STRESS ANALYSIS OF PIN JOINTED QUADRUPED ROBOT

Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of
MASTER of AUTOMOBILE ENGINEERING

By

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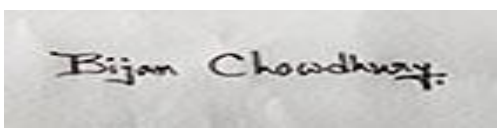

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This is to certify that the thesis entitled "**STRESS ANALYSIS OF PIN JOINTED QUADRUPED ROBOT**", which is being submitted by **BIJAN CHOWDHURY** in partial fulfilment of the requirements for the award of the degree of "**Master of Automobile Engineering**" at the Faculty of Engineering and Technology Department of Mechanical Engineering, Jadavpur University, Kolkata700032, during the academic year 2019-2021, is the record of the student's own work carried out by him under our supervision.

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The foregoing thesis entitled "**Stress Analysis Of Pin Jointed Quadruped Robot**" is hereby approved as a creditable study of an engineering subject carried out and presented in a satisfactory manner to warrant its acceptance as a prerequisite for the degree of "**Master of Automobile Engineering"** at the Faculty of Engineering and Technology Department of Mechanical Engineering, Jadavpur University, Kolkata700032, for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn there in but approve the thesis only for the purpose for which it is submitted.

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ABSTRACT

Mechanical pin joints of a machine or machine component achieve a desirable performance and good life. This paper presents a 3 dimensional pin joint with finite element analysis and a computationally efficient routine is developed for this purpose in ABAQUS followed by a drawing with detailing in solid works. Here a quadruped robot have a torso which will establish to hold and transport heavy weight goods (different types of load like supplies, ammunitions, spares and in some situations human beings) from one place to another. High level of anatomy is required for the robot to sustain this type of bulky load.

To analyze all kind of stress distribution and failure problem of all the components of the quadruped robot we introduced simple 3-D drawing of different components with detailing of all the parameters, after that we should assemble all the parts of a mechanical arm in SOLIDWORKS software. When we use the finite element method we will consider material property, size and all other boundary conditions of the all components and type of joints. This robot can rotate 360 degree with its static gait features rotational joint of all four legs. In the present analysis, a more appropriate analysis is carried out to observe pin joints in laminates with anisotropic properties.

The analysis is mainly concentrates on structural parts like legs and there pin jointed areas to determine highly stress concentration zones and after a proper analysis I can assured about the proper dimension and material selection. Moreover, this type of analysis of pin joints is the changing contact between the pin and the structure with vary the load levels. Numerical studies pointed out the exact location and magnitude of the peak stress along the boundary surfaces of hole are the functions of fiber angle and the property of the material. When we consider a rotation of a pin jointed arm then a cosine distribution of the contact pressure is generated between pin and hole surfaces, it results a tensile and shear failure situation. When we design legs then we have to keep in mind that there will occur a buckling failure, so we have to overcome this situation by adopting not only a proper dimension but also a proper material. Buckling loads of long

structures obtained by analytical calculations and finite element analysis are compared.

NOMENCLATURE

θ : Rotational angle of joints (degree)

a : Links of legs

v : Maximum velocity on flat ground (m/s)

C : Center of gravity (m)

T : Time period (s)

f1, f2, f3, f4 : Four vertices of the robot bed

T_{st} : Stance phase time (s)

S_{st} : Distance covered by the robot (m)

V_{desire} : Desired velocity of the robot (m/s)

L : Length of the bed (m)

W : Width of the bed (m)

H : Height of the bed (m)

w : Maximum weight to carry (kg)

g : Gravitation Acceleration (m/s^2)

F_d : Maximum dynamic force of cylinder (N)

m : Total mass of each leg (kg)

m_1 : Thigh Mass (kg)

m_2 : Calf Mass (kg)

m_3 : Foot mass (kg)

l_1 : Thigh length (m)

l_2 : Calf Length (m)

l_3 : Foot length (m)

r.p.m : Revolution Per Minute

FOS : Factor of Safety

FEM : Finite Element Analysis

DOF : Degree of Freedom

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Chapter 1: Overview

1.01. INTRODUCTION:

In the 21st century, when we talking about any heavy weight material handling or transport from one place to another only one thinking strikes in our mind that is a mechanical moveable device or robot. In ancient age there are mules for transportation of any heavy, bulky goods from one place to another.

When we talk about rough terrain and complex cluttered environments leg robots are more suitable compared to wheel based robots. Our motive is to execute a mechanical device to transport balk and heavy goods to operate in rough surfaces. With respect to different leg designing length, a Leg robot independently touch the ground surface, hence this kind of robots are used for rescuing people in forests and mountains, climbing stairs, to carry payloads in construction sites, and so on. Recently, several quadruped robots are being developed which are equipped with hydraulic actuators or electric actuators. For example, Boston Dynamics developed a series of robots equipped with hydraulic actuators with high energy density. Hydraulic drive quadruped robots, such as Big Dog and HyQ, make use of the characteristics of the high power density of hydraulic pressure to sustain a stronger carrying capacity and motion ability.

Compared to an electric motor driving system powered by batteries, the hydraulic driving system powered by an engine has several important advantages:

- Higher power-to-mass ratio, which makes the robot more compact and with larger load capable.

- High endurance limit.

- More quickly refueled than recharged.
- Faster dynamic response with respect to any external intervention, which makes the robot more stable.
- Better load carrying capacity and stiffness, which reduces the effect caused by varied payload or other external force disturbance.
- More reliable to distribute driving energy to joints according to actual needs.

Often, the oil circuit and the hydraulic arrangement make complicated structure as a whole. On the other hand, high-speed locomotion involves high rate of acceleration and extensive loadings on the legs, which brings a trade-off between weight and strength of legs. Except for the suitable leg design, the stable gait trajectory is the basis of movement stability for quadruped robots. Quadruped animals can achieve various gait patterns such as walk, trot, bound, half-bound, rotary gallop, transverse gallop, etc.

The finite element method is a very convenient tool for the numerical analysis of any type of contact problem between two or more than two surfaces. A lot of FEM codes have ability to analyze the various type of contact problems. However, contact type problems have considerable difficulties so some improvisation and conditions required. The main reason for this is that the contact area is not known in advance and the position of the contact surface is a part of required solution. The nonlinear nature of contact surfaces can create convergence problems and will increase both more complicated design structure as a whole. In electrically controlled robot we use actuators for the rotational movements of any leg.

There are many different ways of applying contact conditions to numerical methods in continuum mechanics. Pin joints, also called revolute joints, are very often deployed to allow folding and unfolding structural components. Usually 3-D modeling of pin was performed in order to determine their actual behavior. In this case new plunger system arrangements is necessary when you rotate component around the pin as our requirement.

The procedure below describes the designing and modeling technique of the actual fissile 3-dimensional structure which are connected with pin joints, after that different type of stress analysis and its graphical representation. This procedure allows the rotation of one component FEM model around a pin. Good example is the rotation of knuckle joint, the revolute joint is a good example. This original method of revolute joints modeling do not require special element type, and therefore can be applied for many structural types.

Therefore, in this paper, the motivation is to design an electrically actuated leg platform for quadruped robots with high-speed locomotion. The method of putting motors at the shoulder is adopted for reducing the leg inertia during the swing of legs. The efficiency is evaluated by measuring the endpoint acceleration, stability, and power consumption compared with the Bezier curve. Furthermore, an optotrak sensor is used for measuring the actual foot-end trajectory of the two schemes. The sensor can track and analyze kinetics and dynamic motion in real-time, which is a more direct and precise method to measure the actual endpoint position, especially when the motor encoder has low precision. Here, Section 2 introduces the detailed design of the leg and the finite element analysis of the leg for the trade-off between the leg weight and strength.

1.02. <u>OBJECTIVE:</u>

Identification of an appropriate physical configuration that can meet our purpose of work. The basic idea in this project work is implementation and innovation of robotic legs and their stress distribution analysis. Here I introduce three jointed articulated leg structures as compared to two jointed articulated leg structures by comparing the differences on the aspect of geometry and kinematics, the manipulability, obstacle avoiding ability, and occupied space for legs were analyzed. Good stability and better manipulation are the key factors that cannot be compromised in this situation. When various type of parameters are taken into consideration is the most feasible and cost effective way of implementation.

Identification of an appropriate physical configuration is very important step for any type of designing, because the mode of operation of the whole system define the design path in which way we move forward. Like an example, when we want to design a hydraulically operated robot that is heavy in weight and bulky, but when we think about electrically actuator operated model then it is more light weight than previous one.

Drafting, designing, modeling and stimulation of the motion stages and intermediate stages mechanisms. That is the main task to perform in this project. We need to have a time study between currently undergoing manual operation and newly designed automated operation. For better stability and efficiency we have to consider as difficult as situation and environmental boundary conditions for stress analysis and stimulation processes.

After drafting and designing all subordinate parts we have to check and analyse with the actual situation or environmental conditions individually to which that part can meet our purpose and capable to execute the tasks. With the help of Finite Element Analysis we easily put the required boundary conditions through which we will reach to the actual result. Estimation of ground reactions with static load as well as dynamic load consideration.

Choice of the material of each components is a big factor that can be chosen suitably according to our requirements of scope. When heavily loaded robot go through off road site there are many types of reaction forces may appear that will damage the internal parts of that robot, so proper material property analysis is very important things to monitor for design.

Chapter 2: Problem definition and modeling

2.01. DESCRIPTION OF CHALLENGES

In goods transportation along different direction we have to design all the limbs or structure of the legs very efficient manners so that they can revolve in all directions according our needs. We want straight-line movement as well as left or right turn according to our requirements for the purpose of transportation of goods Proper use of motor and actuators it is very challenging to turn the whole robot in 360^0 along its ongoing path. In this type of revelatory joints of three links of a robotic legs one link is connected with torso with spherical pair joint that can revolve in any direction in 360^0 in X, Y, Z directions for this 3-D frame analysis. Other two links which are connected with 1st link and 2nd link have only rotational pair that can be rotated around the center of the pin. Conventional revolute joints consist of a clevis and a tang which can rotate around a clearance-fit pin, and due to this ununiformed load distribution developed throughout the curved surface of the pin.

For fast and quick response the curb weight of the whole structure must be light, as a result the whole process will faster compared to heavy curb weight robot. Through this robotic legs, we need to analyse all type of forces on individual component and complete legs one by one. Now let us consider the free body diagrams of individual links. In this situation we need to analyse the static and dynamic properties of the each components. Total load of goods which are mounted on quadruped robot that must be sustain by the 3 legs at a time with a certain factor of safety in design point of view. In this situation extra bending moment that will generated by the reaction forces by the ground reactions that must be neutralized by proper design. There is an essential digital instruments with sensor that can indicate the original weight with accuracy on this.

2.02. MECHANISM DESIGN (ANALYTICALLY)

2.02.01. Detailed view of the robot torso with parameters

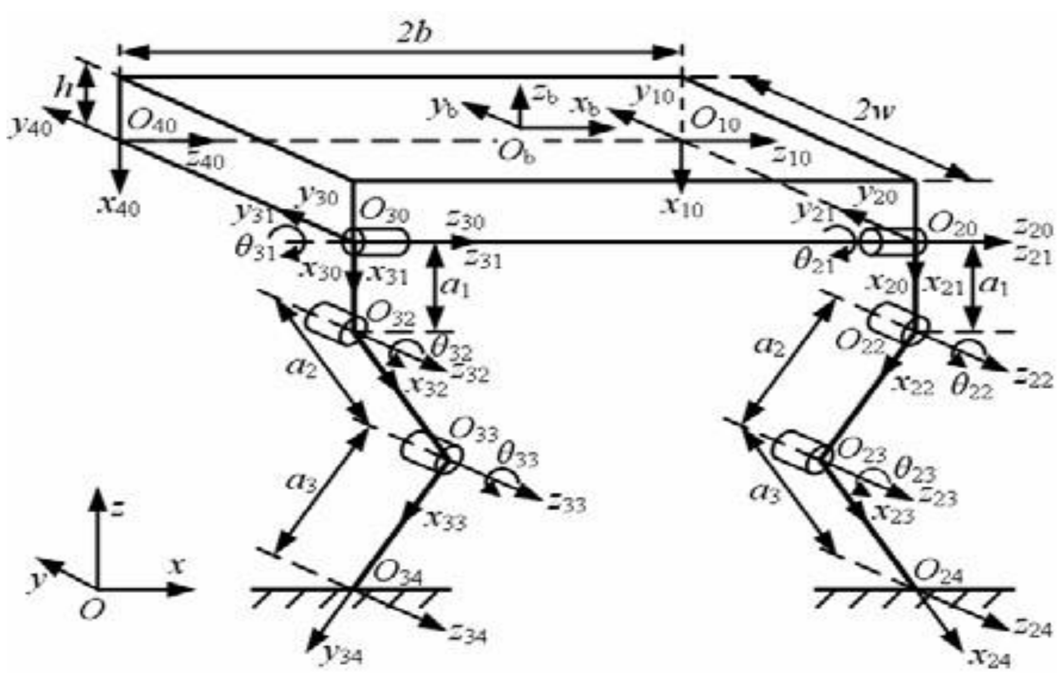

Fig.1. D-H coordinate frames of the robot.

In the above figure we have drawn a skeleton of the robot in 3-D plane, here we have seen all the joints and links through which this robot can be moved. Here, each leg of the robot has 3 links, out of these one is connected rolling rotary joint and remaining two are connected with pitching rotary joint. There are 12 actuators which are mounted at each and every joints of the links (as shown in the fig. 1.). Each actuators consists of a linear hydraulic cylinder, into this cylinder a piston is mounted which can travel both ends of the cylinder. There are one servo valve, one displacement and two pressure sensors are located on the cylinder surface. Valve actuators perform a major role in automating process control. The design and dimensions are vary with respect to its work situations.

Major specification in brief:

Specifications	Values
Weight (without power pack)	about 100 kg
Dimensions (L × W × H)	1 m × 0.4 m × 0.6 m
DOFs per leg	3 active (rotational)
Hydraulic pressure	21 MPa
Major locomotion gait	trot
Optimal stride frequency	1 Hz to 3 Hz
Maximum payload on flat ground	200 kg
Maximum velocity on flat ground (v)	1.5 m/s

Maximum dynamic force of cylinder (F_d)	about 4700 N

Table 1.

There is an inverse relationship between body weight and running speed (in robot case it is stride frequency). That means, when the curb weight of a body increases the running speed and velocity will decreases. It is very wisely applicable on our quadruped robot also. As a result stride frequency will be decreases for the robot. We have to keep in mind that, For this reason the curb weight of the robot cannot be exceeded by 120 kg with the all electrical and mechanical instrument installation. As far this calculation the maximum linear velocity will be 1.5 m/s.

Major specifications are listed below in the table 2. According to these data total volume of oil flow and its pressure can be determined later.

			Joint variables		Theoretical range of θ_{ik}	
Link (k)	a_{k-1}	α_{k-1}	θ_{ik}	d_{ik}	Fore legs	Rear legs
1	0	0^o	Θ_{i1}	0	$-90^o, 90^o$	$-90^o, 90^o$
2	a_1	90^o	Θ_{i2}	0	$0^o, 90^o$	$90^o, 0^o$
3	a_2	0^o	Θ_{i3}	0	$-180^o, 0^o$	$0^o, 180^o$
4	a_3	0^o	--	0	---	---

Table 2.

2.02.02. MATERIAL PROPERTIES

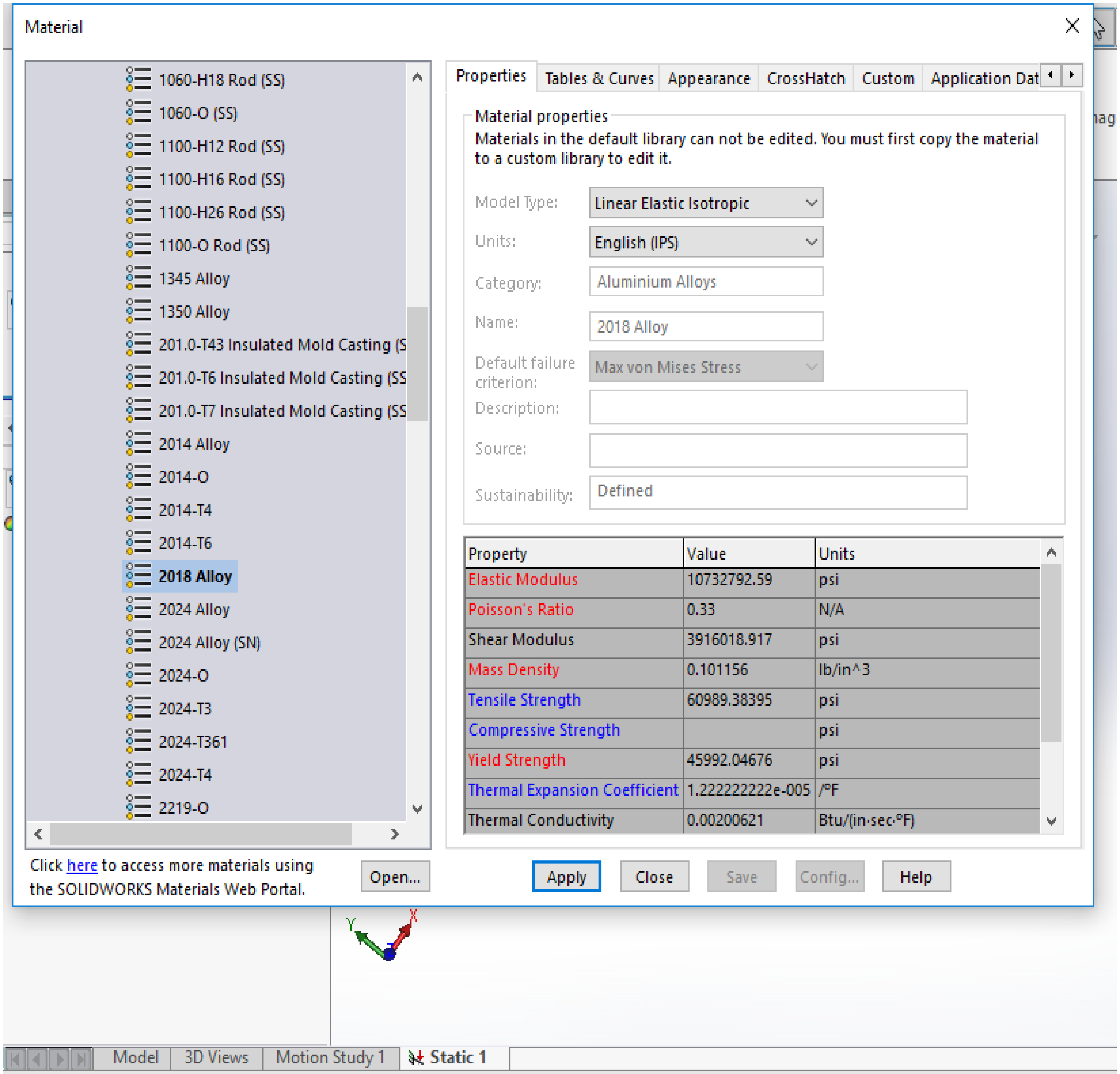

Fig. 2. Material properties of legs of the robot

2.02.03. Forward kinematic equations

According to the above figure fig.1, we have clearly seen that O_b is geometrical center and the center of gravity of the whole frame in static condition. Here, we draw the schematic diagram in Cartesian co-ordinate system, where x_b indicates to the forward direction, y_b indicates lateral direction of the robot and z_b represents vertically upward direction.

Basically there are four reference frame given as, $[O_{i0}]$ (i=1, 2, 3, 4) which are fixed at the four corners of the robot bed respectively. The subscript i and j represent the subsequent number of four links and legs. Mechanical arrangement and configuration of these four legs are exactly identical but only difference in there posture of motion. The motion details are shown in the table 2.

There are forward kinematic equations for the kinked joint robot, these forward kinematic equations from $[O_{i1}]$ to $[O_{i4}]$. The transmission from $[O_{i0}]$ to $[O_b]$ for these four legs can be represented by the following transformation matrix, for special value of λ and δ.

$$^{b}T_{i\,0} = \begin{bmatrix} 0 & 0 & 1 & \delta b \\ 0 & 1 & 0 & \lambda w \\ -1 & 0 & 0 & -h \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{..........(1)}$$

Here b, w and h are the length, width and vertical height of the robot bed respectively, which are shown in figure 1. Sign convention of λ and δ are shown below:

$$\lambda = \begin{cases} 1, & i = 1, 2 \\ -1, & i = 1, 2 \end{cases}$$

$$\delta = \begin{cases} 1, & i = 1, 2 \\ -1, & i = 3, 4 \end{cases}$$

$$
{}^{i0}\mathbf{T}_{i4} = \begin{bmatrix} c1c23 & -c1s23 & -s1 & a1c1 + a2c1c2 + a1c1c23 \\ s1c23 & -s1s23 & c1 & a1s1 + a2s1c2 + a3s1c23 \\ -s23 & -c23 & 0 & -a2s2 - a2s23 \\ 0 & 0 & 0 & 1 \end{bmatrix} \ldots(2)
$$

Equation (2) represents forward kinematic equation for four legs.

Where, $c_k = \cos\theta_{ik}$, $s_k = \sin\theta_{ik}$, $c_{23} = \cos(\theta_{i2}+\theta_{i3})$, $s_{23} = \sin(\theta_{i2}+\theta_{i3})$

2.03. <u>Foot trajectory analysis</u>

2.03.01. Stance Phase Trajectory Design

When this type of robots are in motion we can see two types of phases, one is Stance Phase and other is Swing Phase. We have to design to keep in mind the worst situation that is high acceleration and high external loading condition. Whether we talked about static loading condition then this phase design is to be considered for position control only, and we can achieve good stability of the quadruped robot's structure. If we consider walking or running situations this type of design cannot meet our goal properly, it may damage other parts of the robot. Hence, we have to design the swing phase separately.

In order to compensate the reaction between legs and the ground when its any legs leave the contact of the ground we consider uniform velocity of the robot in any directions. When four legs are rest at the ground the relation is given below:

$$R_1 = R_2 = R_3 = R_4 = W / 4$$

Formula for the distance cover in x direction is:

$$(S_{st}, x) = V_{desire} \times T_{st}$$

$$T_{st} = \frac{L}{Vdesire}$$

Where, L is the leg stride length in a gait cycle, T_{st} is the stance phase time, and $\mathbf{V}_{desire}$ = desired velocity of the robot.

When we talked about motion or displacement in the y direction we will consider cosine function of motion and displacement along the x direction. When any of the leg touches the ground, it rasist maximum reaction forches from the ground. Equation in the y direction can be written as

$$\mathbf{(S_{st}, x) = -\Delta \times \cos\left[\pi \left(\frac{1}{2} - \frac{V_{desire} \times Tst}{L} \right) \right] - p_0}$$

2.03.02. Swing Phase Trajectory Design

Main objective of swing phase design is to minimize the reaction forces which are imparted to the legs avoiding obstacles or resistances. As a result excess energy could not be consumed by this robot. Therefore, the period of the swing phase T_{sw} is consider to be 0.25sec, it is calculated at the maximum r.p.m of the motor.

$$X_{sw}(t) = \delta b + L\left(-\frac{16}{T^3} t^3 + \frac{12}{T^2} t^2 - \frac{1}{T} t - \frac{1}{4}\right)$$

$$Z_{sw}(t) = -H_b + H_f\left(-\frac{128}{T^3} t^3 + \frac{48}{T^2}\right)$$

Where L is defined as stride length, T defined as cycle time, trepresents real time situation as a variable. H_b and H_f are represent maximum elevation of a leg as a reference of the ground.

3. Chapter 3: Detailed design of the robot with the help of software

3.01. DETAILED DESIGN OF THE ROBOT LEG:

To make any part or component a draft is necessary, without this stage we cannot proceed to the further stages. Here we consider SOLIDWORKS software for drafting purpose. There we first drafting all individual solid 3-D parts, after that assembles all the parts at suitable places. According to our thinking a particular structure is made with proper dimension. Erroneous dimension of any object may create unnecessary forces or stresses that cane create a little bit problem at later stages.

First of all I draw individual sub component parts along with proper dimensions, then I have assembled all the parts at a proper place. Pins are made with a particular diameter, along with develop the diameter of the hole clearance with maintaining a proper tolerance limit. This clearance is made for free and frictionless rotation of a joined arm. Extra clearance is filled with lubrication for smooth performance. All the structural members are designed with diamond cut truss members instead of solid link for better design.

First of all, considering the leg part, here model is shown in X, Y co-ordinate

Fig.3. Structural design of a leg of the quadruped robot

When we think about high speed quadruped robot, the total weight of the robot must be as light as possible considering the weight carrying capacity. As per our convenience, we select aluminum alloy for its robust structure and light in weight. Physical leg parameters are shown below, total mass of the leg 6.5 kg out of which the rotational or swing part weight is 1.4 kg which is almost 22% of the total mass of one leg. Moreover, the center of gravity of each part of the robot has to be nearest position from the rotating part or motor axis, so that inertia force is to be minimize during the rotational movement as our requirement, as a result better stability can be achieved. Shoulder and knee actuators are mounted with planetary gear and co-axially mounted at the shoulder end part for creating a couple (moment generation) formation of this two joints, hence the mass of any leg inertia moment is reduced. In a detail discussion, the knee actuators drives the knee joint through some sensor activities followed by some parallel linkage mechanism. Here we use Fuji Automated Numerical Control (FANUC) for actuator motion control. One leg mainly consists of three parts, are thigh, calf, and foot, where the parallel linkage adopt on calf and foot.

PARAMETER SYMBOL VALUE UNITS

Here, we consider a maximum permissible limit of 200 kg weight to carry.

Leg Mass (m) = 7.500 kg

Thigh Mass (m1) = 0.770 kg

Thigh Length (l1) = 0.645 m

Calf Mass (m2) = 0.546 kg

Calf Length (l2) = 0.520 m

Foot Mass (m3) = 0.368 kg

Foot Length (l3) = 0.301 m

3.02. ASSUMPTATION AND SIMPLIFICATION:

When we consider a rotational or swing motion about a pin joint or cylindrical pin, a knuckle joint arrangement is needed for this particular purpose. I consider two knuckle joint per leg for rotational movement. There is a space for motor mounting, here I do not consider these two motor mounting part because there are very nominal stress affected zone with the compared to three links and their joint parts.

3.03. DETAILED ANALYSIS OF THE BED:

The most important aspect and backbone of this paper is the mechanical design of the every individual components. First of all we consider a proper dimension, certain specifications and planning for that torso where we load goods as per our needs. Now varieties of designs come to in mind at the initial stage of the design. Every applied methods may be fruitful after solving trial and error methods with setting some terms and conditions. So, keeping all these things we have to design a model which is willingly acceptable and meet our purposes. This type of numerical calculations are essential for mechanical design to find the critical area where maximum stress has been developed.

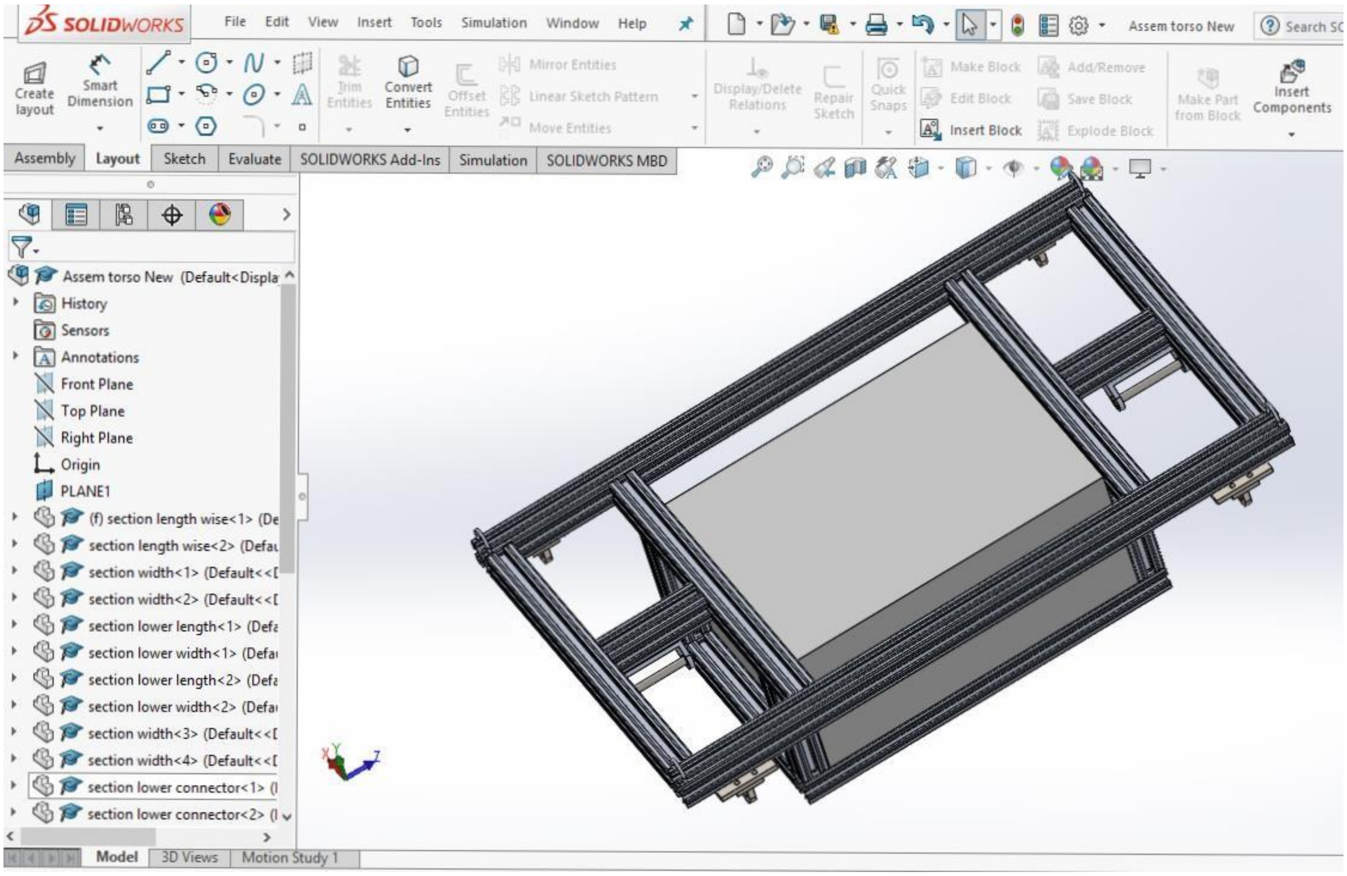

Fig.4. 3-D view of the bed without electrical equipment

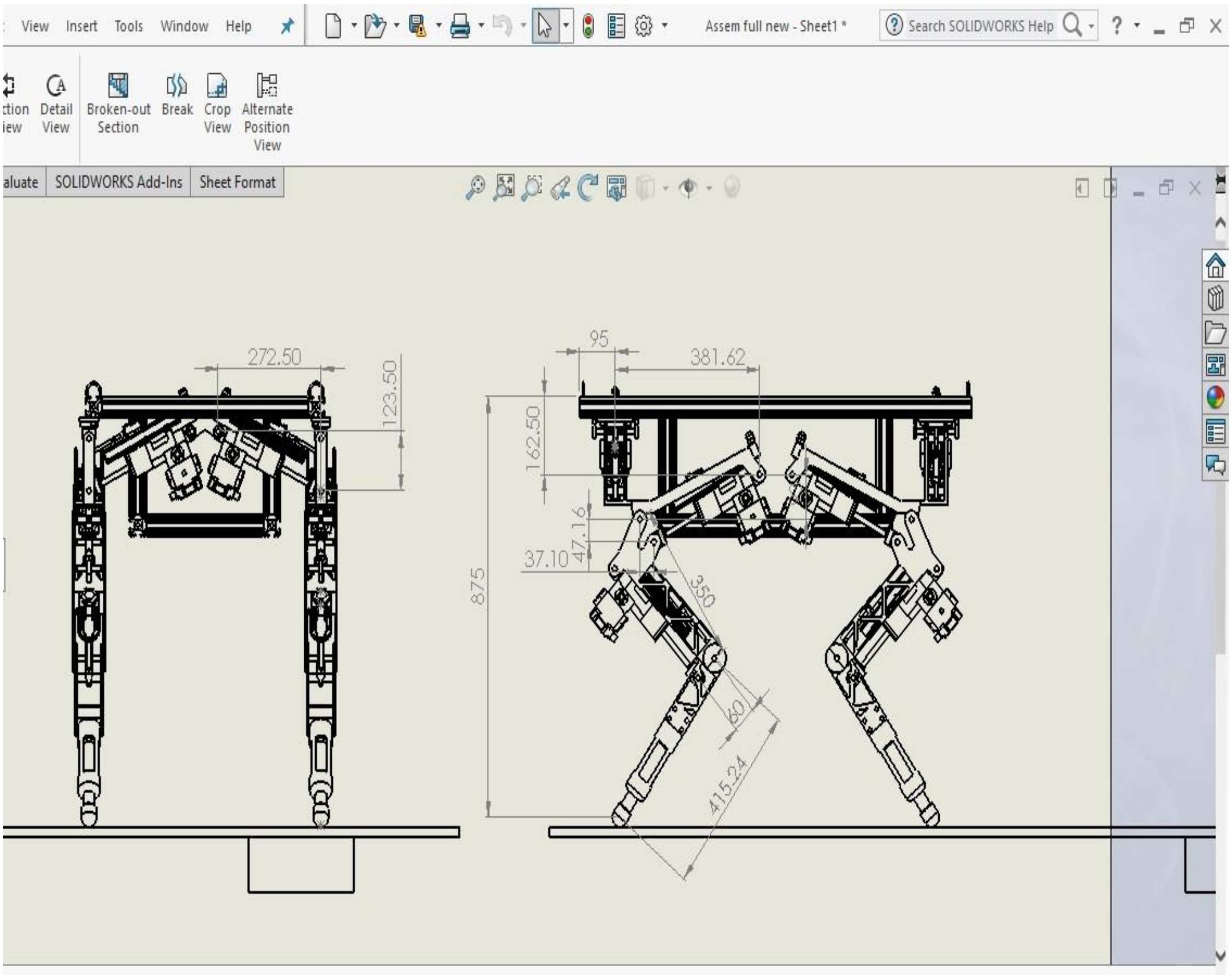

Fig.5. Top view and front view of the robot bed

We have to set a limit of 200 kg weights that can permit this quadruped robot with a factor of safety (f.o.s. = 1.5) consideration i.e. I have done the full design with the 300 kg weight basis. For design point of view this maximum load is distributed in equal magnitude through all the 4 legs which are placed in rectangular manner with consideration of static loading condition. In this case the center of gravity of the total structure is acting from the point C (as shown in the figure) vertically downwards, so no unbalanced moment not come into picture.

When robot is in motion, in account of dynamic loading consideration this total load distributed through the 3 legs which are placed in triangular shape not equal magnitude. The center of gravity of the whole structure is now shifted towards left side as shown in the right side figure. There is generating an unbalanced moment because a leg, which wants to move forward direction that is in air, and also there is a traction force acting along the horizontal direction.

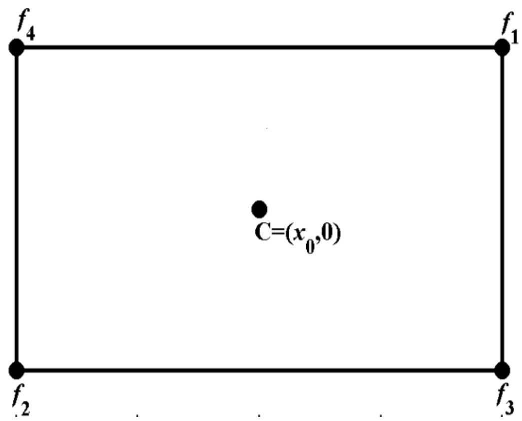

Fig.6. f1, f2, f3, f4 are four vertices of the robot bed through which four legs are connected, and C is center of gravity of the total body in static condition, which is exactly middle of the bed.

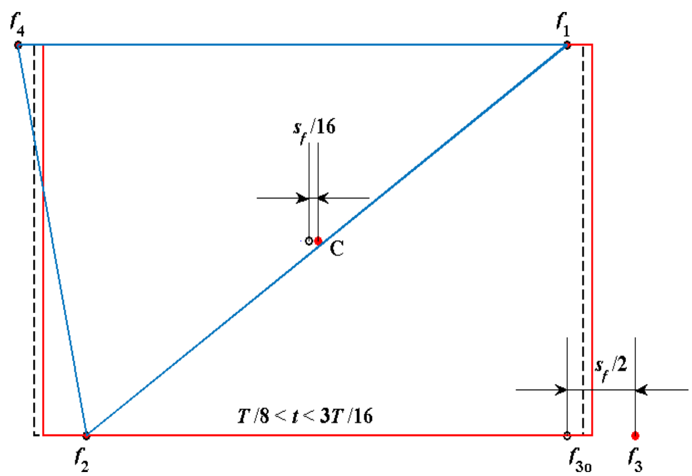

Fig.7. Triangular support from ground in dynamic situation, when center of gravity (C) is shifted from its initial static position.

The four legs are the main pillers to carry out the whole load during transportation. Material selection and design of the structure of a leg is playing a key role in this part. Diamond cut truss members may be a good selection of design for this purpose, because prass members will give an extra rinfocement to the structures to better handelling of heavy load carring capacity.

In this senario enough build maretials are save as well as light weight can be acheved, due to this when we operate this robot movement less power is required to move the whole structure from one place to another. For good grippings and stability of the robot on the ground the extream lower portion of the legs are flat with some surface extention, and lower portion of that extended surface should coversome flexible rubber materials for better grippings with off road terrain.

When we look at the design pin joined portion then there is enough stress developed due to heavy loading on it. When the clearance between pin and hole is more than a tolarence limit then comprssive and shear stress or tensile or shear stress combination has generated to the pin and structural members thoes are connected with this pin joint.

Chapter 4: Results and Discussion

RESULTS AND DISCUSSION:

According to model design followed by loading and boundary condition, followed by meshing, followed by stimulation by Finite Element analysis (FEA) these picture are properly indicate the stress distribution of each and individual parts.

These studies are performed with the consideration of a single aluminum alloy plate, but actually in the real scenario these two similar types of plates are joined by a passer. So load carrying capacity will be double in the practical case than this FEA in Solidworks.

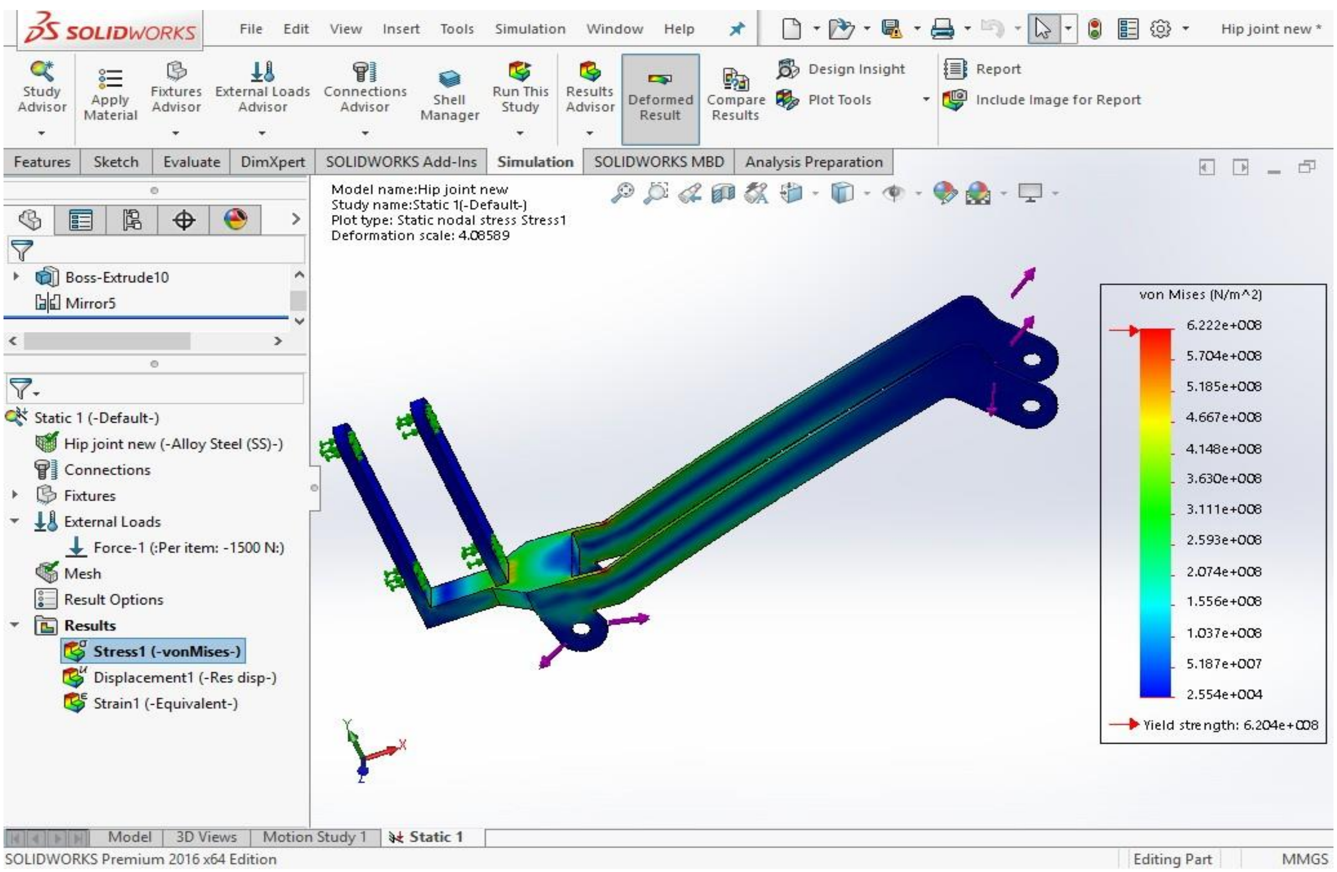

Fig.8. Finite Element Analysis (FEA) : (a) the equivalent stress of the thigh

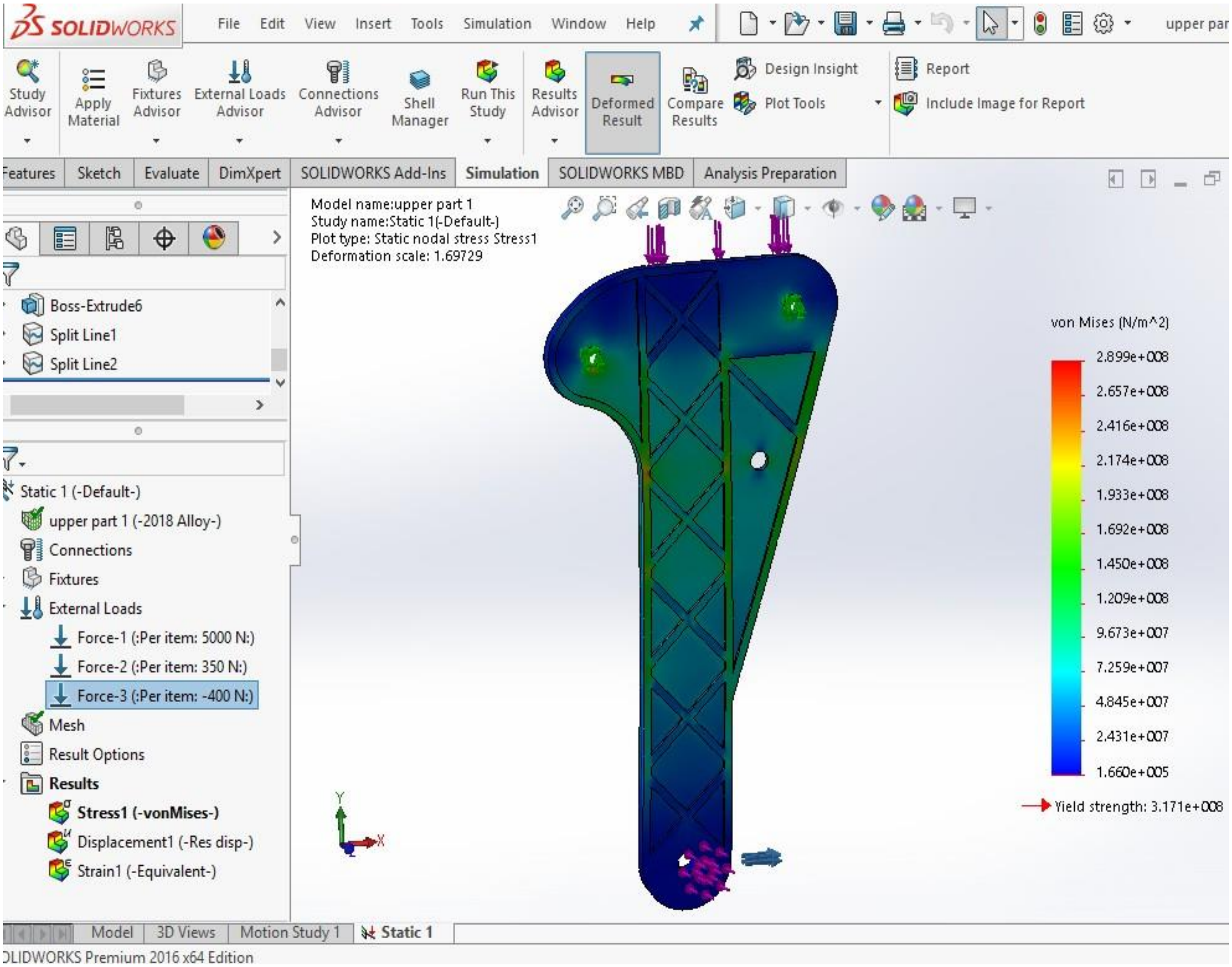

Fig.9. Finite Element Analysis (FEA) : (b) the equivalent stress of the calf;

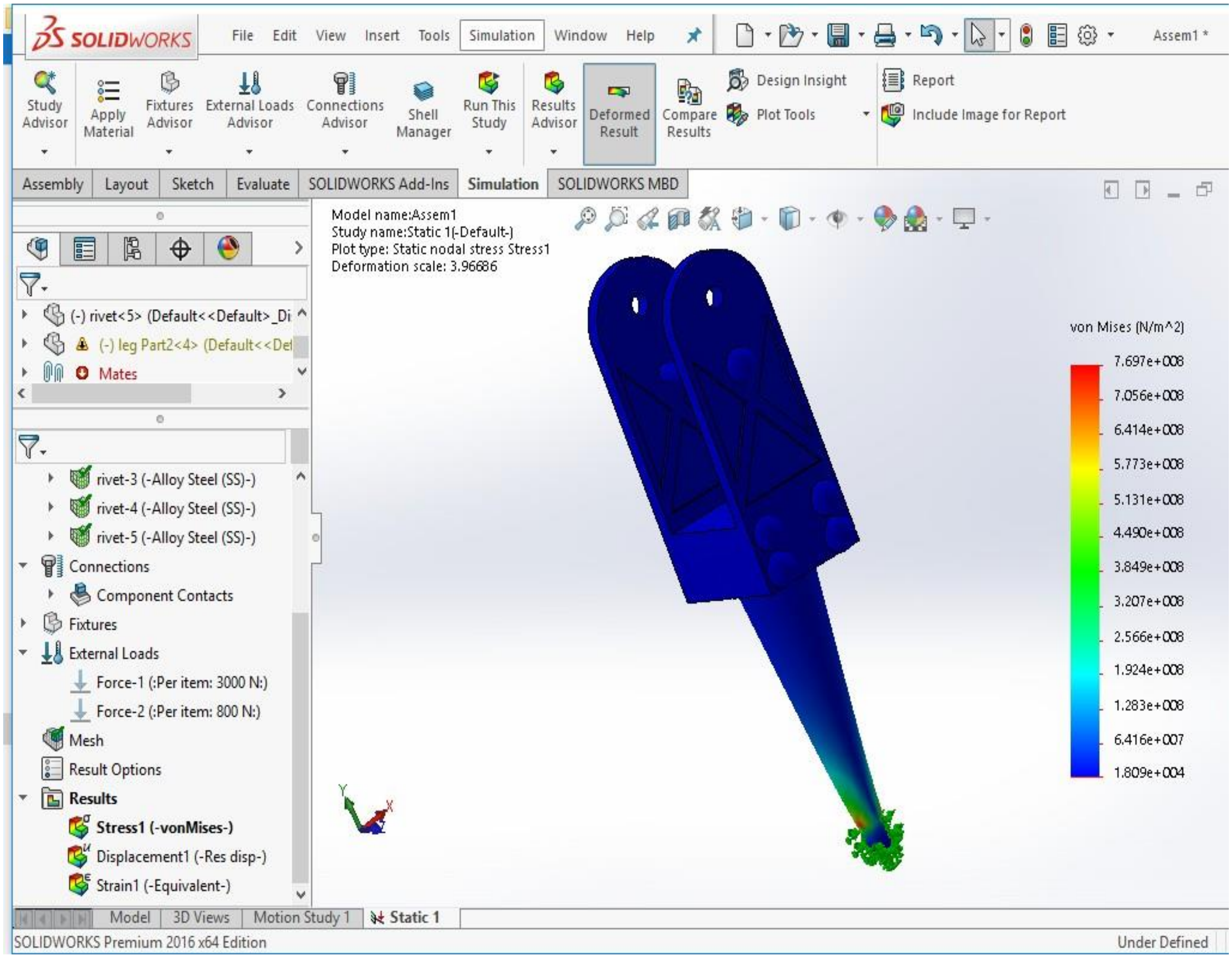

Fig.10. Finite Element Analysis (FEA) : I the equivalent stress of the foot

4.03. DISCUSSION:

Our leg design focus on mainly leg parts and its shoulder joints to its bed structure with motor. As per our “Thigh” design top part thicker and bottom part thinner, as a result the moment of inertia of this part has to be reduced, and well stable. Due to achievement of higher stability the leg can reach at higher acceleration level and faster response facility. This leg design adopted in previous robots also, like MIT cheetah, Laikago robot etc.

According to design and operation we can found that the knee joint is mainly meet the purpose of up and down the legs in vertical direction, it is also found that this kind of movement is slow and flexible about the knuckle joint. This type of leg design made to sustain high magnitude vertical reaction forces throughout its dynamic process. Hence, this type of leg easily stable in heavy load condition and motion acceleration is noticeable throughout its movement.

Our leg’s thigh part consists of 6 mm thin ribbed plate in the middle portion, and its both side are reinforced by the truss members for the better bending moment and vertical pressure sustainable capacity with low material weight. This type of structure has good quality bearing pressure carrying capacity because of its manufacturing design and properties.

Here we use spherical joints in the joint of leg and bed, so that when we want to turn the whole structure it is feasible to us otherwise it move only in straight direction. Here we use dry bushing for its unique self-lubrication characteristics to minimize the friction in the linkage joints. The foot part is cylindrical in the bottom most position to deal with uneven ground surfaces where it works properly.

Moreover, two high torque generated motors are used in a single leg (one is in the joint of bed and thigh, and other is in the joint of thigh and calf), which can provide a low gear ratio. The single stage gear reduce energy loss in the mechanical transmission process, as a result a good energy efficiency can be developed through this arrangement.

Chapter 5: **Conclusion**

5.01. CONCLUSION:

In this paper, we design the robot taking consideration of all types of forces static and dynamic loading conditions. In the analytical part transformation matrix formed for the forward movement of the each legs, some simplification has been done by us to avoid complicated situation. After that we have planned some motion planning of each and every leg and the whole structure with a periodic time frame.

Here we design a well-defined structure of a quadruped robot leg and stress analysis of its bed. To avoid a heavy curb weight of this robot we use aluminum alloy for its various important properties like light weight, robust infrastructure to sustain heavy stresses. Moreover, it is already proven by the stress and deformation analysis in the laboratory. Rotational motion phase and stance motion phase trajectories were designed individually under different loading situations and various circumstances while assuring smooth and continuous trajectories. According to our three part leg design, the moment of inertia with respect to its rotational axis or motor axis, as a result better stability and acceleration can be achieved for this robot. As per our bed design in dynamic condition the extra generating moment can be balanced by its leg operations. This four legs are electrically operated by motors and actuators. This paper give a hint to develop this robot electrically efficient (reducing power consumption against frictional forces and rotational motion) and better stability in its operation for rough and uneven terrain.

5.02. REFERENCES:

- Yu, J.; Hooks, J.; Zhang, X.; Ahn, M.S.; Hong, D. A proprioceptive, force-controlled, non-anthropomorphic biped for dynamic locomotion.

- WildCat-TheWorld's Fastest Quadruped Robot. Available online: https://www.bostondynamics.com/wildcat

- Ananthanarayanan, A.; Azadi, M.; Kim, S. Towards a bio-inspired leg design for high-speed running. Bioinspir. Biomin. **2012**, 7, 046005.

- Spröwitz, A.; Tuleu, A.; Vespignani, M.; Ajallooeian, M.; Badri, E.; Ijspeert, A.J. Towards dynamic trot gait locomotion-design, control, and experiments with Cheetah-cub, a compliant quadruped robot. Int. J. Robot. Res. **2013**, 32, 932–950.

- Rosendo, A.; Liu, X.; Nakatsu, S.; Shimizu, M.; Hosoda, K. A combined cpg-stretch reflex study on a musculoskeletal pneumatic quadruped. Biomimetic and Biohybrid Systems. Living Mach. **2014**, 417–419.

- Walter, R.M.; Carrier, D.R. Ground forces applied by galloping dogs. J. Exp. Biol. **2007**, 210, 208–216.

- Saputra, A.A.; Tay, N.N.W.; Toda, Y.; Botzheim, J.; Kubota, N. Bézier curve model for e_cient bio-inspired locomotion of low cost four legged robot. In Proceedings of the 2016 IEEE/RSJ International

Conference on Intelligent Robots and Systems (IROS), Daejeon, South Korea, 9–14 October 2016.

- Lee, Y.L.; Lee, Y.H.; Lee, H.; Phan, L.T.; Kang, H.; Kim, U.; Jeon, J.; Choi, H.R. Trajectory design and control of quadruped robot for trotting over obstacles.

- Yoshikawa, T. Manipulability of Robotics Mechanism. Inter. J. Robot. Res. **1985**, 4, 3–9.

- Hogan, N. Impedance control—An approach to manipulation. I. Theory. II. Implementation. III. Applications. J. Dyn. Syst. Meas. Control **1985**, 107, 1–24.

- Jung, S.; Hsis, T.C.; Bonitz, R.G. Force tracking impedance control of robot manipulators under unknown environment. IEEE Trans. Control Syst. Technol. **2004**, 12, 474–483.

- Liu, M.; Xu, F.; Jia, K.; Yang, Q.; Tang, C. A stable walking strategy of quadruped robot based on foot trajectory planning. In Proceedings of the 2016 3rd International Conference on Information Science and Control Engineering (ICISCE), Beijing, China, 8–10 July 2016; pp. 799–803.

- Haberland, M.; Karssen, J.G.D.; Kim, S.; Wisse, M. The e_ect of swing leg retraction on running energy e_ciency. In Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, CA, USA, 25–30 September 2011; pp. 3957–3962.

- Laikago: A Four Leg Robot Is Coming to You. Available online: https://www.youtube.com/watch?v=d6Ja643GqL8