience when it is passing through some terrain. Because machine is going to experience different force on front and rear wheel, and the angle machine is going to make, all these factors have to consider in the designing of the hydraulic cylinders. According to that upward force we have to see how much the required force from the hydraulic cylinder leg need. Obviously speed of the machine is also the factor to see that which speed leg is moving has to move with this upward force and variable rough terrain.

4.2.1. Main hydraulic cylinder

The block diagram of the main hydraulic cylinder is given in the Figure 4.4. It shows how main hydraulic cylinder is connected in rolking leg.

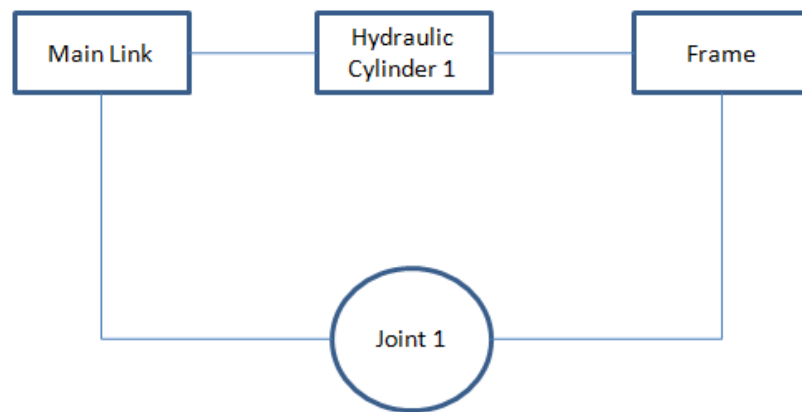


Figure 4.4. Main Hydraulic Cylinder Connections

Main hydraulic cylinder is in between the frame and the main link. According to the design specification and the required actuator the parameters for the selected hydraulic cylinder are rod diameter is 64 mm, piston diameter should be the 40 mm so that it meets the requirement of the rolking leg. The stroke length of the hydraulic cylinder is 213 mm. First we are going to do the calculation of the hydraulic cylinder so that we can figure out how much force it is going to exert to carry on the load on the leg.

Piston side area

As we have taken the diameter of the rod is 64 mm and its area calculation formula is given as

$$A_p = \pi * r^2$$

$$A_p = \frac{\pi * d^2}{4}$$

$$A_p = \frac{\pi * (0.064)^2}{4}$$

$$A_p = 3.217 * 10^{-3} \text{ m}^2$$

Rod Side area

When we take the piston side area we are going to subtract the rod diameter from the piston diameter, and the piston diameter selected is 40 mm,

$$A_r = \pi * r^2$$

$$A_r = \frac{\pi}{4} * (d_p^2 - d_r^2)$$

$$A_r = \frac{\pi}{4} ((0.064)^2 - (0.040)^2)$$

$$A_r = 2.00 * 10^{-3} \text{ m}^2$$

Rod side area is more than the piston side, from that we can conclude that has more Volume than the piston side, as stroke length of the cylinder is been taken as 0.213 m, So Volume of the Piston and rod side is calculated as

$$\text{Length of stroke} = l_s = 0.213 \text{ m}$$

Piston side volume

Maximum capacity of fluid that the piston side can have

$$V_p = \left(\frac{A_p * l_s}{2} \right)$$

$$V_p = 0.342 * 10^{-3} \text{ m}^3$$

Rod side volume

Maximum capacity of fluid that the rod side can have

$$V_r = \left(\frac{A_r * l_s}{2} \right)$$

$$V_r = 0.2087 * 10^{-3} \text{ m}^3$$

Piston side force

The supply pressure which is been chosen is 210 bar, and the total force that piston side will exert is been calculated as

$$P = 210 * 10^5 \text{ N/m}^2$$

$$F_p = P * A_p$$

$$F_p = 65.45 \text{ kN}$$

Rod side force

Similarly with the same pressure the force on the rod side is been calculated as

$$F_r = P * A_r$$

$$F_r = 39.05 \text{ kN}$$

4.2.2. Tilt hydraulic cylinder

Hydraulic cylinder block diagram shows its connection in the rolking leg is shown in the Figure 4.5.

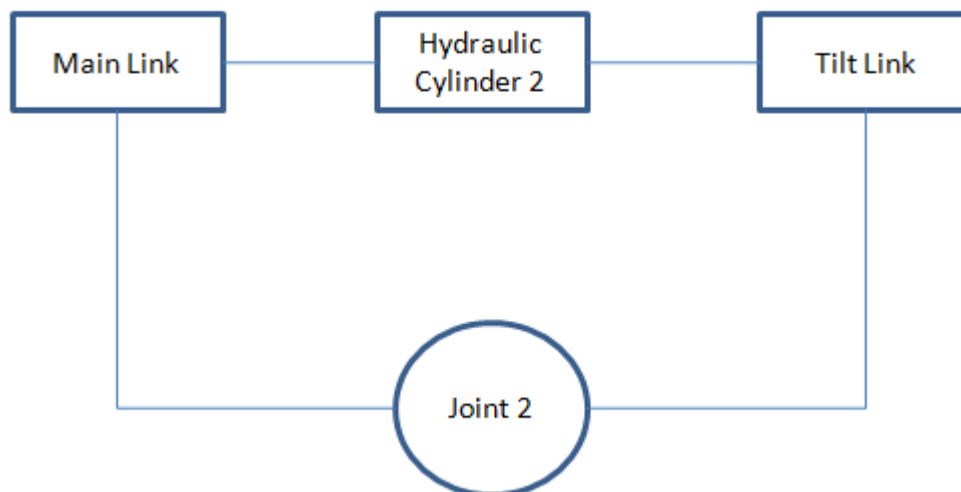


Figure 4.5. Tilt Hydraulic Cylinder Connections

Main link and the tilt link of the rolking leg they are connected by the joint 2. The second hydraulic cylinder which is also named tilt cylinder is connected between the main link and the tilt link in such a way that one side of the hydraulic cylinder is connected to the body of main link while second end is connected to tilt link near to wheel hub. Before the selection of hydraulic cylinder is been made the factor that the hydraulic cylinder parameters meeting the required design parameters had to be verified. Hydraul-

lic cylinder should be of enough size that it fit in the rolking leg. The initial length of the hydraulic cylinder is 1 m. As leg is in supporting phase means when wheel is touching the ground when moving on the rough terrain it is going to experience the force and due to design parameters length of tilt hydraulic cylinder is greater than main hydraulic cylinder so hydraulic cylinder is been chosen of higher diameter that is 90/45 mm. Some parameters selection is and calculations are given as

Piston side area

Piston side diameter has been chosen 0.090 m, Area has been calculated as follows

$$A_p = \frac{\pi * d^2}{4}$$

$$A_p = 6.4 * 10^{-3} \text{ m}^2$$

Rod side area

Rod diameter has been chosen as 0.045 m. Area on the rod side has been calculated in such away that diameter of this piston is been subtracted from diameter of rod. Calculation is given as

$$A_r = \frac{\pi}{4} * (d_p^2 - d_r^2)$$

$$A_r = \frac{\pi}{4} ((0.090)^2 - (0.045)^2)$$

$$A_r = 4.8 * 10^{-3} \text{ m}^2$$

Now we do the calculation for the volume of the hydraulic cylinder, so that we can see the maximum capacity of both sides of the hydraulic cylinder.

Piston side volume

Piston side volume is been calculated from the following formula

$$V_p = \left(\frac{A_p * l_s}{2} \right)$$

Where, l_s = length of stroke = 0.213m

$$V_p = \left(\frac{6.4 * 10^{-3} * 0.213}{2} \right)$$

$$V_p = 0.677 * 10^{-3} \text{ m}^3$$

Rod side volume

Rod side volume is been calculated similarly

$$V_r = \left(\frac{A_r * l_s}{2} \right)$$

Where, l_s = length of stroke = 0.213m

$$A_r = 4.8 * 10^{-3} \text{ m}^2$$

Putting all the values in the above formula we get the volume at rod side

$$V_r = 0.508 * 10^{-3} \text{ m}^3$$

Piston side force

The supply pressure which is been given is 210 bar, and the total force that rod side will exert is been calculated as

$$p = 210 * 10^5 \text{ N/m}^2$$

$$F_p = p * A_p$$

$$F_p = 134.4 \text{ kN}$$

This is force which piston side of the hydraulic cylinder exerts in order to lift the rolking leg. We also called it as push force of the hydraulic cylinder.

Rod side force

Rod side force or pull force is been calculated from the following formula

$$p = 210 * 10^5 \text{ N/m}^2$$

$$F_r = 10.08 \text{ kN}$$

4.2.3. Market analysis of hydraulic cylinder

As we mathematically conclude that in what limitation we are going to use these hydraulic cylinders. In the next step we are going to see these hydraulic cylinders in the market that what kind of hydraulic cylinders are available in the market. For that purpose a search is been carried on Rexroth Bosch hydraulic cylinders and found out that the hydraulic cylinders of “**Series CD210/CG210**” is of most likely to be used in rolking leg mechanism and these series hydraulic cylinders will fulfill our requirement [13].

Now some of salient feature of these series hydraulic cylinders due to which these are our choice are the following

- Nominal pressure of the hydraulic cylinders is around 210 bar
- Hydraulic fluid temperature range is from $-20\text{ }^{\circ}\text{C}$ to $+80\text{ }^{\circ}\text{C}$
- Optimum viscosity range is 20 to 100 mm^2/s
- Effective filtration prevents malfunction
- Stroke velocity up to 0.5 m/s

After the selection of hydraulic cylinders the next important step is the selection of hydraulic valves for the rolking leg.

4.3. Selection of Hydraulic Valves

The selection of hydraulic valves is been made according to need of actuator, that how much flow is needed that cause the movement of piston position of cylinder. In rolking leg this can be fulfill by the proportional valve. As per requirement of rolking leg we have two active actuators so we need two hydraulic valves. In case of rolking leg the choice has been made for the proportional valve due to reason that they have distinct operating characertistics. As mainly the function of the proportional valve is to make smooth and continous flow that is what required in rolking leg that hydraulic valve make opening and closing to the flow according to the flow. In proportional valve flow depends upon the position and movement of the spool of hydraulic valve. Spool movement is proportional to control current due to proportional solenoid in the valve.

Some of the parameters which are designed for the hydraulic valves in the rolking leg is that for how much flow capability of the valve. In case of rolking leg it is been designed for the flow range of 150-200 l/min. Some of the features of the valves which are needed to fulfill requirements are

Delay of valve = 20 ms

Valve deadzone = 0.05%

Nominal Pressure difference = 10 bar

Nominal flow rate = 11 l/min

These are the parameter which gives required flow and actuate the hydraulic cylinder so that leg attain the desired stability and can load bearing capacity. After getting the theoretical values from the Matlab R2011b, a research work is been made in the market available vavles with these required parameters.

4.3.1. Market survey

With these parameters maket survey has been made for the available hydraulic valve which can be used for the test bench of rolking leg. For that purpose the Rexroth Bosch hydraulic valves of series SX 14 proportional control valves are available in the market which will be used for the rolking leg. The characteristics which makes them suitable

for the rolking leg is that the inlet flow range is 175 l/min. Maximum pressure it can exert on the piston side is 250 bar while on the actuator side it is 300 bar.

4.3.2. Functional description

The functional description of the SX 14 proportional valve is shown in Figure 4.6 in which all the elements of valve and how they are connected is given as [14].

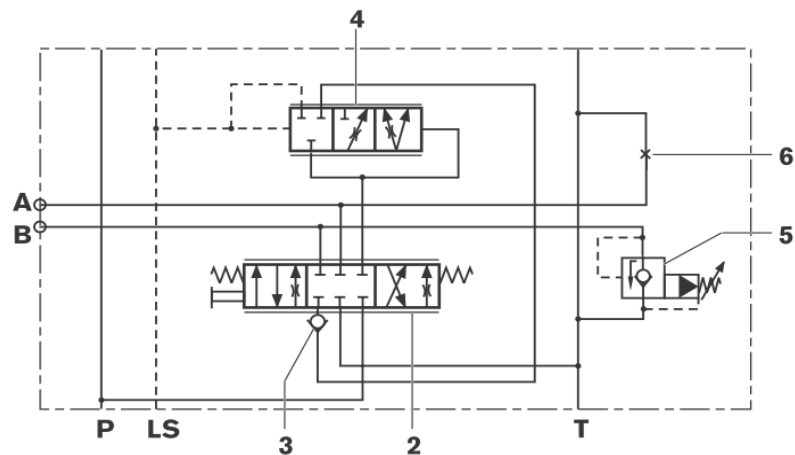


Figure 4.6. Functional Description of Hydraulic Valve [15]

In proportional control we have four ports with pressure port denoted by P, tank by T and A and B are the outputs for the actuators. In Figure 4.6 (2) represent the valve opening being proportional to control current, (3) represent the check valves that restrict the movement of fluid in one direction and stop it in the other direction, (4) is the pressure compensator in the valve if some how pressure is increased this compensator maintains the pressure by moving the fluid to the tank. The most important function of valve is (5) which is pressure relief valve combined with anti-cavitation check valve, because cavitation is very dangerous in hydradynamic flow as it can damage the valve or can affect the required output flow while (6) represents the plugs for the anti-cavitation. [14], [15]

4.4. Orifice

It is known that the proper functioning of the hydraulic system mostly dependent on the selection of hydraulic cylinders and valves, as they contributes major in the hydraulic system. To get the good and controlled result orifice is generally been implemented in the hydraulic circuit. Orifice controlled the amount of fluid flow and pressure and can help in the stability of the system. It directly controls the dynamic pressure of the system to make it clear from pressure ripples.

In rolking case we have used the orifice, because we have the proportional control valve been used. Basic phenomena when the spool of the valve moves it change the position according to the flow, without the orifice the dumping of oil will happen from

the spring chamber and will cause the instability in the system. So when orifice is used it can provide the oil cushion in the chamber of the proportional valves.

Fluid flow through the orifice can be laminar flow or turbulent flow and it is determined by the Reynolds number. Laminar flow makes the fluid particles to move uniformly while in case of turbulent flow they move randomly.

Reynolds number is been calculated from the following formula

$$R_e = \frac{\rho v d}{\mu}$$

Where

ρ = Density of fluid

v = Flow velocity

d = Hydraulic diameter

μ = Dynamic viscosity

Now from the calculation of Reynolds number, flow behavior is characteristised as

$$R_e < 2300 \quad (\text{Laminar Flow})$$

$$R_e > 4000 \quad (\text{Turbulent flow})$$

The phase between these two flows is called transition flow. The flow streaming of the fluid after passing the orifice can give the better visualization in Figure 4.7. [16], [17]

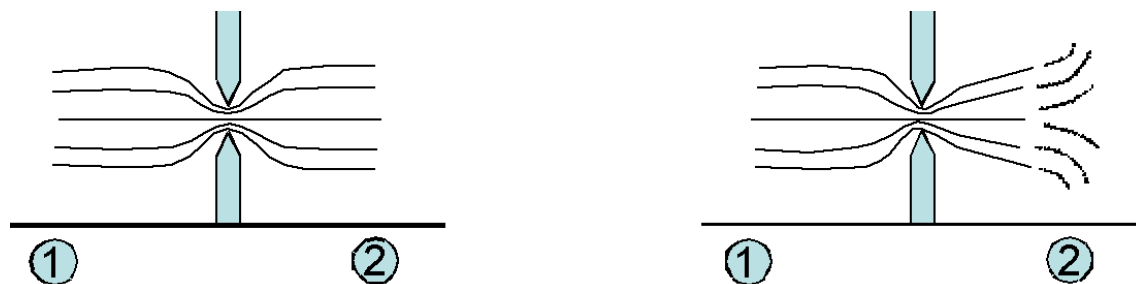


Figure 4.7. (a) Laminar Flow

(b) Turbulent Flow [16]

The parameters of the orifice they generally been selected according to the requirement. Generally it is been considered to use a little bit larger diameter orifices in series than by using one with smaller diameter, because smaller diameter orifice will reduce overall efficiency of the system and can be contaminated more likely.

We use the orifice phenomena in our case because to get the stability of the system. As rolking leg experiences some kind of rough terrain it bumps but do not get the required stability as it is required and expected from the system. The frame of the system oscillates, when carrying the heavy weight such oscillation can cause the crash of the

system. So we use the orifice between the valve and the hydraulic cylinder as damper to make hydraulic actuator movement more smooth and more stable.

5. CONTROL DESIGN OF ROLKING LEG

Control system is considered to be very important part of the system, because proper designed technical system cannot work up to the mark if it does not have good control system. The basic control system connection in hydraulic system is given in the schematic diagram in Figure 5.1. Control system is a feedback control system which get feedback signal from the position of actuator and send signal to make valve opening and closing.

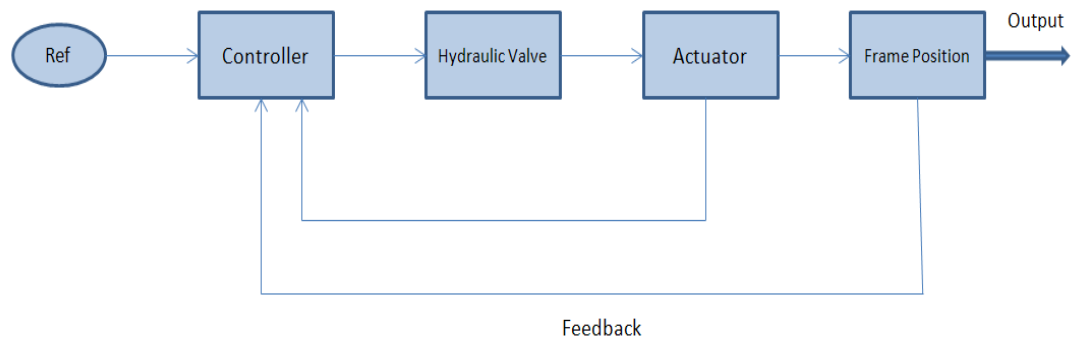


Figure 5.1. Hydraulic Control System

Control is an important aspect of rolking leg. Some of the challenges, which have to face during the control design is that both hydraulic cylinders are connected in such way in the rolking leg that the hydraulic cylinder of tilt link also affected by the joint movement of main link because both actuators are coupled together. So this factor is of worth to consider in control design that when and how much flow one hydraulic cylinder should get to exert required force to move the rolking leg so that frame remains stable in rough terrain. Another challenge is the joint limitations which are decided during the design. During control design the limitations of the joint had to be considered so that both joints should fulfill the joint design requirement. The requirement in the rolking leg case for the joint 1 is ± 40 degree, while for the joint 2 is ± 45 degree. The whole control mechanism is shown in block diagram in the Figure 5.2. The approach has been adopted by dividing into sub-controls. These controls separated by the joint angles limitations. Controller 1 is mostly responsible for the lowering the leg between middle and lower position while controller 2 is responsible for uplifting the leg from middle position to upward position. These adjustments have been made by considering and assigning the joint limitations to these sub-controls.

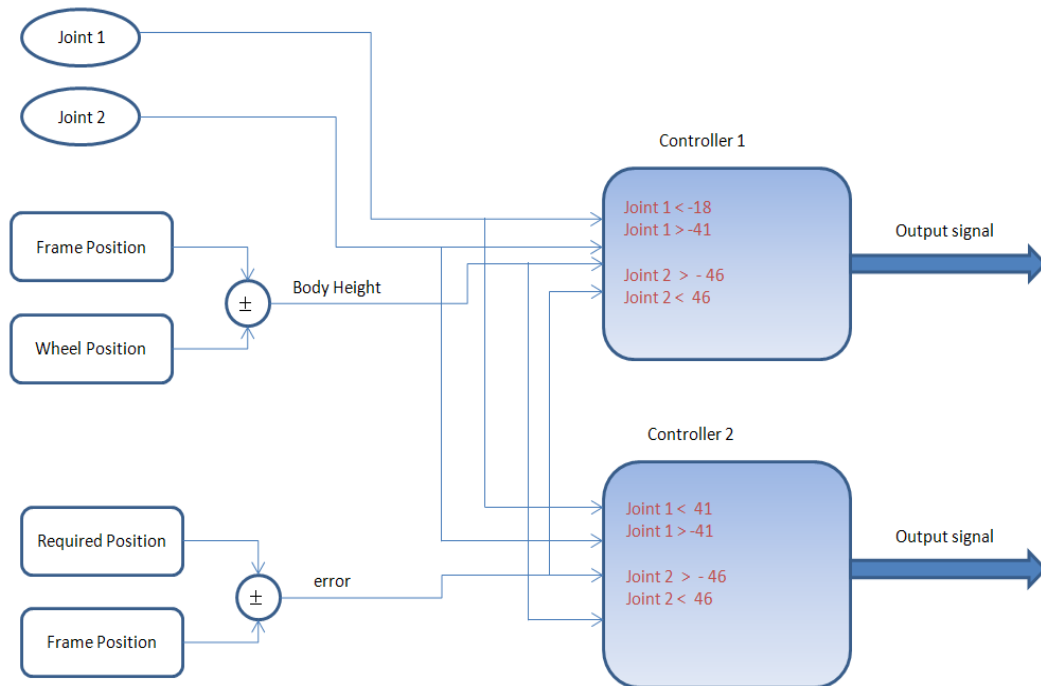


Figure 5.2. Block Diagram of Control System

The basic of the control system of the rolking leg is that the feedback from frame position of the machine will be compared with the original value and error will be sent to controller. The controller gives the signal to make opening and closing of the hydraulic valves for the required flow of hydraulic cylinders which are the actuators for the rolking leg. Body height factor is taken into consideration as wheel position is subtracted from frame position, which will vary as with different terrain, so by taking these factors control system decides how leg should behave according to different terrain. The power which will be generated by actuators to helps carry on load of machine and move the frame of the rolking leg. When leg is moving from different kind of terrain and the hydraulic components should react as planned, control of rolking leg play's significant role.

5.1. Basic principle of control

Now the basic control principle of Rolking leg leg is been explained from the simulation model. Figure 5.3 shows the input and feedback which comes to control system of rolking leg.

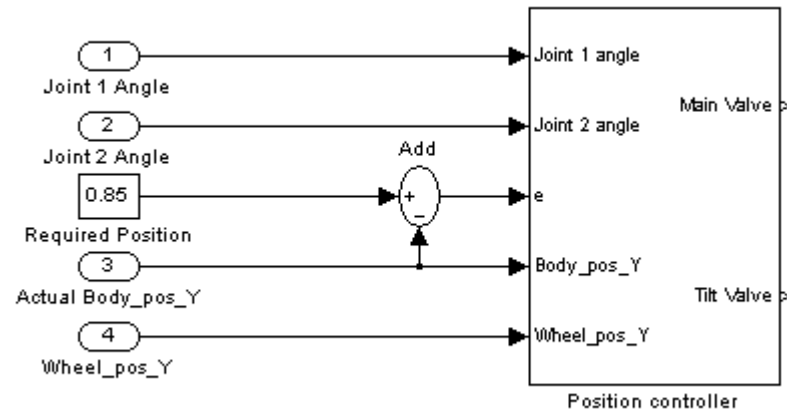


Figure 5.3. Input Connections to Control

In the basic control of the rolking leg the required position of the body of the machine is given. And in the feedback we got the actual body position of the frame which is then compared with the required position and generate the error to the control system.

$$\text{Error Required} = \text{Reference Frame Position} - \text{Actual Frame Position}$$

As the feedback system of the control system wheel position is also been taken into consideration it will be explained latter how the position of the wheel is been used in the control system. The most important factor which is been taken into account is the joint angles connection to control. Figure 3.2 simply shows all the connection that has been made to control the rolking leg.

Now how these connections make the control principle works. The simulation model of controller of the Rolking leg is given in the Figure 5.4 explain the phenomena by itself

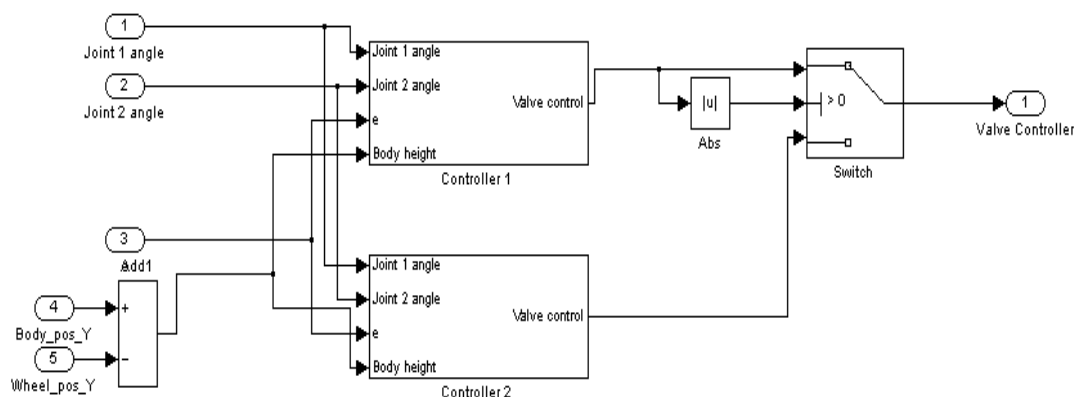


Figure 5.4. Basic Principle of Control

Control system is divided into two sub-controllers, controller 1 having input connections both joints as well as error. Controller 1 is designed when leg is moving on the rough terrain and in the middle position or when it is moving in the downward position means when leg is moving downhill in forward direction. While the controller 2 is been used when leg has to move in the upward directions, error and both joints they are been taken into input connection but besides that body height is also taken into account.

$$\text{Body Height} = \text{Body Position} - \text{Wheel Position}$$

In controller 2 the main reason of taking the body height is that when leg is in upward direction it means it is in transferring phase so the frame position with respect to wheel hub position will be considerable change. So in transferring phase this factor is also taken in the control design. Both these controller they are connected to switch which state that if input 2 is greater than zero than switch will allow the input 1 to go through as output controller otherwise rolking leg will be controlled by the input 3.

As the overall view for the control system is already discussed now look briefly inside at the both the controllers and see how they both work.

5.2. Controller 1 Simulation

Controller 1 as discussed already control the rolking leg when leg is moving in the downward direction or when rolking leg is lowering. The simulation model of controller 1 is shown in the Figure 5.5.

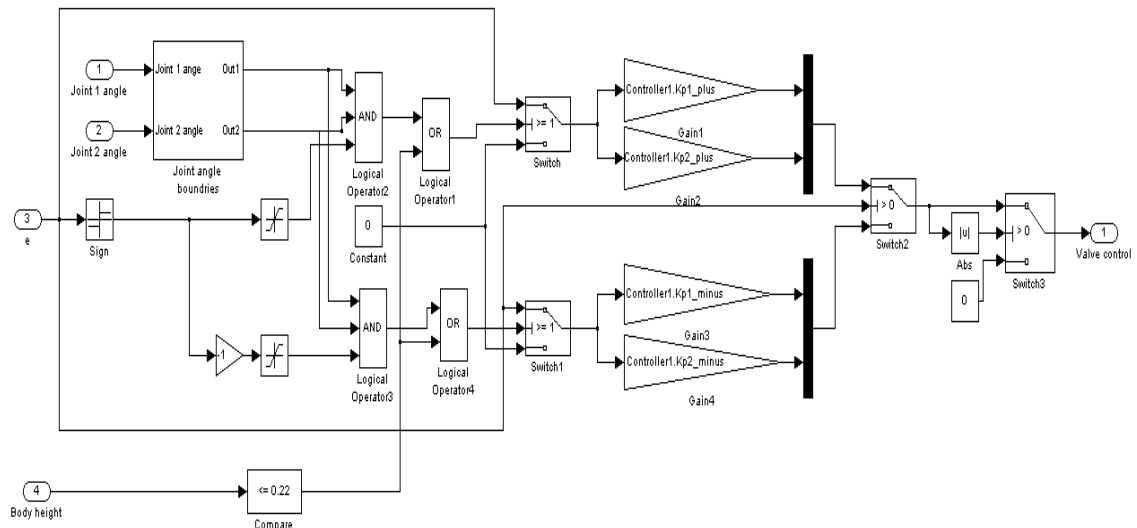


Figure 5.5. Simulation of Controller 1

In controller 1 simulation first we discuss on the joint angles that a joint limitation is been described. In that case Joint 1 limitations are

Lower limit joint 1 $< -18^\circ$

Upper limit joint 1 $> -41^\circ$

The controller 1 will be response only when the joint 1 angle fulfills the Specified limitations.

Similarly for the controller 1 to work joint 2 also has been defined with some limitations. Here Joint 2 angle limitations is given as

Lower limit joint 2 $> -46^\circ$

Upper limit of joint 2 $< 46^\circ$

So in controller 1 when both the joint angles conditions are fulfilled then they will send positive signal to output. Further in control they are connected to switch where switch send saturated error or constant value as output to proportional gain. In control system proportional controller approach is been used as hydraulic system provides the required Integration, so only proportional gain is used in simulation. Proportional gains in case of controller 1 is given as

```
Controller1.Kp1_plus = 11;           % Gain for valve 1 (main) control up-
wards motion

Controller1.Kp2_plus = -11;         % Gain for valve 2 (tilt) control up-
wards motion

Controller1.Kp1_minus = 2.42;       % Gain for valve 1 (main) control
downwards motion

Controller1.Kp2_minus = -2.42;      % Gain for valve 2 (tilt) control
downwards motion
```

Proportional gain values are given by hit and trail method. These control gain are designed when a rolking leg is moving between down and middle position and it has to move up and down during that position. So these control gain has been made for the specified motion of the rolking leg.

5.3. Control 2 Simulation

Controller 2 which is basically designed for the rolking leg to move it in the upward direction, so the trajectory which is been sketched for the controller 2 is to move the leg up and down from middle position to the upward position. According to these joint limitations controller 2 simulation and design concept is given in the following Figure 5.6.

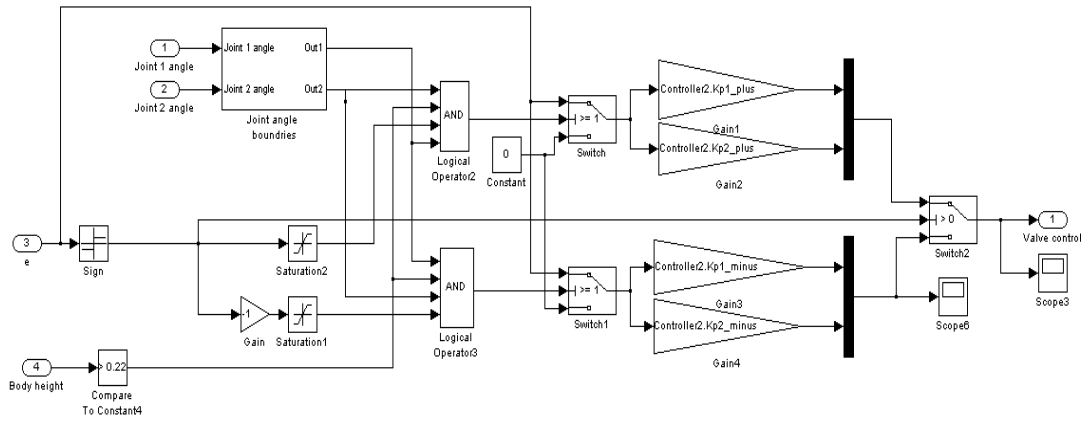


Figure 5.6. Simulation of Controller 2

The joint limits have been defined, so when both joints come into that range controller 2 will start work. Their range is defined as

$$\text{Lower limit of joint 1} > -41^\circ$$

$$\text{Upper limit of joint 1} < 41^\circ$$

Similarly the range for the joint 2 is defined as

$$\text{Lower limit of joint 2} > -46^\circ$$

$$\text{Upper limit of joint 2} < 46^\circ$$

Joint 2 in the controller 2 is also defining the joint full range like in the controller 1. So basically it is limitation of joint 1 who defines which controller will be functioning.

In the simulation of controller 2 can see that one more factor is been added which is the body height. Body height is calculated as

$$\text{Body Height} = \text{Frame Position} - \text{Wheel Position}$$

As controller 2 is designed for moving the rolking leg in the upward direction so it will definitely change the frame position up and down, so in the feedback body height is taken. As the rolking leg undergoes rough terrain, wheel hub position will change and leg movement also change the position of the frame, So body height will differ and according to that feedback, controller send the signal so that frame of the rolking leg remains constant.

Controller 2 is also proportional controller in which Integration part is been provided by the hydraulic actuator and proportional gains they are been used in the controller. Here gains they have assigned values by hit and trial method.

```
Controller2.Kp1_plus = 3.3;           % Gain for valve 1 (main) control  
upwards motion
```

```
Controller2.Kp2_plus = 3.3;           % Gain for valve 2 (tilt) control  
upwards motion
```

```
Controller2.Kp1_minus = 3.85;        % Gain for valve 1 (main) control  
downwards motion
```

```
Controller2.Kp2_minus = 3.85;        % Gain for valve 2 (tilt) control  
downwards motion
```

Both plus controllers make movement of the rolking leg in upward direction by making opening and closing of valves for the main and tilt link. And similarly the minus controllers create downward movement of main and tilt link of rolking leg.

6. RESULTS AND DISCUSSION

After making the selection of hydraulic components and control design for the rolking leg, it's time to analyze the results of selected hydraulic system on rolking leg movement and stability. Point of focus will be the stability of frame of the machine as different kind of rough terrain through which it will be passed. The required situation is when machine experienced some obstacle, it should get stable and can be able to move smooth. In order to get stability rolking leg and selected hydraulic system has to perform accordingly. To analyse results before making leg practical simulation has been done of hydraulic system as well as control system. A rough terrian will be given to machine in simulation, to analyse the stability and the results of all simulated phenomena including control. Results of all simulation will be analysed and discuss in this chapter.

6.1. Terrain Demonstration

Demonstrate of the rolking leg phenomena when it going to experience the some terrain or obstacle having height of 0.1m. The demonstration of the rolking leg is given in Figure 6.1.

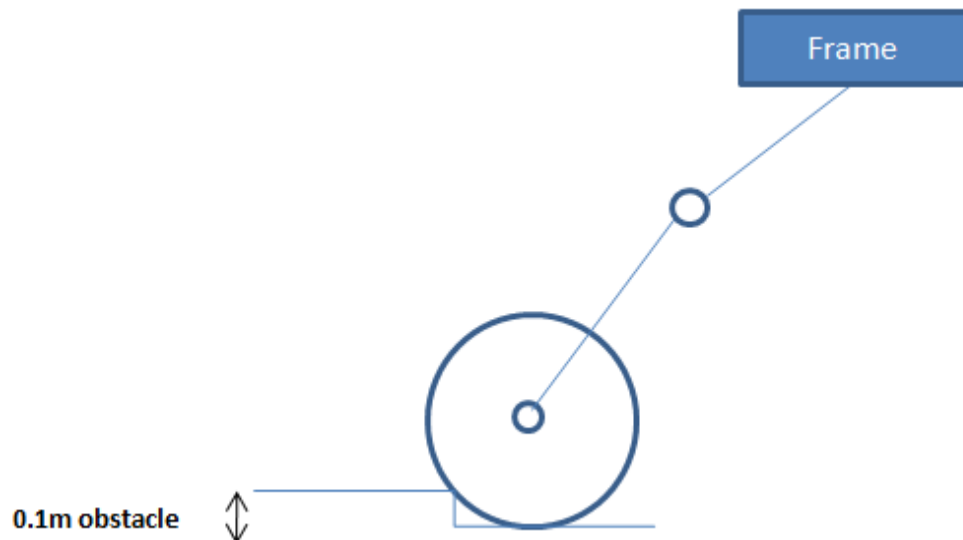


Figure 6.1. Rolking leg Experiencing the Obstacle / Terrain

In the Figure 6.1 rolking leg with two link mechanism is moving on the terrain and it has to pass through an obstacle of 0.1m. This demonstration is to give a clear picture of

rolling leg experience to some terrain in order to see the behavior of machine frame. When leg experiences obstacle while carrying heavy load that is the time to see the machine frame behavior. The main analysis issue will be that how much machine will bump and how quickly it will get the stability phenomena. Because frame should not oscillates much as with heavy load it can crash the rolling leg and whole hydraulic system.

Demonstration in the Figure 6.1. is shown in the real world when leg experience the obstacle, now it is shown as input signal in Matlab to leg, this input signal is given in the Figure 6.2.

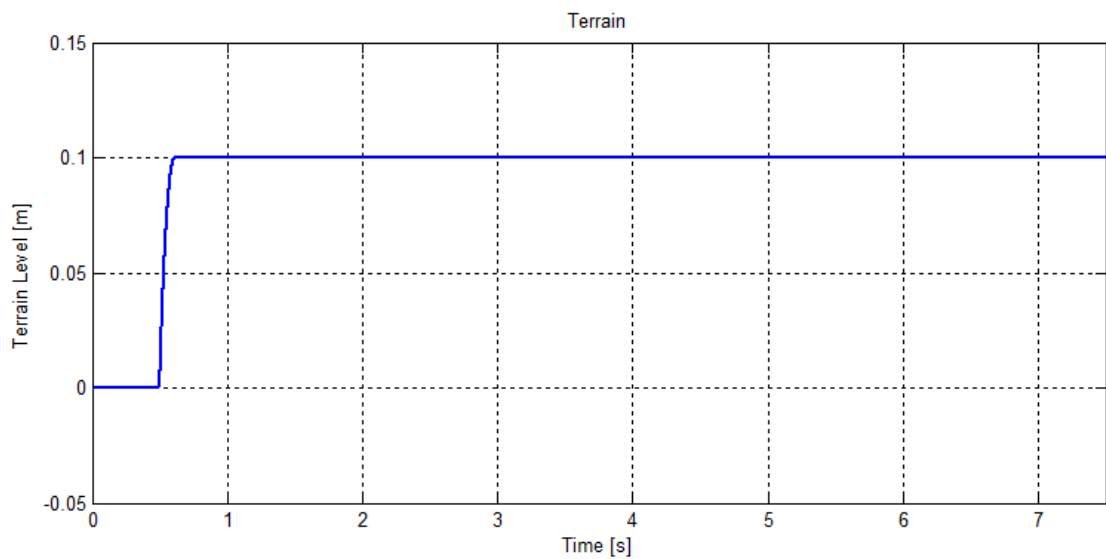


Figure 6.2. Change of Level of Terrain as Function of Time

After giving the input signal or terrain to rolling leg, the behavior of the frame of the leg will be experienced. Important result will be that after having such kind of rough terrain, what is the stability position of the frame. In this regard two different results of frame position will be shown. One is when using the hydraulic system without damping, than briefly discussed the errors it generate for the system to work. Then in second case the same system will be analysed with having some damping effect.

6.2. Frame Position

After providing rough terrain the result which is taken from the system when hydraulic fluid flows directly from the valve to hydraulic cylinder, without induction of any kind of damping effect on it, the result is given in the Figure 6.3.

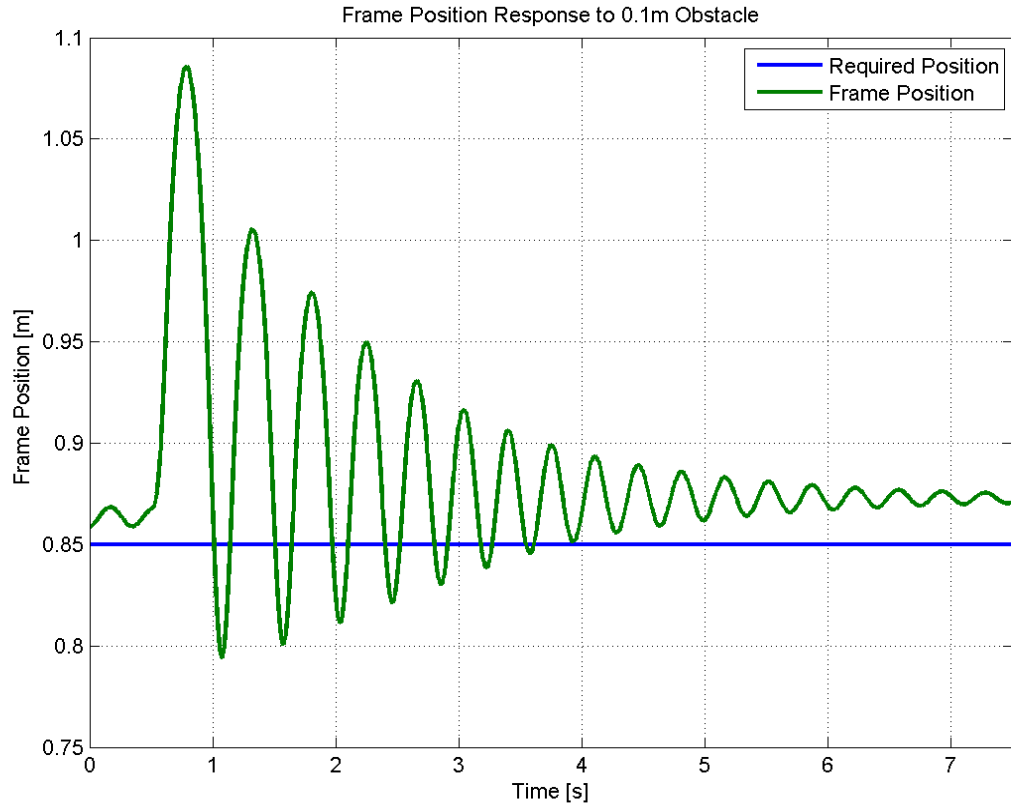


Figure 6.3. Frame Position without Damping

Figure 6.3 shows the position of the frame without the damping effect, the frame position shows as wheel of rolking leg hit the obstacle, the required position is at 0.85m and it is seen that after hitting the obstacle position of the frame starts to oscillates and it took 5 to 7 second to get stable, with carrying heavy load such kind of oscillation can break the rolking leg.

So there is a need to introduce the damper in a system to get the stability, the approach which is been adopted in rolking leg case is that orifice is been introduced but it is only side of the hydraulic cylinder which is plus side while the other port remain the same, this makes the good combination for having the damping effect. Orifice induction can be seen in the Figure 6.4. Orifice has been introduced to port A of hydraulic cylinder or the plus side of hydraulic cylinder.

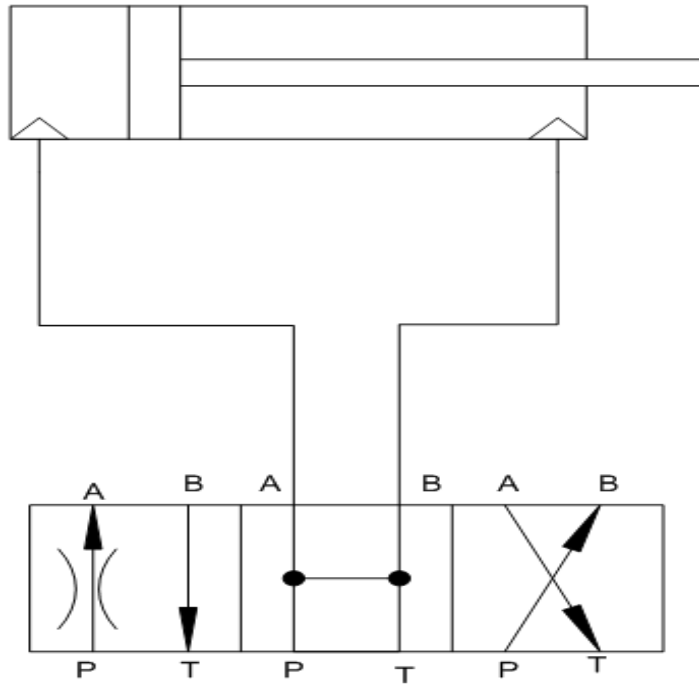


Figure 6.4. Orifice Induction

The result after introducing the orifice is given in the Figure 6.5.

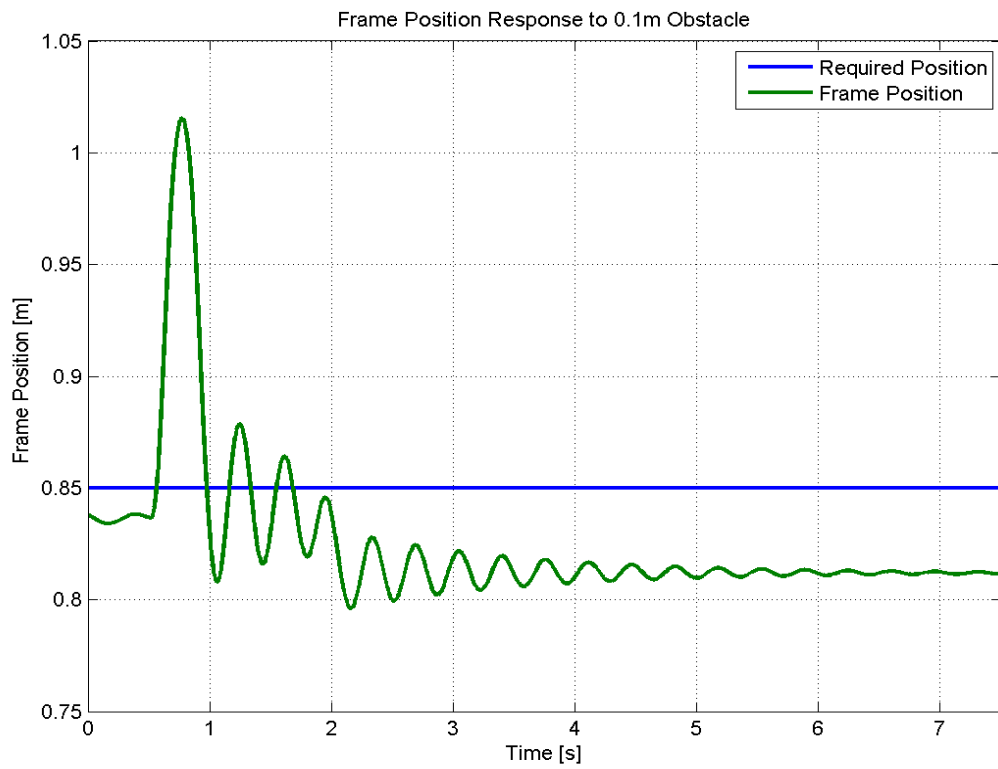


Figure 6.5. Frame Position with Damping

Figure 6.5 is the result after introducing the damper, result analysis shows that the damping effect smooth the result, after having the obstacle the frame of rolling leg bumps up from 0.5 sec to 1 sec, but in a very next moment it starts to get stable. Oscillations are much less than we have without damping. Here satisfactory stability has reached after 1.5 sec. With rolling leg carrying heavy load such kind of stable system is needed. So that is the favorable system for the rolling leg results. Now all the possible affect on hydraulic components what kind of behavior they have shown due by applying the approach of damping effect.

Now before going to analyze the results one thing that need to be cleared that how the simulation of hydraulic actuators has been done. In that case when piston is at the center point it is considered as zero position. Rod side is taken as negative just as a symbol, while piston is taken as positive or plus side. That simulation assumption is given in the Figure 6.6.

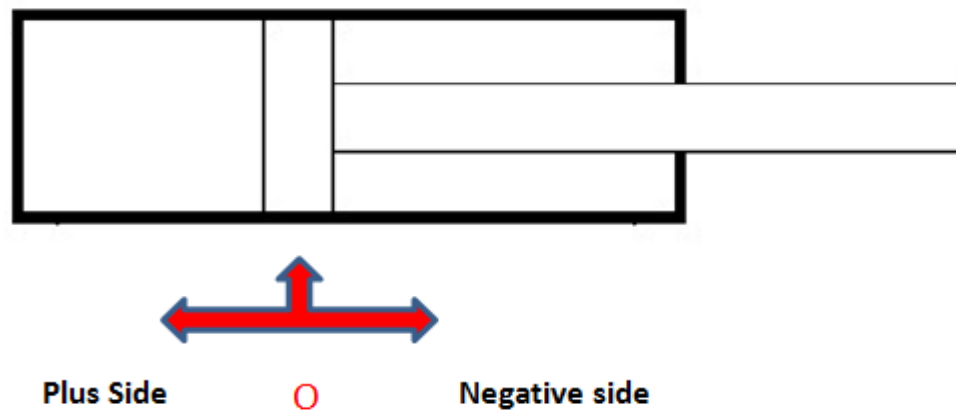


Figure 6.6. Hydraulic Cylinder Simulation Assumption

With this assumption approach of hydraulic cylinder, all the results which cylinder gives the positive and negative sign become just symbolic. It is clear that pressure exerted on the rod side will be with positive sign, while on the piston side will be with negative sign. Same in the case of force exerted by rod side will be with positive symbol, while rod side will be with negative. So here positive and negative they are used just to show which side of hydraulic cylinder is under discussion. These symbols have no mathematical importance and they do not play any part in calculation.

The effect of control signal will be discussed as control plays an important role in order to get stability and required result, because it is control signal which gives the signal for opening and closing of valves for flow to hydraulic actuators. Control signals are given in the Figure 6.7.

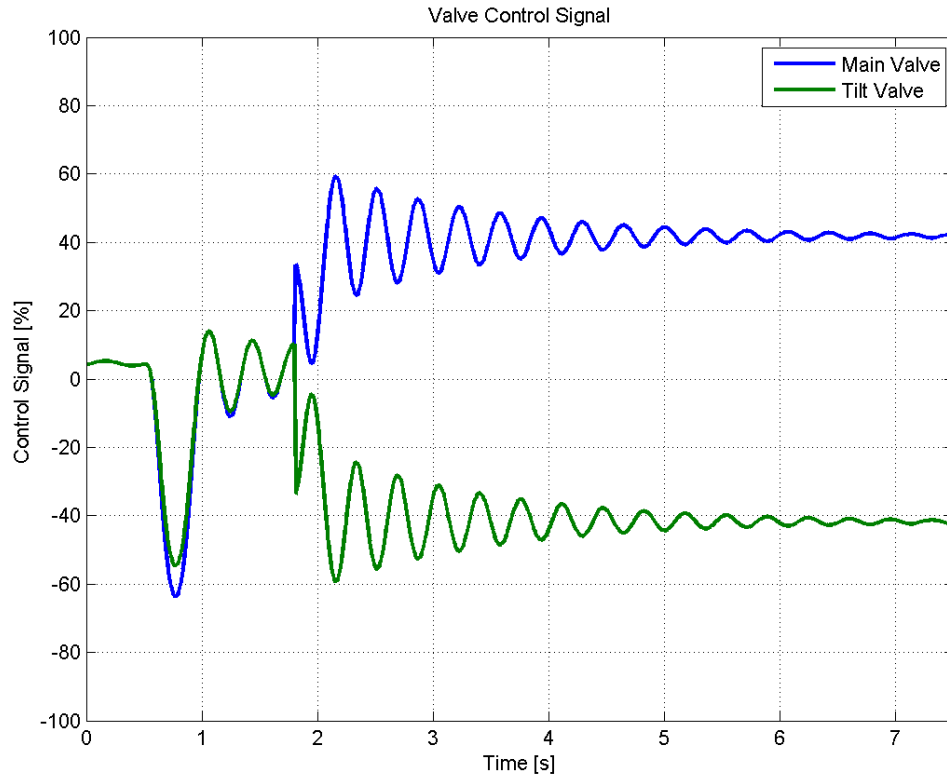


Figure 6.7. Control Signal to Valves

Control signal plays the vital role in opening and closing of valves ports and directs the required amount of flow. Figure 6.7 shows that for both the valves how much control signal open valves for the flow, when leg experiences the obstacle. In the Figure 6.7 it shows that when signal is zero the Control signal did not open both main and tilt valve for the flow to actuator. For the plus and negative symbol it is cleared in Figure 6.6 that these are symbols to show piston or rod side without having any mathematical importance. When it is positive it means that control signal open the port A and causing the flow to plus side of the hydraulic cylinder. In case of main valve, control signal opens the 60 percent of the main valve and direct the fluid to port B or the negative side of the hydraulic cylinder. After 1 sec as system starts to stable due to induction of orifice, main valve flow is directed towards the plus side of the actuator i.e. it opens the port A of the main valve and cause the flow to positive side of hydraulic actuator.

Now discussed the tilt valve behavior in response to control signal that is opposite to that main valve in response, when leg experience the obstacle it open 60 percent of tilt valve. Tilt valve makes flow to port B and direct flow to negative or rod side of tilt hydraulic actuator. Control signal directs the tilt valve to port B and open 40 percent during the stability of the leg after it hit the obstacle.

Reason that why there is pressure on piston or plus side of hydraulic cylinder in case of main link is due to design constraint, because that is side which is connected to frame. So in order to lift the frame that side of hydraulic cylinder need's flow pressure to exert required force for frame lifting. Similarly in case of tilt link it is modeled that

rod or negative side is connected to wheel hub, so that is the side of cylinder which will exert force so pressure will be on the rod side of the tilt cylinder.

With having such control signal shown in the Figure 6.7 to the valves opening for the flow, pressure situation on hydraulic cylinders will be analysed, that how much pressure is been exerted on ports as leg experience the terrain and get the stability. Pressures on hydraulic cylinders are given in the Figure 6.8.

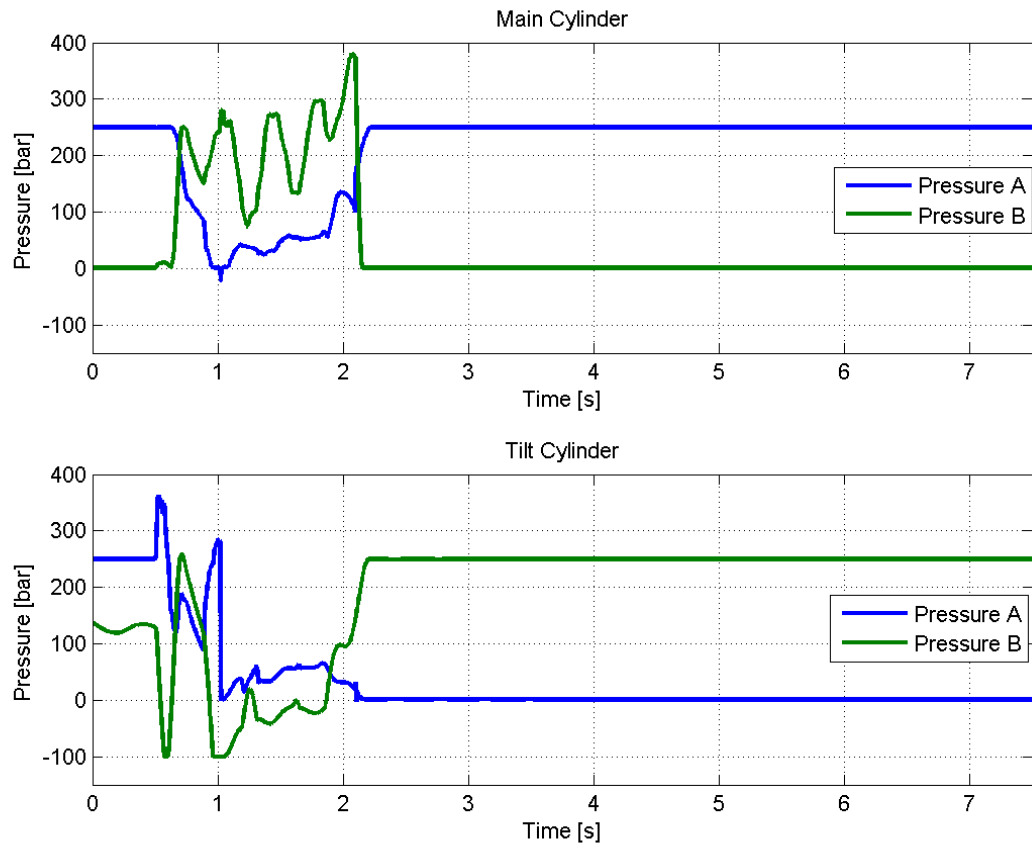


Figure 6.8. Pressure of Hydraulic Cylinders

Figure 6.8 shows the pressure on the hydraulic cylinders. After the fluid flow from the valves, pressure is been generated on the hydraulic actuators so that they can generate required power to lift up the leg and can move it smooth. The comparison of main and hydraulic cylinder ports is shown in the Figure 6.6 and now we will explain both separately. In case of main hydraulic cylinder, when leg experience the terrain, pressure at port A will certainly decrease from 250 bar to 0 bar while pressure at port B is increase from 0 to 250 bar. During time period from 1sec to 2 sec pressure fluctuate in both the ports but due to orifice induction on port A makes the pressure fluctuation bit smoother than the port B. But when leg gets smooth after the bump the pressure at port A get stable around 250 bar while at port B at 0 bar.

Pressure on different side of tilt hydraulic cylinder is shown in the Figure 6.8. Same like the main hydraulic cylinder the orifice is been introduced at the port A, So in tilt cylinder case when leg experience the terrain, there is sudden pressure fluctuation on

port B but it get stable and continuous at 250 bar, while pressure at port B remains zero as leg get the stability.

One more phenomena in the Figure 6.8 is need to be cleared that after leg get stable as it pass through the terrain, the pressure also becomes constant. As terrain which is provided is of 0.1 m during that time pressure fluctuate, but as leg get stable pressure also become stable. Reason is that both in the main and tilt valve there is pressure at one port while other is 0 bar. As it is two link mechanism, so both links they are interconnected to each other. So even when leg is moving on stable terrain due to movement of one link the other one also effected, so due to that reason even after stability ther is pressure at port A or piston side of main cylinder due to direct in contact with frame. Similarly in case of tilt cylinder there is a pressure on port B or rod side of cylinder because it is in contact with the wheel hub. So pressure on theses port will remain constant.

After the control gives the signal to makes valves opening, and flow which cause pressure at ports of the hydraulic cylinders what the net force that actuators will exert during lifting of leg and stability. Figure 6.9 shows the overall force exerted by the actuators in order to lift the weight of machine and gives leg stability.

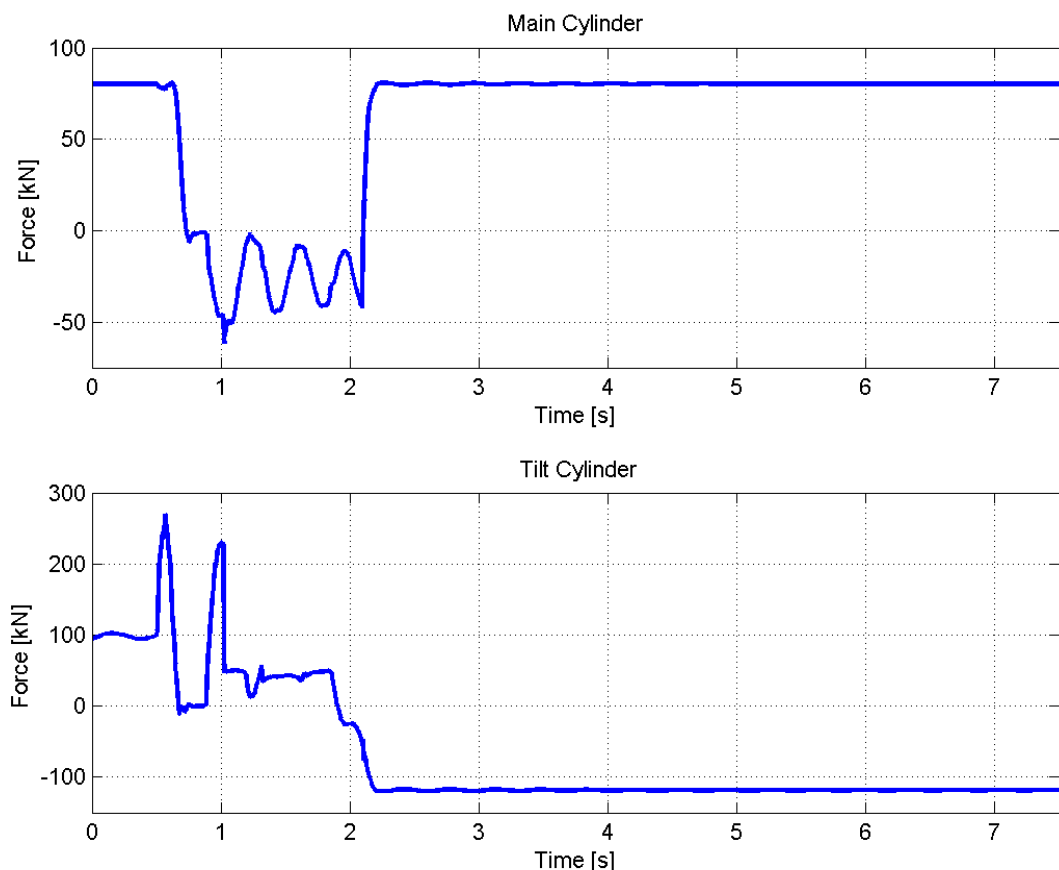


Figure 6.9. Force Analysis of Hydraulic Cylinders

Figure 6.9 gives the overview of the force which hydraulic cylinders gives to rolking leg during all the phases, from the point where leg moves from the terrain and hit the bump

to the point where it get stable and smooth the machine frame movement. First discuss the main hydraulic cylinder force phenomena. In the main hydraulic cylinder as wheel hit the bump, the negative side of hydraulic cylinder which is piston rod side generates force of 50 kN, but as the leg get stable main cylinder gives the force of 80 kN continuously.

In case of tilt hydraulic cylinder which is in between the two links and rod side which is connected near to wheel hub. As machine is moving smoothly tilt hydraulic cylinder generates force only on piston side as it is represented by plus symbol of hydraulic cylinder. At 0.5 sec as shown in Figure 6.9 leg experience rough terrain, causing the force fluctuation on tilt hydraulic cylinder piston side, that is the reason the force shown is with the plus sign to represent that this force is exerted by the plus or piston side of hydraulic cylinder. After 2 sec as leg got the stability, force is only on the rod side of tilt hydraulic cylinder.

In hydraulic cylinder force behavior on main and tilt hydraulic cylinder, one thing that came common to both that both show force fluctuation on bump or terrain that is expected with two link mechanism, but as leg get stable still force is continuous and constant. There are some different behaviors which are present due to design and modeling implementation of two link mechanism. As this design approach always makes both hydraulic cylinders dependent of each other, if one moves it will certainly effect the other one too. That is the reason why there is a continuous force in cylinders as leg get stable due to movement of leg.

7. CONCLUSION

A rolking leg phenomenon was designed for the heavy machinery who has to move from different kind of rough terrain. Due to rough terrain and heavy load rolling and walking kind of legs are not suitable. Both has disadvantages of its own type, like if rolling leg can move from with good speed but it will lack ability to move from hard and rough terrain. Similarly in the case of walking or mammal leg mechanism, it is mostly suitable for rough terrain but it lack speed and performance. So all these disadvantages are compensated in the rolking leg phenomenon which is hybrid form of both rolling and walking leg. Reasons which make the rolking leg suitable for rough terrain with some good speed. With having immense advantages, it is decided to make these kinds of legs suitable for heavy machinery, so fitting of hydraulic cylinders in place of electric actuators makes it favorable for heavy load. Specially use in the industry of such legs in machines like forest harvesting machines, which face quite rough and different terrain so a approach for such kind of legs is that which not only can carry heavy load but also can move on different terrain with some good speed and stability.

Rolking leg covers all these advantages by having rolling as well as walking phenomena. Designed leg was having two link mechanisms which is governed by two actuators. Hydraulic cylinders also the actuators of the system get required fluid flow and power from hydraulic valves which are designed to give and direct required flow to these cylinders. These hydraulic valves are connected to tank, from where they get fluid and bring back extra fluid to tank.

Rolking leg mechanism including hydraulic system for the rolking leg is simulated to see the working result of rolking leg. As already have simulation of rolking leg, control is simulated according to that, which mainly controls the valves opening and closing according to the need of actuators. Because these actuators are in contact with the frame and provide force to bear load. When leg is moving on different terrain both actuators provide needed power to drive system, so all this phenomena is analyzed and control design approach is associated with the link joints and height of wheel hub as well as with frame height. As rolking leg has two joints and they have been designed with some limitation, so taking into consideration these joints limits

After simulating the rolking leg and all hydraulic components it is been testified by different rough terrain to see the effects on frame stability. For that testing is done in Matlab simulation by providing an obstacle with 0.1 m, as leg experience the given terrain at that time all result have monitored. When controlling the response of the frame special focus is given to controlling the valve. As stability was the core issue because of heavy load capability.

By putting all work into nut shell, it is concluded that this control system and hydraulic actuated mechanism made the leg compact that it can bear the load as well as can maintain the stability. So the main task of the project has been achieved is to make it hydraulic actuated stable leg.

8. FUTURE WORK

Rolking leg in this master thesis was two link mechanism, which is not favorable for all type of difficult terrain, So in future work can be done on the design of the rolking leg. With having improved design leg can acheive more stability. If leg has more than two link mechanism it will automatically favor the stability phenomena, because in that way the problem which two link mechanism face that during movement if force is exerted on one mechanism it effect the second mechanism indirectly. That sometime make's the controller ineffective in rough terrain and cause the unstable behavior as well as energy inefficiency.

In the future, work should be done to make more precise and sophisticated controller in rolking leg. The controller in this thesis is implemented by the joint angles and frame position, which can be further worked on to improve. Because factor of improvement in controller is always present. And that improvement will effect he overall result of the rolking leg.

Some of the task for future in rolking leg those are interconnected with the energy efficiency of the leg. System can be more efficient if work is done on the implementation of digital hydraulic valves. Digital valves will insure that flow to hydraulic cylinder will be accurate to the requirement and no loss of flow occur which will increase the efficiency of system.

These are some of important factor which should be considered when working on rolking leg in future. Already this idea remove many flaws present in other kind of legs, but by working on these aspects can make leg more accurate, useful and favorable for more heavy weight carrying capability and with better frame stability.

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Appendix 1: Tool Description

For the simulation of rolking leg, Matlab environment is used for the simulation. Reason for the Matlab selection is the advance and easily available tools. In rolking leg simulation control design approach was more related to joints movement and limitations. Specific tool which is used in simulation of rolking leg is sim mechanics tools, because it ahs variety and tool related to mechanics, joints and sensors, which were really necessary in simulation.

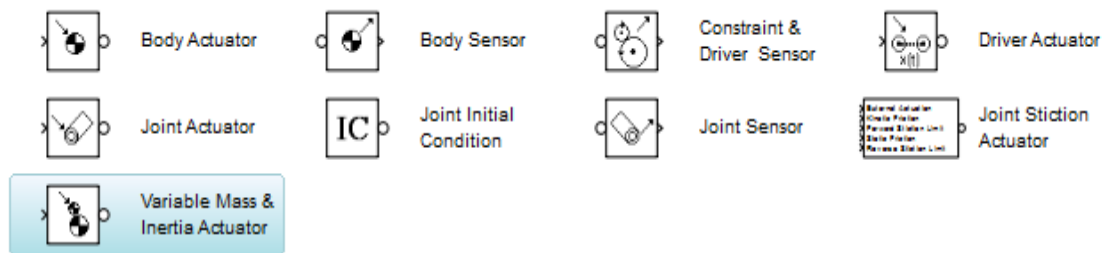


Figure A.1. Sim Mechanics Tools

Some of the common used blocks of Matab simulation are also used in the thesis by time to time. They are shown in the Figure A.2.

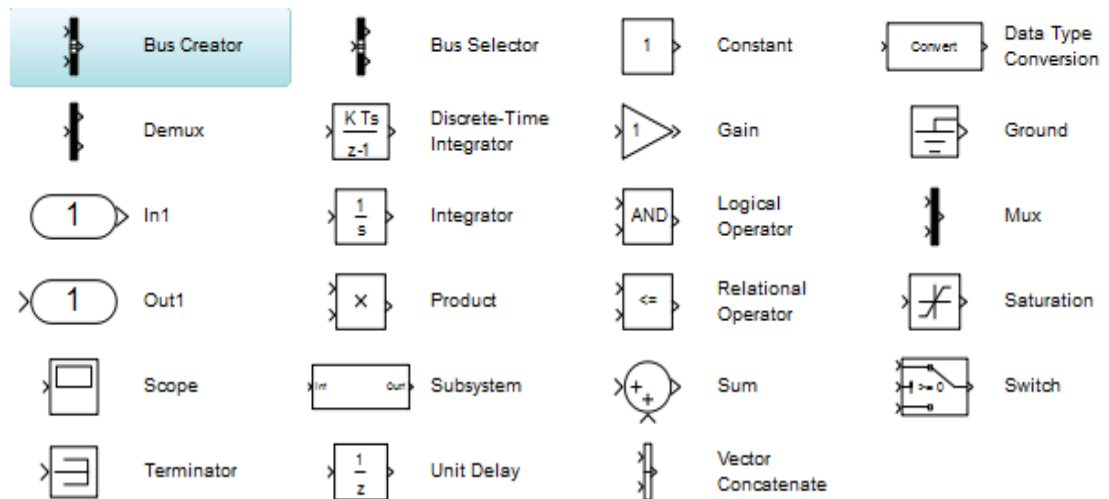


Figure A.2. Common Used Tools

Most of these common tools they act as bridge for the whole simulation process.

Appendix 2: Step Terrain

As detailed explained a rough terrain of 0.1m has been used to test the leg behavior. Taht step function is made in Matlab

```
%% Step Terrain

h=0.1; % step height [m]
r=0.546; % tire radius [m]
Vz = 10/3.6; % horizontal velocity [m/s]
Alpha_s = asin((r-h)/r); % starting Angle [rad]

t = (cos(Alpha_s)*r)/Vz; % t is the end of the time, r is not
inside of cosine

t_c = [0:0.01:t]; % From initial point 0 to end

Alpha = acos((cos(Alpha_s*r)-Vz.*t_c)/r); %as angle is known
Alpha_deg = Alpha.*180./pi; % Matlab uses radians in angle
Calculation
Vy = Vz./tan(Alpha_deg) % step in the upward direction

z_start = sqrt(r^2-(r-h)^2); % horizontal movement when vertical
velocity
t_end = z_start / Vz; % End of time (now same than yours)
t_step = t_end/1000; % time step for calculation
t_new = 0:t_step:t_end; % time values during vertical movement
z_new = z_start - Vz*t_new; % horizontal position as function of
time
alpha_new = acos(z_new/r); % angle as function of time
Vy_new = Vz./tan(alpha_new); % vertical velocity as function of
time
y_new = cumsum([diff(t_new) 0].*Vy_new); % vertical position of
terrain
time_final = [0 3 3+t_new+t_step 100]; % time for repeating se-
quense in simulation (step of terrain at simulation start at 3s and
repeats after 100s)
y_final = [0 0 y_newy_new(length(y_new))]; % vertical position values
for lookup table in simulation

%plot(time_final,y_final,'DisplayName','y_final vs.
time_final','XDataSource','time_final','YDataSource','y_final');figure
(gcf)
```

Appendix 3: Rolking Leg Visualization

To see how simulation works in the real world, there is a real world simulated visualization. Which give the idea about how leg mechanism behave as it is passing through the terrain. Visualization before moving the terrain is shown in Figure A.3.

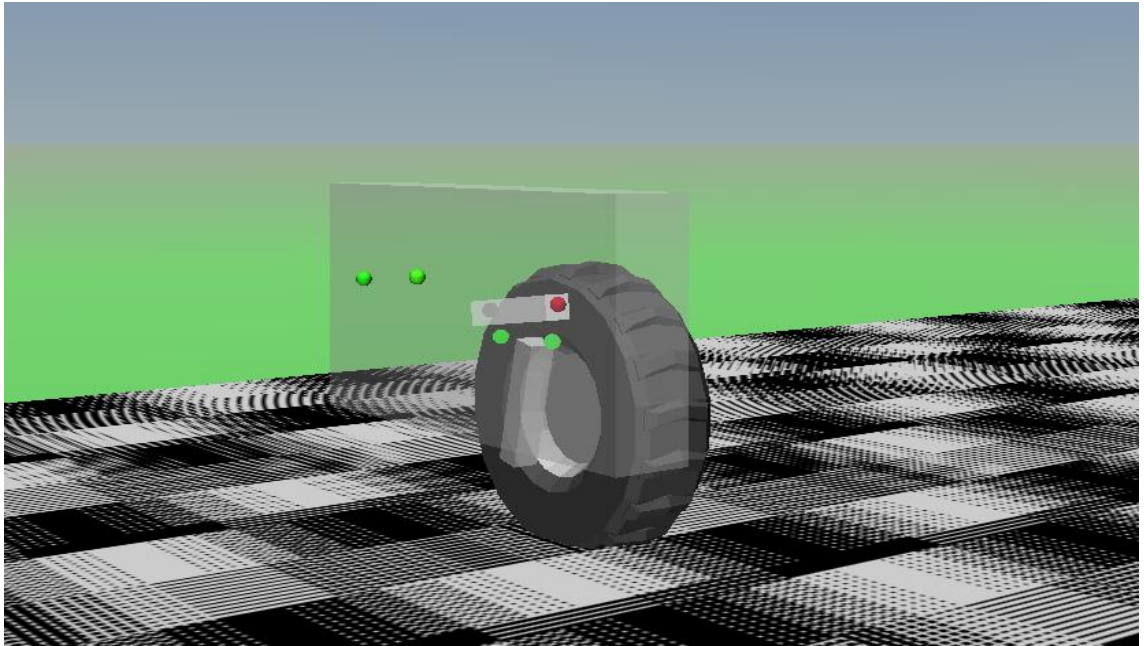


Figure A.3. Visualization Before the Rough Terrain

When leg experience some terrain at that time visualisatio look like in Figure A.4.

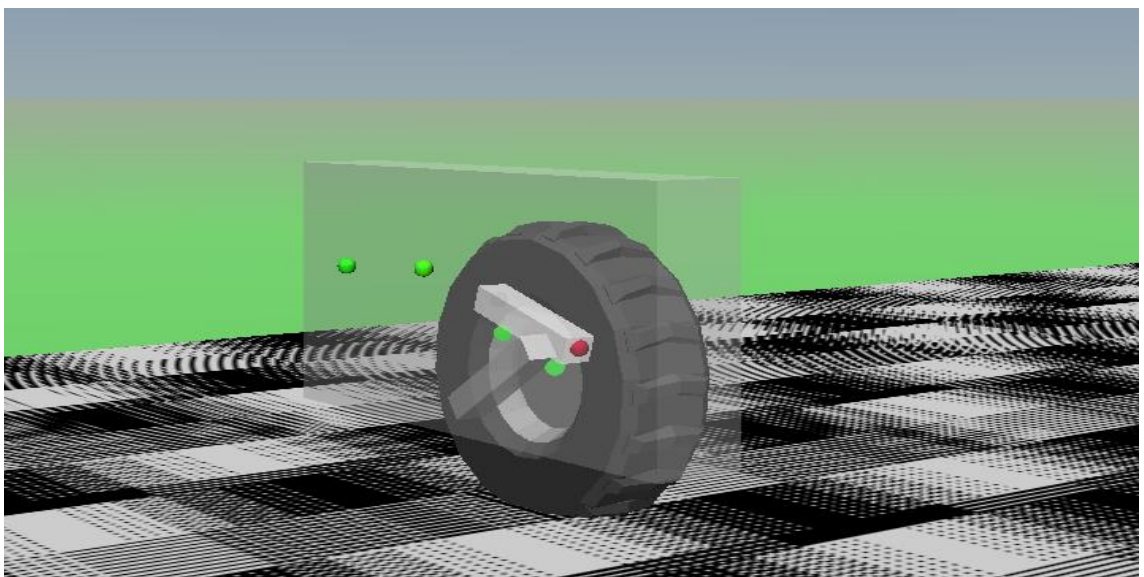


Figure A.3. Visualization After Experiencing the Rough Terrain

