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Modelling and Analysis of Hexapod walking Robot

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Abstract: In comparison with the majority of other animals, the spider can access all kinds of environments where other animals or even humans can't. These important attributes are taken into consideration, to design and develop a Hexapod Walking Robot, in order to perform various movements such as ascend and descend in all the directions. Hexapod Robots have always been a centre of attraction for several years. Many universities, research centres, and industries have carried out studies but in the past few years, systematic walking robots have been formulated, fabricated, and built with implementations that can be suitable for experimental demands. The paper presents a model to understand how, mathematically, a hexapod animal walk. The aim is to develop a suitable bio-mimetic model of hexapod walking robot that is lighter in weight with reduced number of motors and easily controllable. Modifications in the design is adopted by using solid works. Thereafter, a detailed analysis of the model is conducted along with the moment and force analysis. Moment analysis is carried out to check the walking capabilities of the legs at extreme joint positions. The robot leg motion is checked by applying loads at which the robot turns to fail and it has been found that the proposed model is suitable to bear different forces while walking to perform any desired task. This research also gives an outline of the design considerations of the Hexapod Walking Robot and a detailed design procedure is also discussed for the feasible and systematic design of a walking robot. In particular, these design procedures covers the main features such as mechanical structure and leg configuration, actuating and driving systems, motion controls, and walking gaits.

Keywords: Degree of Freedom (DOF); Hexapod Robot; Tibia; Coxa; Six Legged walking Robot.

1. Introduction

The Gujarat earthquake that hit south-southwest of the village of Chobani in Bhachau Taluka of Kutch District in 2001 and the terrorist attacks on the Taj hotel, Mumbai in 2008 and also currently the Bihar flood in 2019 which made dozens of people homeless are clear indication that the world is not prepared for these enormous disasters [1]. Unfortunately, the infrastructures were not stand infront of natural disasters, even in case of terrorist attack in Taj hotel the local police and rescue teams like NDRF were not prepared for rescue missions. In any disaster whether it is manmade or natural the primary tasks are to reach the affected destination safe, find and get the information of victims, to rescue as many of them safely. These things clearly proof that unusual skilful robot can respond to incidents immediately after the collision of major disaster [2].

Hexapod robots plays a very outstanding role in disaster rescue mission. It is possible for these robots to reach affected areas more easily than a human being [3]. Hexapod robots are one of the best designs for robots and highly efficient than other robots. It is compact and have an advantage than other multi legged robots (four and eight legged robots) because it maintains static equilibrium efficiently when moving and maintain balance at irregular surfaces [4]. These robots can go forward, right, backward and left with several type of gaits for the purpose of unusual speeds and weight. Also, six-legged robot have extra legs i.e., robot can do its work continuously even if legs are disoriented. Along with this these robots applications involves high dependability works such as rescuing, searching, examining, etc [5].

There are several types of body design of robot but the most used and efficient are rectangular and hexagonal. In rectangular type of robots there are six legs along two sides which are in symmetrical apart i.e., individual sides have three legs each. In six-legged type, there are six legs which give out axis-symmetrical posture around the body. These are also known as circular body type [6].

Hexagonal hexapod robot has better performance than rectangular hexapod robots because in rectangular body it requires another gait for sharp moving or turning action i.e., need four to five steps more to recognising turning actions [7].

When it comes to the analysis of inverse kinematics for motion prediction among the different kind of biped robots, the six-legged robot is studied thoroughly which have a strong stability of legs, even if one or more legs are gone defected then robot can easily be functionable [8-9]. Also, the six-legged robot structure used the arm manipulator approach for an easy analysis [10].

1.1 Early Design

In early times, the Hexapod Robots were designed with a rigid predetermined motion hence, the ground adaptations were not possible [11]. In the 1950s, researchers focused on designing a robot and assigning motion control completely to the operator physically [12].

The first successful robots were built in 1972 at the University of Rome. It was a walking machine which was controlled by computers with electrical drivers. In the middle of 70s, a six-legged machine with an archetypical model of motion control was designed in the Russian Academy of Science in Moscow [13]. The model had radiation scanning range finders and was connected with two systems which were controlled by computers [14]. In 1976, at Moscow State University, a robot with tabular axial chassis articulated designed leg and 3 degrees of freedom was designed [15].

In the 90s, there was an enormous development of the theory of walking robots and servomechanism based on classical and nonneural networks theory. They were proposed in the USA, Europe, and Japan. Artificial Intelligent (A.I.) systems were used for the examination of surroundings and the motion on compound surfaces [16].

The *Dante project,* which was financed by NASA in 1993, was the biggest development of the period. Both Octopod robots – *Dante 1 and Dante 2,* were developed under the leadership of Prof. Whittaker and were designed for the locomotion of very rough terrains on different planets. It had been developed at CMU (Field Robotics Centre, USA) [17].

1.2 Recent Growth

In the past decades, there have been enormous growth and development in control system technology. These newly developed robots were accoutred with highly intense sensing systems. A.I. technologies have been used for the better examination of the surroundings and smoother motion of the robots on compound surfaces [18].

At the end of the 90s, a number of bio-inspired robots were designed in the Case Western Reserve University (USA). Robot III, for the instance, was the robot that was made based on a cockroach architecture and had a total number of 24 DOFs, to be more specific, each rear leg had 3 Degree of Freedoms (DOF's), each middle leg had 4 DOF and each front leg had 5 DOF [19].

2. Proposed Methodology

The hierarchical procedure is an aid to select the most favourable preliminary design solution among those under consideration. The Fig. 1 shows the flow-chart of the proposed research architecture methodology adopted in order to design a well-equipped Hexapod robot. The Preliminary architecture design is identified based on the requirement as well as the analysed design considerations. A refined model is obtained by synthesizing every part including the body and legs of the robot [20]. The design is made considering all the important factors like Mechanical structure of the body, leg structure, actuator and control mechanism, cost and operational features. The most important part is the selection of the material which will be used. Aluminium 6061 is used because it is less costly and has yield strength of 2.75×10^{8} $\mathrm{N}.m^{2}$. A kinematic model is developed for the proposed design in order to analyze the form of walking pattern, the working space, and the payload [21]. Kinematic Analysis helps to determine the motion capabilities of the robot along with its workspace and the area required for its operation [22]. Literature have shown that there are a number of leg types currently working for hexapod walking robots. Every type has their own advantages and disadvantages [23]. The dynamic model is developed and optimized with the adoption of the best suitable actuators [24].

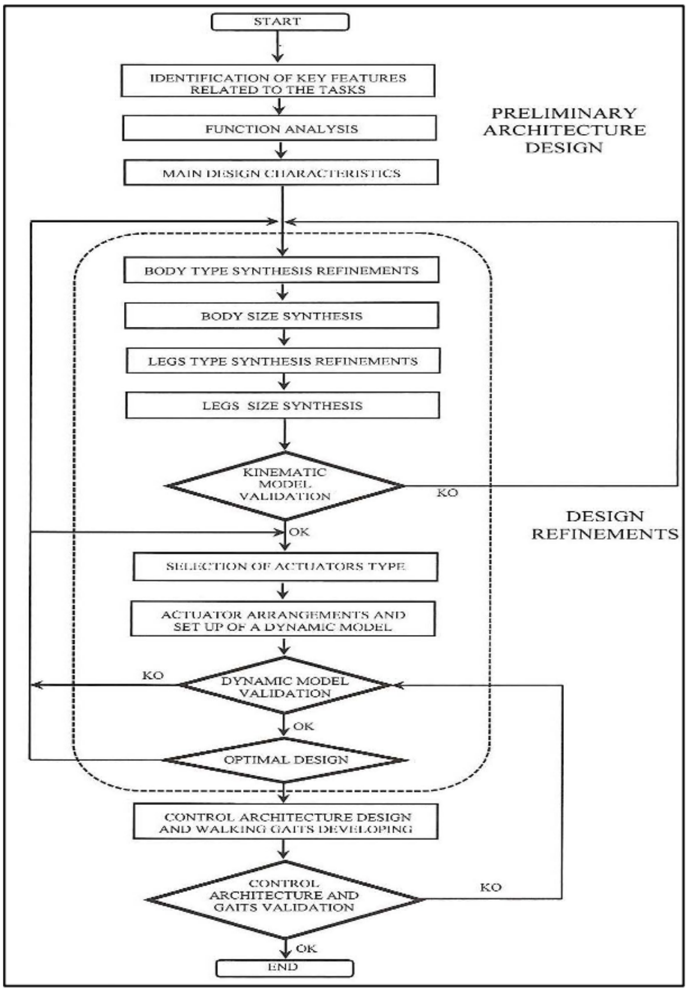

Fig. 1: Flow Chart of Proposed Methodology.

This paper aims to provide an in depth view of the current scenario of the robotics industry specially the mechatronically controlled legged robots domain of the vast field by the means of the flowchart [25]. Then the authors proceed to provide a systematic roadmap or procedure for designing and analyzing a hexapod robot (Six-Legged robot) for any specific operation [26]. In the present study the aim of the design was to create a robust and agile system that can operate in retrieval and reconnaissance field condition. The study develops a design and then validates the design by the use of FEA analysis that can be used to evaluate the structural integrity of the design. The study also provides a work frame for FEA analysis using optimized meshing control and develops a procedure to evaluate the design of the Hexapod robot [27].

3. Modelling of Hexapod Robot

3.1 Base or Trunk

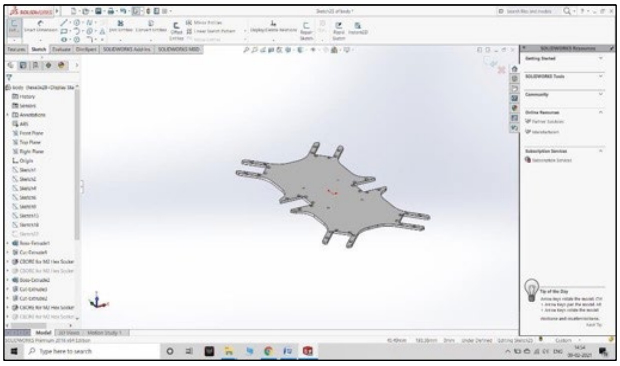

Fig. 2: Solidworks model of the Trunk.

Fig. 2 shows the 3-D design of the trunk of the hexapod. The complete design and structure of the base or the trunk plays a vital role in establishing the desired walking stability of the hexapod robot.

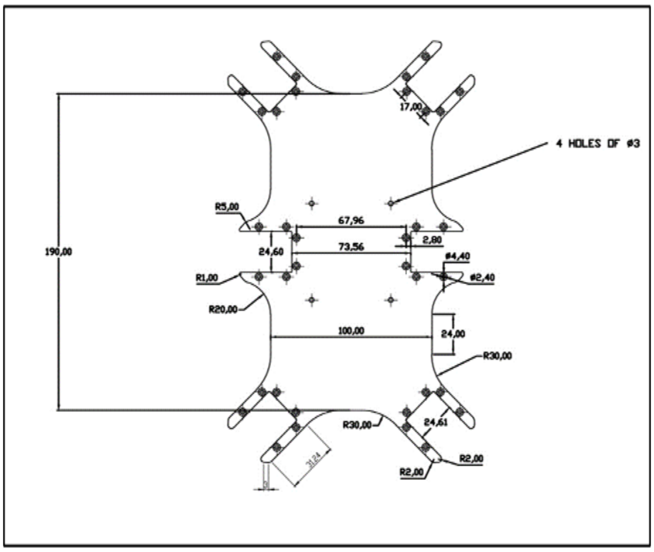

Fig. 3: Dimensions of the Trunk.

Fig. 3 Shows the dimensions of the trunk which is designed using solid works and drafting is done on both solid works and AutoCAD. Here first figure is the side view and the second figure shows planar view showing all the dimensions. The Trunk is the most important part as it is able to hold the forces that are acting on it while moving in any direction. The Trunk holds the legs and motor attached to it providing the whole spider Bot to move smoothly.

3.2 Coxa

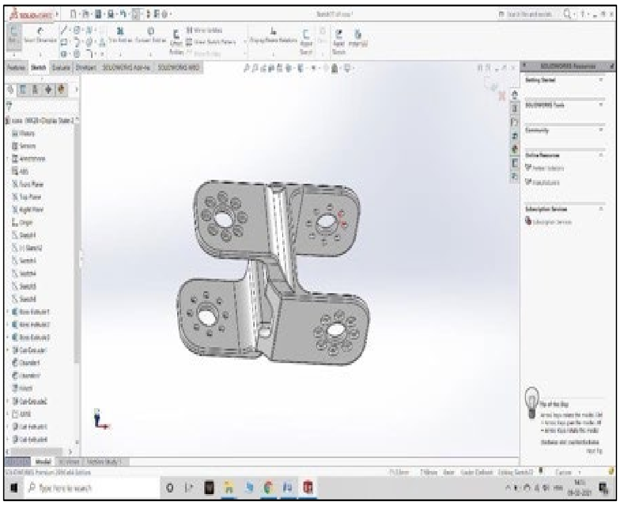

Fig. 4: Solidworks model of the Coxa.

Fig. 4 shows the 3D model of coxa. A revolute joint of one degree of freedom in the horizontal direction is provided at the junction of coxa and the trunk structure, also known as the base joint [28-29]. However, the other end of the coxa is connected to the femur, forming a revolute pair in a vertical direction, called a hip joint. Fig. 5 and Fig. 6 shows the dimensions with two different views of Coxa. Here First figure is the planar view and the Second figure is the isometric view. The Material used is Aluminium 6061 that encompasses yield strength of 2.75 × 10^8 N.m^2.

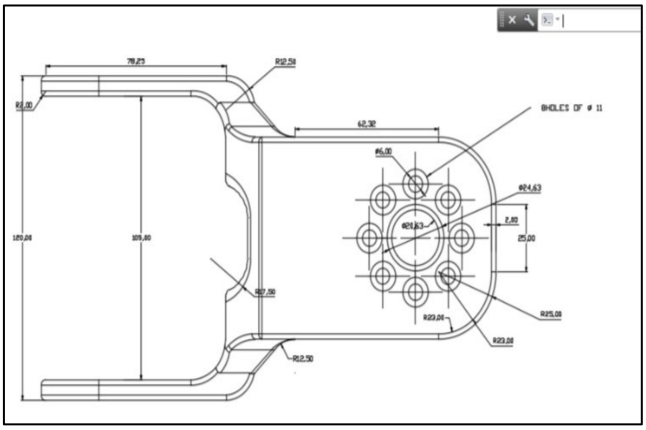

Fig. 5: Planar view of Coxa.

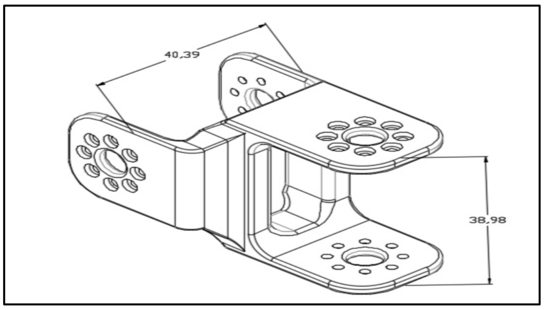

Fig. 6: Isometric view of Coxa.

3.3 Femur

Fig. 7 shows the 3D model of Femur. The femur is appointed in between the coxa and tibia with the help of revolute joints having one degree of freedom each. The connection of femur with is known as the hip joint. The Material used is Aluminium 6061 that encompasses a yield strength of 2.75×10^8 N.m^2. Fig. 8 shows the dimensional views of design. The other end of the femur involves the tibia to form a pair of vertical revolutions, known as the knee joint. The design is optimised in order to make the model more concise and fulfils all the strength requirements.

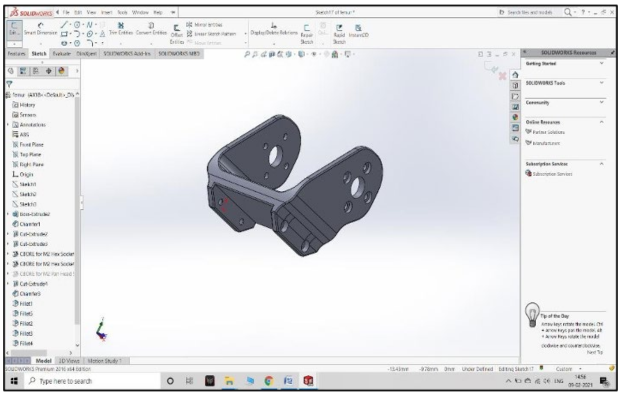

Fig. 7: 3D model of Femur.

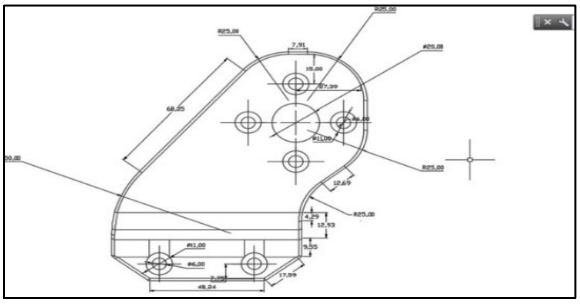

Fig. 8: Side view of Femur.

3.4 Tibia

Fig. 9 and Fig. 10 shows the 2D and 3D model of Tibia. The tibia is the final joint of the leg of the hexapod robot design. Tibia is an importangt part as it is through which the hexapod moves forward or in any direction. The Material used is Aluminum 6061 that encompasses a yield strength of 2.75×10^8 N.m^2. The end of the tibia pertains to the femur to shape the revolute pair with inside the vertical direction, referred to as knee joint. The different end of the tibia is in contact with the ground, forming a friction pair to help the moving, turning, and different motion of the hexapod. Below Tibia a small rubber foot is positioned to assist with inside the motion of leg and offer the support.

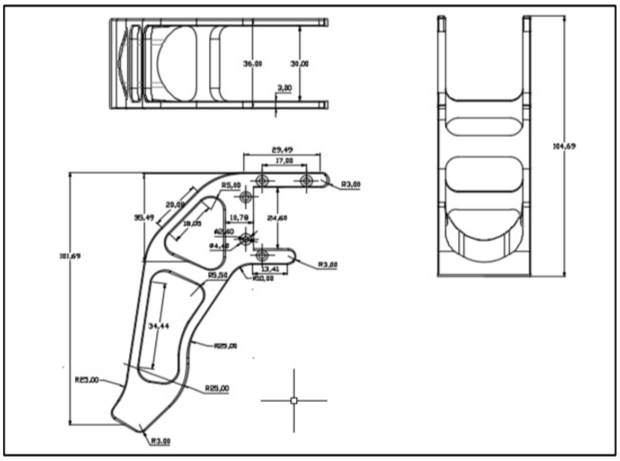

Fig. 9: 2D model of Tibia.

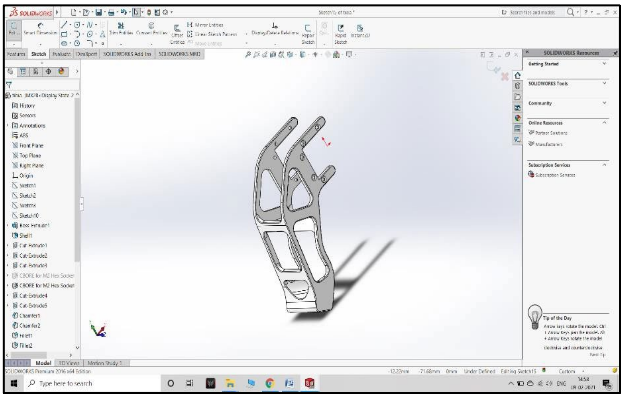

Fig. 10: 3D model of Tibia.

3.5 Motor

The motors used are servo motors with maximum rotation angle of 180 degrees (210 degree maximum). A lithium polymer battery is used as power source for the entire system. Fig. 11 and Fig. 12 shows the dimensional views of motor used for the joint movement of the leg of Hexapod Robot and Fig. 13 shows the 3D design.

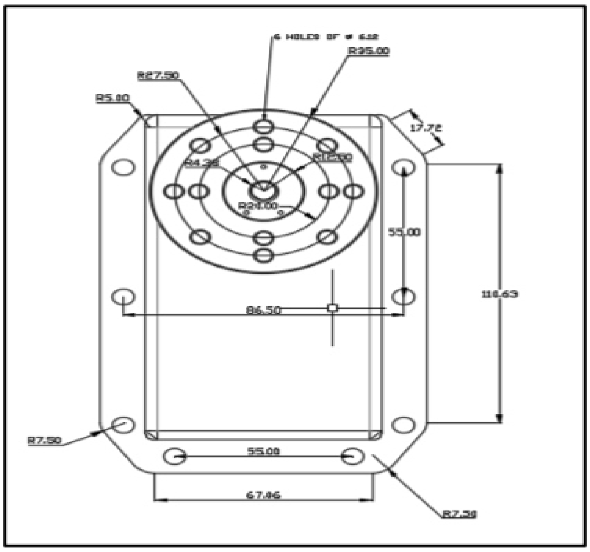

Fig. 11: Side view of Motor.

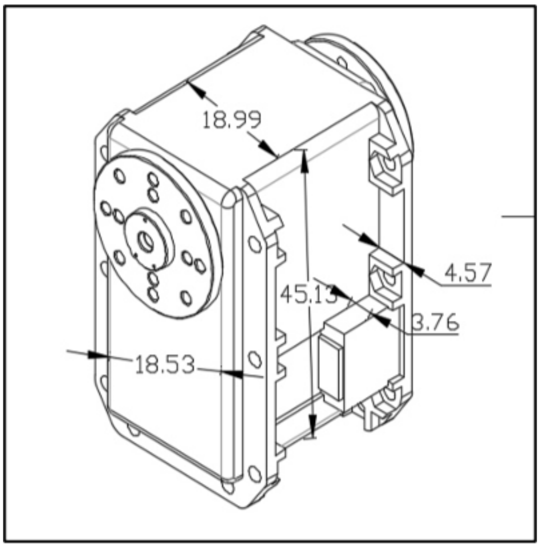

Fig. 12: Isometric view of Motor.

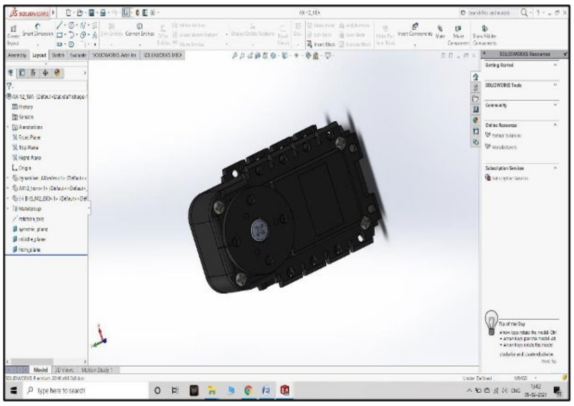

Fig. 13: Design of Motor.

3.6 Leg Sub-Assembly

After assembling the coxa, Tibia and Femur with the three motors a complete leg assembly is obtained as shown in Fig. 14. Here Three (3) Motors are used for each leg which helps in the proper movement of the leg and Degree of Freedom (DOF) of each leg is Three (3). The leg consists of three revolute joints having one degree of freedom each making a total of three degrees of freedom in the entire leg. The entire mechanical structure of the hexapod robot mainly focuses on the leg mechanism. The length of each links of the legs along with the selection of optimal material for construction is the main concern while designing this robot.

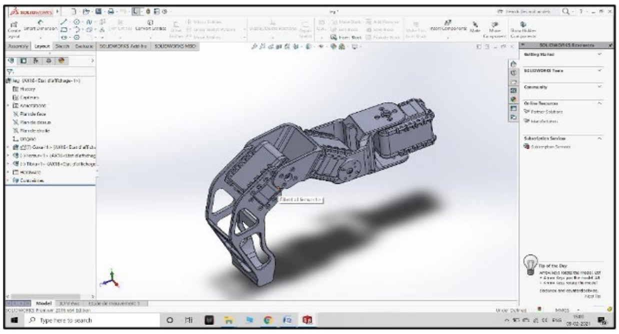

Fig. 14: Design of Leg Sub-Assembly.

3.7 Assembled Body of Hexapod

The Final 3D model of Six-Legged Hexapod robot is shown in Fig. 15. Each part was created with accuracy and using Assembly feature in Solid works, Each and every part was mated using mate feature. The final structure of the Spider Bot was designed while looking at the design considerations as well. The legs of the robot, in order to realize all-terrain walking algorithms were designed in the same type.

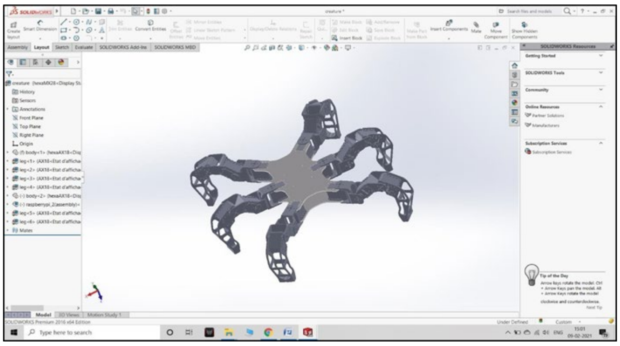

Fig. 15: 3D Model of Hexapod Robot.

Overall the final design consist of 18 servo motors where in each limb there are 3 servo motor that represents the three pinned kinematic joints. To secure the assembly together bolted connections were used, welded connections were avoided to create the possibility of dis-assembly for easy maintenance of the hexapod. A total of 390 M5 screws are required to fully assembly and bolt all the sub assembly together. For the entire model various parts are required for which a summary is provided in the Table 1.

Table. 1: Number of Sub-Assemblies in the Final design.

S.no	Name of the Part	No's	Material used	Weight/Per
1	Servomotor	18	-	54.5 g
2	Body	2	Aluminium 6061	173.2 g
3	Tibia	6	Aluminium 6061	56.2 g
4	Femur	6	Aluminium 6061	41 g
5	Coxa	6	Aluminium 6061	67.8 g
6	Screw	390	Steel	30g

4. Analysis of Hexapod Robot

The shape of the Hexapod walking robot decided the amount of flexibility that can be incorporated in the performance of the robot. In Comparison with eight-legged hexapod robot it is hard to conduct movement completely according to its physiological characteristics. Therefore, as per the literature and analysis, six-legged robot design could be more optimal. The mechanical structure involves the two main components including the base or body frame of the robot and the leg architecture. It is due to leg and the trunk; the shape is balanced and the entire hexapod walking robot actions smoothly. This research particularly specializes in the structural analysis layout of the hexapod robot in order to optimize and improve the authentic model. Thereafter, all the key components of the robot are checked.

Analysis of parts of Hexapod is done using Finite element analysis (FEA) using Autodesk Inventor Professional. The Finite element analysis is a technique which is used to identify how much load or pressure can a particular object hold by dividing the body or object into number of nodes and elements. Moment Analysis is done where moment is calculated and the Angular range with the help of which Moment is calculated for lower and extreme upper cases.

4.1 Moment Analysis

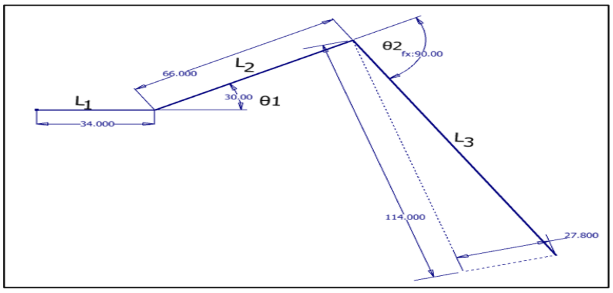

Fig. 16: Angles between Femur, Coxa and Tibia.

Fig. 16 shows the angles that are between Femur, Coxa and Tibia. The Values from our Design: θ_1=30° (Initial State). The Limit of θ_1 to induce motion is set as 25°≤θ_1≤60°.Based on the conditions of robot motion and position control: θ_2-θ_1=60°. Basically, with the help of these angles and other parameters, the Moment M_1 and M_2 are calculated respectively.

The formula for calculating Moment is given as follows:

$$M_1 + \frac{1}{2}m_1 g L_2 \cos\theta_1 + m_2\left[L_2\cos\theta_1 + \frac{1}{2}L_3\cos(\theta_2-\theta_1)\right] = NL_2\cos\theta_1 + L_3\cos(\theta_2-\theta_1)) \quad (1)$$

$$M_2 + \frac{1}{2}m_2 g L_3\cos(\theta_2-\theta_1) = NL_3\cos(\theta_2-\theta_1) \quad (2)$$

Where:
M_1: Moment in the Hip Joint
M_2 : Moment in the Knee Joint
θ_1: Angle between the Femur and the Horizontal
θ_2: Angle between the Tibia and the extension of Femur
N: The Ground Reaction from ground contact (Vertically Upward)
m_1: Mass of Femur
m_2: Mass of Tibia
L_1: Length of Coxa
L_2: Length of Femur
L_3: Length of Tibia

The value from the robot design is stated as follows [23]:
m_1 = 95.8 grams (Femur + Actuator)
m_2 = 110.7 grams (Tibia + Actuator)
L_1=34 mm
L_2= 66 mm
L_3= 114 mm
And g = 9.81 m/s^2

Also, using the robot motion and position control:

Using these we can calculate the Moment M1 and M2 for the extreme cases of 25° and 60°

We can say that the minimum number of legs supporting the hexapod at any given moment during the translation of the robot must be Three.

Hence, we can calculate the maximum reaction force as:

$N = {}^1/_3\,(mg)$, Where m is the total weight of the model 2.5 kg + 500g of misc. Therefore, Load

$N = \frac{1}{3}(3 * 9.81)$

N = 9.81 newton

Now using the eqn. 1 and 2, the Moments M_1 and M_2 for lower and upper extreme cases.

For the Lower Extreme Case:

M_1=154.8200062 N.m

M_2=16.78 N.m

For the Upper Extreme Case:

M_1=123.56 N.m

M_2=15.64 N.m

4.2 Force and Stress Analysis

The Element size is=2e-002. During the Literature review it has been identified that for the knee and hip joint where most of the reactions are supported by actual material and not by some electronic part an element size from 1e-002 to 3e-002 is optimal and therefore a size of 2e-002 is chosen to get an accurate enough result without making the solution computationally expensive. The Grading Factor=1.2 and to make the mesh smoother around the curves and sharp corners a high grading factor is required after experimenting with various grading factor ranging from 0.8 to 1.8 a factor of 1.3 is determined to be optimal for optimizing the topology [30-32)]
Element type = Second order Tetrahedron element
Tetrahedron element are chosen to get finer mesh along the curves surfaces and a Second order variant to increase the accuracy of the model.
Other alterations:

1. Inflation Layer = 10 layers along the outer surfaces.
2. Edge Sizing Filter = 1.12 for the fillet edges.

4.2.1 The Base or Body Frame

The Finite element analysis results of the Trunk or body frame comprising of the Von Misses Stress and Displacement diagram is Shown in Fig 17 (a) and (b) respectively. The Material used is Aluminum 6061 which has a yield strength of 2.75 × 10^8 N.m^2. The maximum stress of the trunk is 2.541×10^6 N.m^2 which is less than the yield strength of the material. Therefore, Aluminum 6061 satisfies the movement of the trunk and can bear the load.

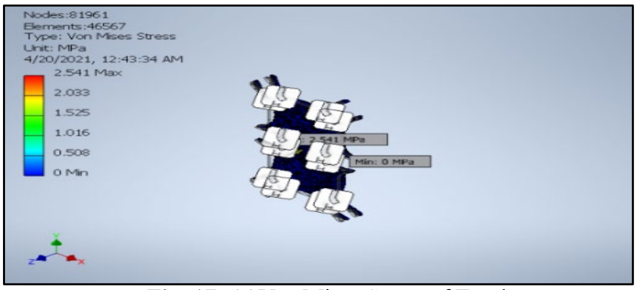

Fig. 17: (a) Von Mises Stress of Trunk

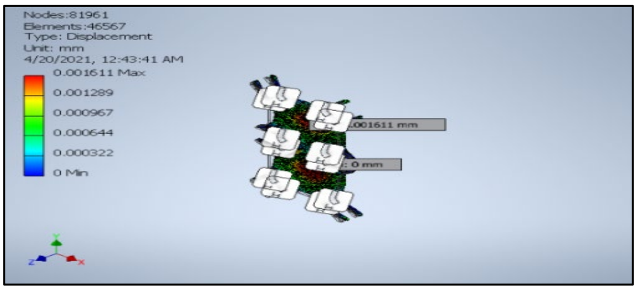

Fig. 17: (b) Displacement of Trunk

4.2.2 Coxa

The Finite element analysis results of the Coxa comprising of the Von Misses Stress and Displacement diagram is Shown in Fig 18 (a) and (b) respectively. The Material used is Aluminum 6061 that encompasses yield strength of 2.75×10^8 N.m^2. The Moment calculated above M1 is applied at both the bolt joint of the other end of the coxa to simulate the working condition of the robot and from this the maximal stress of the coxa is 2.196×10^6 N.m^2 which is a smaller amount than the yield strength of the material. Therefore, aluminum 6061 satisfies the movement of the coxa and can bear the load.

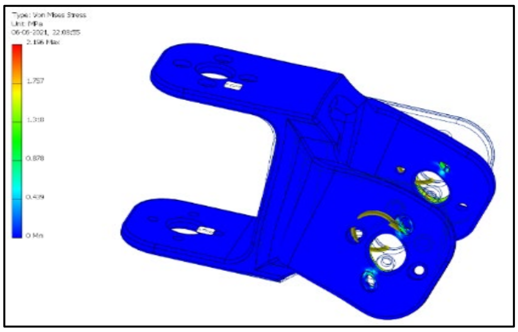

Fig. 18: (a) Von Mises Stress of Coxa

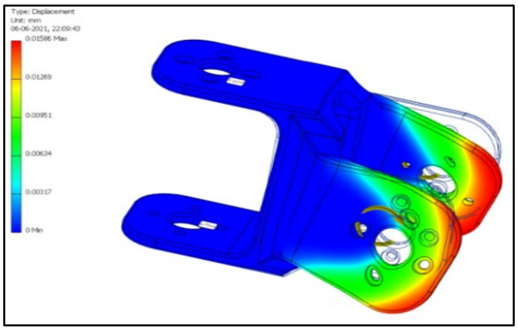

Fig. 18: (b) Displacement of Coxa

4.2.3 Femur

The Finite element analysis results for Femur comprising of the Von Misses Stress and Displacement diagram is Shown in Fig 19 (a) and (b) respectively. The material used is Aluminum 6061 that features a yield strength of 2.75×10^8 N.m^2.

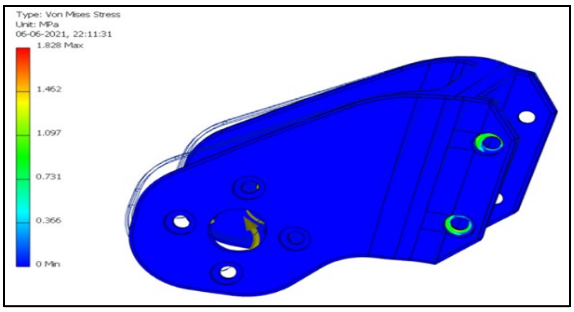

Fig. 19: (a) Von Mises Stress of Femur

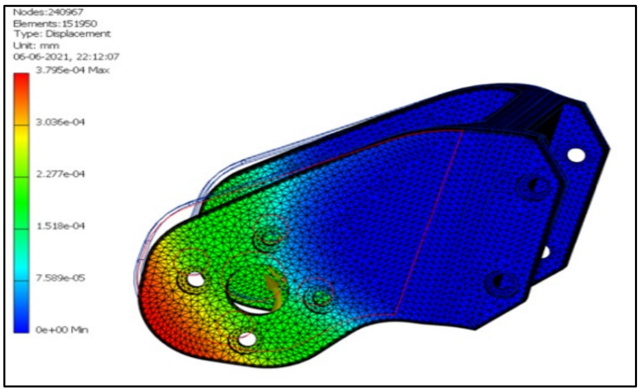

Fig. 19: (b) Displacement of Femur

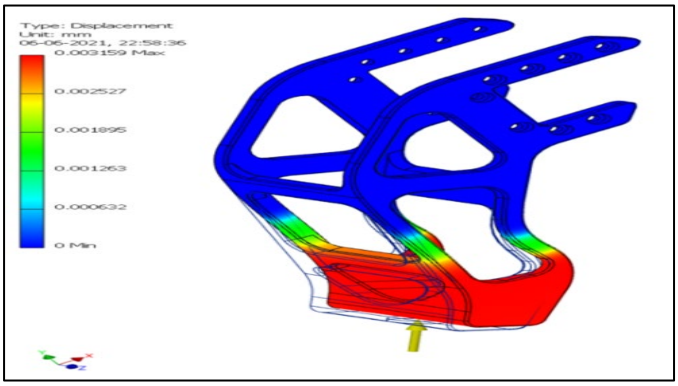

Fig. 20: (b) Displacement of Tibia

All the four holes were fixed from inside to simulate bolt joints and the front bigger holes from where the actuator will resist the torque from the ground reaction were used to place the calculated moment to simulate operation condition.

The Moment is applied at both the connection holes in the inner surface. Now with the help of Moment Calculated (M2) above on the Knee Joint, it is known that the maximal stress of the Femur is 1.828×10^6 N.m^2 that is a smaller quantity than the yield energy of the material. Therefore, aluminum 6061 fulfills the motion of the Femur and may bear the load.

4.2.4 Tibia

The Analysis results of the Trunk or body frame comprising of the Von Misses Stress and Displacement diagram is Shown in Fig 20(a) and (b) respectively, exhibiting the location of Reaction forces.

The holes where the actuator will be placed are constraint with the pin joints boundary condition; this will stop the translation in the entire axis but will allow rotation in all of them. This system will simulate the operating condition and can be used to find the stress generated in the leg part of the model. The force calculated is applied on the point where the leg will come in contact with the ground to simulate reaction condition The material used is Aluminum 6061 that features a yield strength of 2.75×10^8 N.m$^{2.}$ The most stress of the Tibia is 3.292×10^6 N.m^2 that is a smaller amount than the yield strength of the material. Therefore, aluminum 6061 fulfills the motion of the Tibia and can endure the load.

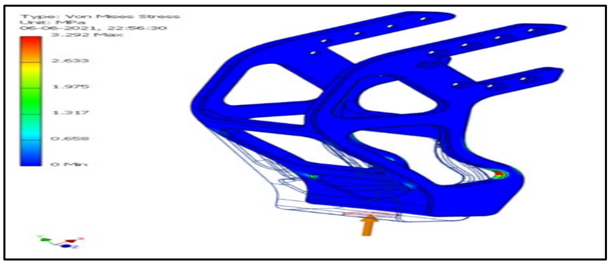

Fig. 20: (a) Von Mises Stress of Tibia

4.2.5 Full Body Analysis of Hexapod Robot

Looking at the final results from the full body analysis several outcomes are recorded to better understand the stress formulation and deformation characteristics. Fig. 21 shows the complete analysis carried out in ansys software.

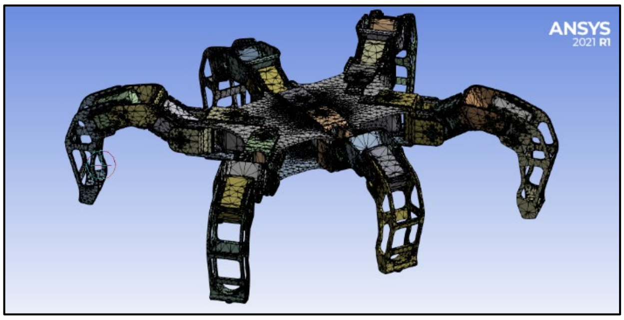

Fig. 21: Analysis of Hexapod Walking Robot.

Out of which the most important outcomes are summarized below:

1. The highest magnitude of stress is observed at the point where the limb of the robot is bolted (pinned) to the main body.

This can be understood by looking at the fact that the only forces acting on the assembly are the reaction forces from the ground due to the self-weight of the hexapod and the place where these forces experience any resistance is at the rigid joint between the limb and the main body and hence, the stress is highest at this point.

2. The thickness of the coxa needed to be increased by 0.45mm. The coxa of the robot is the part at the joint between limb and body and hence, due to the reason stated in the above point it experiences a very high local stress concentration. To ensure that the coxa won't fail in its operating range the thickness of this part is increased by an additional 0.45mm.

3. The Main body experience the highest deflection in the overall body of the robot. The main body of the robot acts like a sagging beam with loads that act almost like several point loads from the point of the pin connection. After the analysis it has been observed that the maximum deflection of 2.86e-5 m is well below the desired value. And hence, no additional changes are needed in the frame of the main body of the robot.

4. The payload location in the hexapod is decided at the boundaries of the main body frame. The deformation in the body follows a rough circular profile which indicates that the highest deflection is at the center of the frame, this can be easily understood by fact that the center of gravity of the body is in the center of the robot and hence a point load of the weight can be assumed at that location which will droop the whole frame causing deformation.

Hence, additional payload cannot be placed at the center because that will increase the local deformation and therefore the position of the payloads is finalized to be at the boundary of the frame for safety reasons. Fig. 23 and 24 shows the Von Mises Stress and Displacement analysis of the assembled model of Hexapod Robot.

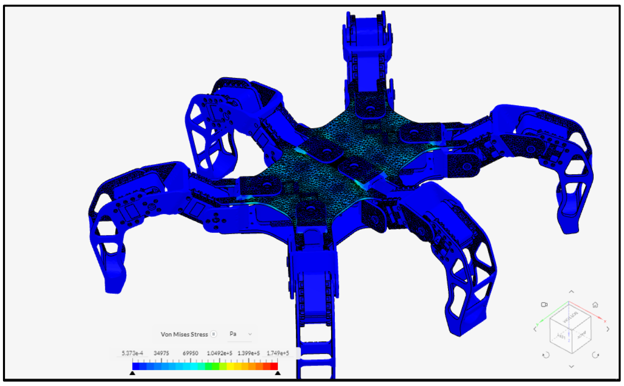

Fig. 22: Von Mises Stress of Tibia

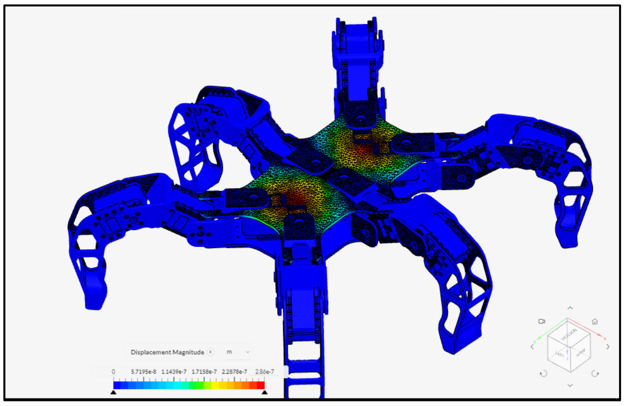

Fig. 23: Displacement of Tibia

5. Results and Discussions

5.1 Coxa

Using various material and options for thickness a parametric study is done and thicknesses from 2.5 mm to 4 mm is considered. As a result, Al 6061 having thickness 3.5 mm are found Optimal with the results. The material Aluminum 6061 is selected considering the previously established literature and research owning to its high density, availability, high load carrying capacity and high strength against direct stress. AI 6061 has been used in various studies in the domain of robotics as well as other domains because it is fairly cheap comparatively.

5.2 Femur

Using various material and options for thickness a parametric study is done, Thicknesses from 2.5mm to 4mm were considered. Al 6061 with 3 mm thickness were found Optimal with the observed results. Femur can made relatively thinner from the coxa due to the fact that the most of the resistive forces act on the coxa as it is the joint between the main body and the limbs of the robot. Hence, Because of this the stress concentration at femur is lower than the coxa.

5.3 Tibia

In case of the Tibia, the thicknesses range from 2.5 mm to 4 mm is considered. Therefore, Al 6061 with 3.48 mm (Which as rounded off to 3.5 mm) is optimal to be used for this design.

6. Conclusions

Intelligent biological notion has been used to layout an easy and greater insect-like robotic on the way to use for powerful and higher software of the modern-day technology. The design has been modified along with the reduction in the number of motors leads to a lighter structure and easy to control. Modifications in the design is adopted by using solid works. The design is checked and analyzed of all key parts of the hexapod robot. The proposed design will incorporate various sensors for long-range communication since the robot sensors could send the live forward view to the ground station. Due to the similar movement of all six-legged, the Hexapod robot has the ability to walk on the abrupt terrain. The walking level can be seen as a low level of locomotion that keeps the robot advancing on rough terrain comparable to the level at which a wheeled vehicle keeps the robot advancing on the flat ground by turning wheels by constant speed. The robot is checked on all the loads at which the robot turns to fail to do its own task. After checking all possibilities and taking all the consideration the design has been finalized for the Hexapod Robot.

While the structural integrity of robot was widely tested using computational means the kinematic locomotion of the robot is still not optimized such an analysis was out of scope of this study but it can be easily understood that the next step to further the optimization of the design given in the study is Kinematic and Inverse Kinematic analysis.

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