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DESIGN AND DEVELOPMENT OF VALKYRIE – AN AUTONOMOUS QUADRUPED ROBOT

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A mobile robot needs locomotion mechanisms so that it could be able to move and navigate through its environment. Legged locomotion mechanisms which are often inspired by biological systems are more efficient and stable when compared to their counterparts such as wheeled mechanisms due to their ability to traverse across rough and uneven terrains. Motivated by the rapid evolution of legged robots, this work focuses on the design and development of a 2 DOF Quadruped robot that incorporates 4 Hip and 4 Knee joints as its locomotion element. The robot was designed, modeled, and prototyped based on a multidisciplinary mechatronics design approach integrating CAD modeling and Structural analysis. Three types of designs were carried out in Solidworks and analyzed based on the number of joints for locomotion, mobility, and structural integrity. The static and transient structural analysis was performed in ANSYS to analyze the stress and deformation acting on the robot during static and dynamic conditions. The robot is prototyped by integrating various components that are fabricated in-house through a CO_2 laser cutting machine and 3D printer along with the servo motors, drivers, and camera. This robot can be implemented in such a way that it can operate in different terrains of environment for a wide spectrum of applications such as Military border reconnaissance, Search and Rescue, Exploration, and so on.

1. Introduction

In recent years, the use of mobile robots is increasing rapidly, and have found an important and inevitable position in automating an industry, or society, and so on. These mobile robots are broadly divided into two classes – Wheeled robots and legged robots. Wheeled robots are primarily used in places where the surface is flat and smooth. These wheeled robots are capable of performing any kind of operating efficiently and the same is also capable of improving and automating society. Despite having lots of advantages, wheeled robots have disadvantages too. Wheeled robots are not suited to operate in uneven terrain which is harsh, rough, and bumpy. Kim S et al. [1] proved experimentally that legged robots play an effective role. As compared to wheeled robots, legged robots perform the task with high accuracy and improve the efficiency of the overall process, as they can overcome the disadvantages faced by wheeled robots operating in both even as well as uneven surfaces. Wheeled robots sometimes fail to operate when a very huge magnitude of external forces is applied to the robot. 2. Raibert MH et al. [2] discussed that legged robots experiencing a huge magnitude of external forces are capable of regaining their original state or original position. There are certain areas where the wheeled robot cannot provide more value and is not handy in uneven, bumpy terrains. On the other hand, legged robots which often mimic animal actions, are well structured and can be more stable in every environment than just a wheeled robot. Legged robots can be used for different kinds of applications like border surveillance in military and defense, used for navigation in shopping malls, in industries for performing operations like pick and place with a robotic arm fitted on the body of the robot, and so on. There are different kinds of legged robots and one among thoserobots is the quadruped robot. As the name suggests, a quadruped robot consists of four legs with a greater number of degrees of freedom. Quadruped robot moves and wanders in the environment by switching the gaits. The animal gait movement allows moving in various flexible ways which can be concluded from the following literature.

Ramil Khusainov et al. [3] focused more on the optimization of the movement of the bipedal robot using two different approaches- Kinematic analyses being the first and latter involving robot dynamics. The author used the optimization technique which is limited to only straight smooth lines. There are limitations to the approaches addressed in this work that is being too unstable when sufficient ZMP compensations are not introduced. M Xiangrui et al. [4], in their work, summarized the development of quadruped robots. The key robots that were taken into consideration for the survey were HyQ Series, StarlETH, ANYmal, MIT CHEETAH, and BigDog. They discussed various techniques like SLAM, feature extraction, identification, etc. to achieve autonomous control of the robot. The coordination and storage of data collected from various sensors generally make the design highly complicated. They suggested that the Multi-sensor data fusion technique can be incorporated to overcome this challenge in quadruped robots. Bin Li et al. [5] presented a new Central Pattern Generator (CPG) controller for quadruped robot rhythmic locomotion control. The gait generation and transition were achieved using the controller called Central Pattern Generator (CPG) based on Wilson-Cowan weakly Neural Oscillator also called as Weakly Neural Network. Their simulation results showed that the developed CPG controller was able to generate different quadruped gaits and change its rhythmic patterns smoothly. The period and amplitude of the CPG model were also easy to control for generating various gaits. B J H smith et al. [6] considered Four Gaits – walk, trot, pace, and gallop for robot locomotion. Their robot was able to operate efficiently in all four gaits and the transition was also achieved effectively. The CPG model used was stable against perturbations and the frequency of the pattern. The robot was only manually operated using this controller. Before, these kinds of robots were not controlled by controllers but through switches fitted in legs. The authors were able to achieve gait control by directly triggering the switches fitted in legs which detect the leg loading and unloading. The robot was able to operate smoothly in even platforms but found it difficult to operate when it comes to uneven terrain which is a tactic. The robot also faced the problem of slipping because of excessive loading on the robot's legs during each movement.

The same kind of work was done by Oak et al. [7] but using the Four Bar Chain Leg Mechanism as the locomotion element. Forward and inverse kinematics for the legged robot was performed and the authors were able to design and fabricate a Quadruped robot that can navigate using trot and pace gaits over flat terrain and attains the maximum mean speed of foot of 34.63 mm/s. Also, trot and pace gait locomotion of quadruped robot was analyzed for parameters such as stride, mean speed of foot, duty factor, cycle time. They mainly focused on mechanical design, gait analysis, and fabrication of quadruped robot that involves 8 DOF which are controlled by servomotors mimicking trot and pace gaits. With the improvement of the previous design, S Kitano et al. [8] propose a Longitudinal acceleration trajectory method focusing the stability. The wire-driven mechanism was used to demote the weight of the robot and also provided dynamic stability. They bounded only the trot movement because other movements caused uncomfortable movement in some environments. The author focused more on the speed and stability leaving the payload behind. However, the payload also plays a vital role in a real-time environment. Chan C.Y et al. [9] designed a compliant mechanism to achieve the walking gait, trot gait, and jumping motions of the robot. The robot was designed in such a way that, the legs are cable-driven attached with tension springs to provide stability and energy-efficient gaits during the movement. They were able to achieve trot gait and turning movements of the robot by regulating the step length during robot movement.

To achieve the jumping actions of the robot, an energy storing mechanism has been developed to achieve different distances and heights. A robot has been designed by the inspiration of an alligator. Mishra A.K et al. [10] developed an alligator-based robot where each leg has 3 DOF namely proximal, middle, and distal. The authors did not intend to mimic the actual behavior of the alligator, instead developed a similar behavioral pattern in the robot. To reduce the complexity of the behavior of alligators, the author developed the legs in such a way that the scaling factor, body length, and body mass were as small as possible. Similar to [9], Sprowitz A.T etal. [11] developed a quadruped robot with a compliant mechanism with segmented leg design along with Crawl, trot, and bound gaits. Even though having various types of Gaits the robot was able to achieve self-stabilized locomotion. A Bipedal robot with 6 DOF has been developedby Kuppan Chetty et al. [12]. Inverse Kinematics has been used to find the unknows joint position with Single as well as double support. The authors addressed the center of mass during locomotion to know the stability of the robot. Khorram, M et al. [13] focused completely on stability during locomotion where constrain elimination method was considered to avoid the struggle of the robot in uneven terrain. Globisz A et al. [14] developed a robot by declaring their kinematic equation in Matlab to compute the coordinates. In their work, the coordinates were mapped in a local and global frame to frame the center of gravity. During the locomotion, ground force was tested in the same software using. During the test phase, rotation of the chassis and external torque was assumed zero. Furthermore, equations were derived with various forces acting on the legs in static and dynamic.

Hence, our work focuses on designing and developing a 2 DoF Quadruped Robot which incorporates 4 Hip and 4 Knee Servo motors as its locomotion element. The designed robot is verified for real-time implementation through formulating the Structural Analysis. The rest of the paper has been organized as follows, Section 2 discusses the robot's design and its parameters. This section also discusses the structural analysis carried out in ANSYS. Section 3 compares the various designs that were considered in the work. Section 4 explains the fabrication of the prototype before we conclude in Section 5.

2. Methodology

The design and development of the proposed quadruped robot focus on optimization of CAD design, Static & Transient Structural Analysis, and finally fabrication. The primitive stage was processed in 3 types of designs and simulated to obtain the optimized result.

2.1. Design Consideration

As this robot is specifically concentrated for military surveillance applications, it is intended to keep the robot light and small. So, every design has similar dimensions. The robot's basic payload is 1.5 kg, which includes the weight acting on the robot due to chassis, miscellaneous weight due to electronic components, etc. It is assumed that the robot will not carry any external load except the basic load. Initially, the robot was built using a cable-driven mechanism, where every motor was controlled by a cable connected to a servo motor. To reduce the complexity, 8 motor design from cable-driven mechanism was upgraded to 6 motor design in connecting rod mechanism. Because of the high number of motors used in the connected rod design, the impact ratio and acceleration were not enough for the robot to locomote from one point to another. As a result, the connecting rod design was upgraded to a four-legged connecting rod design to enhance the performance of the robot. In the four-legged connecting rod mechanism, each knee link is connected to the same servos driving the hip motors by a rod and gear system. The above points are considered and designed with the below approx. dimension.

Table 1. Robot Parameters

Factors	Approx. Dimensions
Body Dimension	155x170 mm
Link 1 Length	60 mm
Link 2 Length	30 mm
DOF	2
Max. Angle for Hip and Knee Joints	20^0
Payload	1.5 kg
Extended Mode	215x115x128 mm

2.2. Mechanical Design and Optimization

2.2.1. Cable Driven Design

This design has been inspired by the 4-legged walking animal which incorporates a Compliant leg mechanism. This mechanism is adopted to give a basic waking mechanism to the robot and itis flexible and transfers an input force or displacement to another point through elastic body deformation [15]. To simplify the process and manufacturing, reduce the number of components and assembly time, reducing wear and tear, a cable-driven mechanism has been adopted. Four servo motors are used to drive the Hip link of the robots. A cable is connected to the Knee link which is passed over a fixed pulley and is driven by the servo motors placed at the top of the robot.

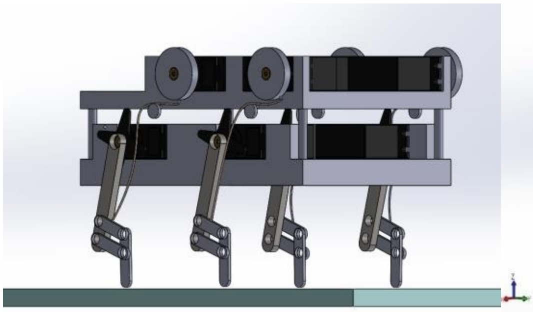

Figure 1. Cable Driven Robot Design

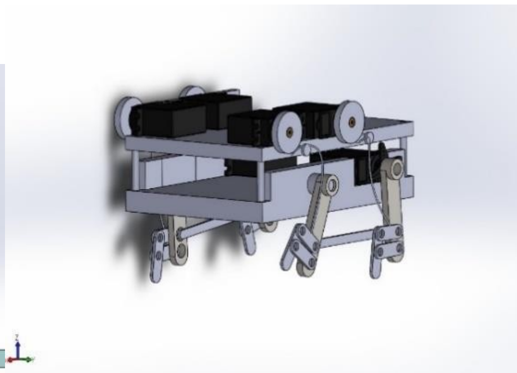

Figure 2. Connecting Rod Robot Design

2.2.2. Connecting Rod Design

Compared to the previous design, this design uses only 6 motors. Hence, the complexity and computational operation are reduced to a considerable extent. A connecting rod is used to reduce the number of motors used and also produce the same motion as the previous design. The hinge joint gives Rotational motion access to link 1 and link 2 to incorporate basic walking motion. Similar to Cable-driven design, the Knee links are individually connected to 4 servo motors and are actuated by the flexible cable passed over a fixed pulley. Two of the four HIP links are connected to 2 servo motors as seen in figure 2. This design is made on the assumption that if the rear leg is in the in-ground phase, the front leg must be in the swing phase. Hence, a connecting rod is placed between the rear and front leg which results in the desired motion.

2.2.3. Four Legged Connecting Rod Design

The design is more streamlined and only has four servo motors which will help in developing a simpler control system. Due to the use of fewer motors and compliant design the impact ratio and acceleration is will become high compared to previous designs [16]. The Hip links are connected to the servo motor directly. The Knee links are connected to the same servo motor using a rod and a gear system. Even though the number of motors is reduced from the previous designs, the robot still has the same number of degrees of freedom.

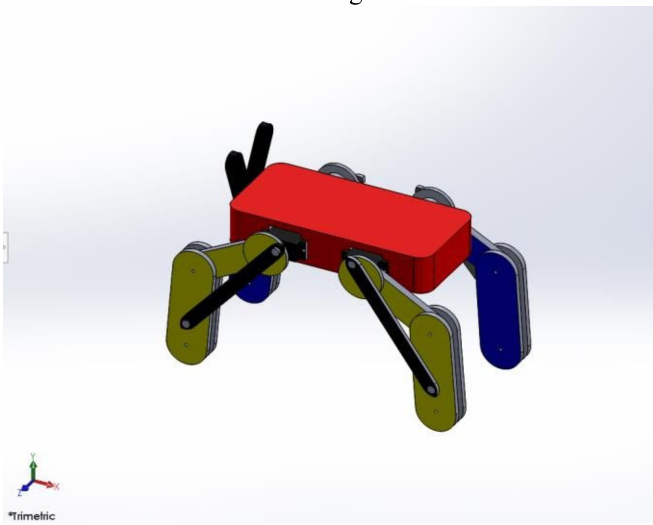

Figure 3. Four-Legged Connecting Rod Robot Design

Table 2. Comparison of 3 Designs and its parameters.

Features	Cable Driven Design	Connecting Rod Design	Four Legged Connecting Rod Design
No. of Motors	8	6	4
No. of independent/ Dependent Links	8/0	6/2	4/4
Move methods for independent links	4 links are connected directly to the motor and 4 are connected using a pulley system	2 links are connected directly to the motor and 4 are connected using a pulley system	4 links are connected directly to the motor
Move methods for dependent links	N/A	2 Dependent links are connected using a connecting rod	4 dependent links are connected using gear and connecting rod system

3. The Final Prototype

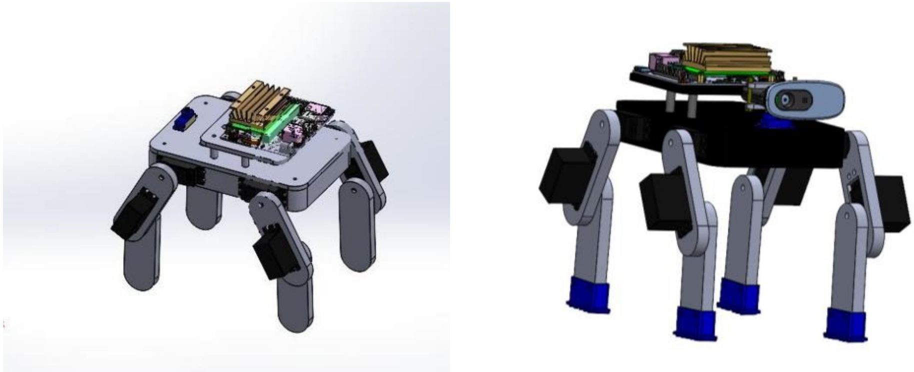

Figure 4. Mechanical Design

The final prototype was designed according to the optimized values obtained from the static and structural analysis shown in the previous section of the paper. As seen in the figure, each leg of the motors has 2 DOF and each link is directly connected to the shaft of the motor. The upper 4 motors represent the HIP JOINTS and the lower 4 represent the KNEE JOINTS.

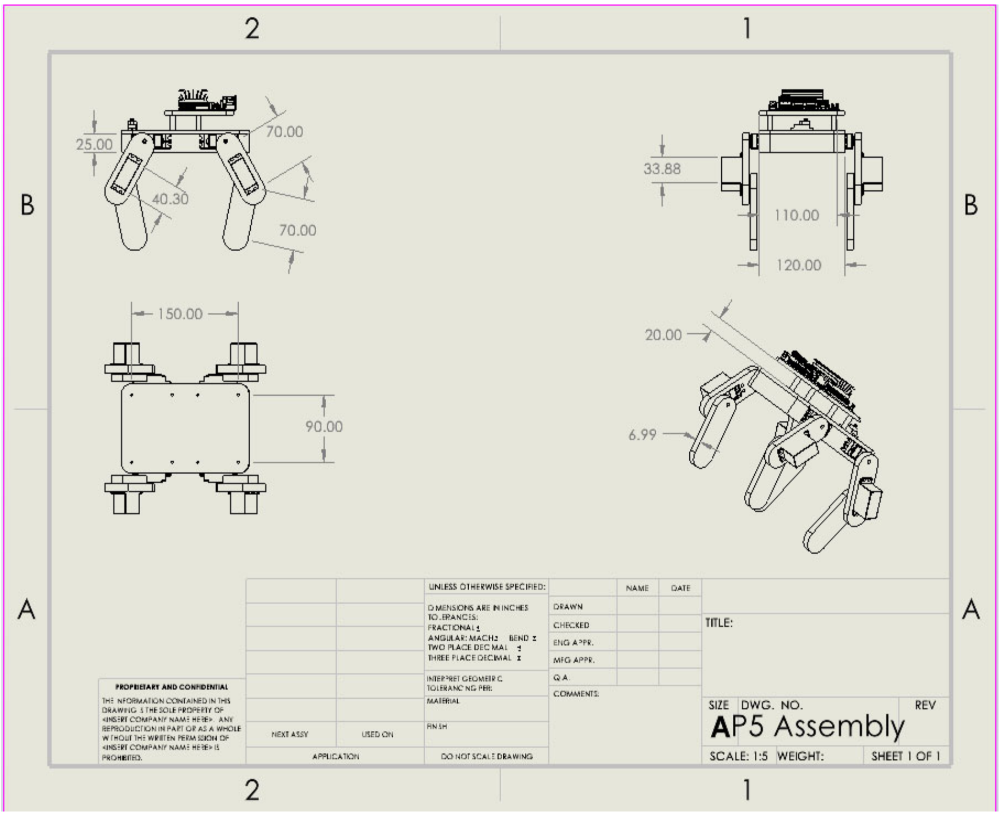

Figure 5. Design Parameters

Figure 4 shows the design parameters considered for the final prototype. The dimensions of the prototype don't change as much from the previous designs. The dimension of the body stands at 150x90x25 mm and each link of the legs has a height of 70 mm with 35 mm and 7 mm as

breadth and thickness. The final dimensions of the robot after the full assembly stand at 221x227x234 mm.
A robot is said to be stable if the robot can regain its original state when external forces or motion start acting on the robot. In quadruped robots, the robot is stable if it can gain its original position or the home position after external forces act on it. This stability in a quadruped robot is of two types, static and dynamic stability.
Static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly concerning time. All the HIP and KNEE joints are given as fixed supports. Analyzing the weight of the robot using ANSYS which comes around600 g and considering the other components such as motors, controller, battery, the total weightof the robot is assumed to be around 900 to 1000 g. Hence a force of 10 N is equally applied and distributed to the 4 legs as seen in the figure below.

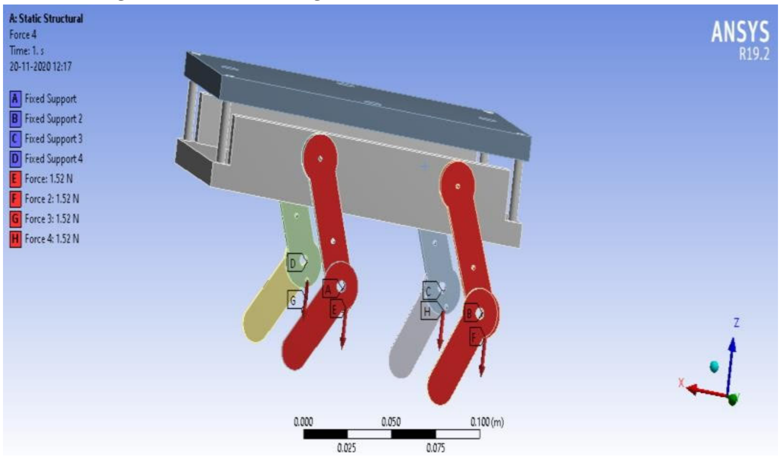

Figure 6 Distribution of the applied force to the robot

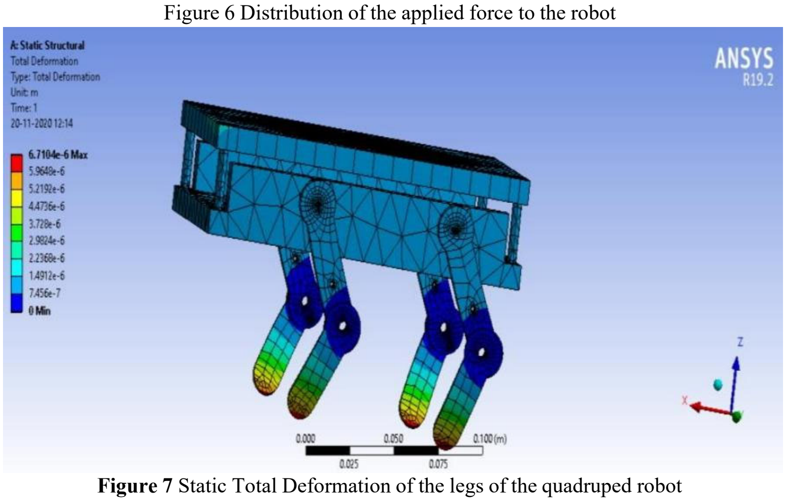

Figure 7 Static Total Deformation of the legs of the quadruped robot

As seen in figure 7, the robot legs are being deformed. Maximum deformation is found to happen at the tip of the legs while the body and link 1 of the robot are found to withstand the force. Total deformation and Equivalent stress are the 2 parameters considered for evaluation.

To find the dynamic response of the structure with the presence of time, displacement, and velocity transient structural analysis is applied. The design is exploded to set up the body joints and support. In this structure, there are 2 revolute joints in each leg. One joint between the bodyand link 1 and the other joint between link 1 and link 2. As seen in Figures 8(a) and 8(b), the bottom of the leg attains the maximum deformation. The rotation steps are set to a range so that it is rotated at the given angle. The duration a joint must take to complete the rotation steps is also given. 10 N force is given to thesurface of the frame to analyze the deformation of the leg. Thus, the final prototype was designed and built by considering the data collected from the transient and static stability analysis.

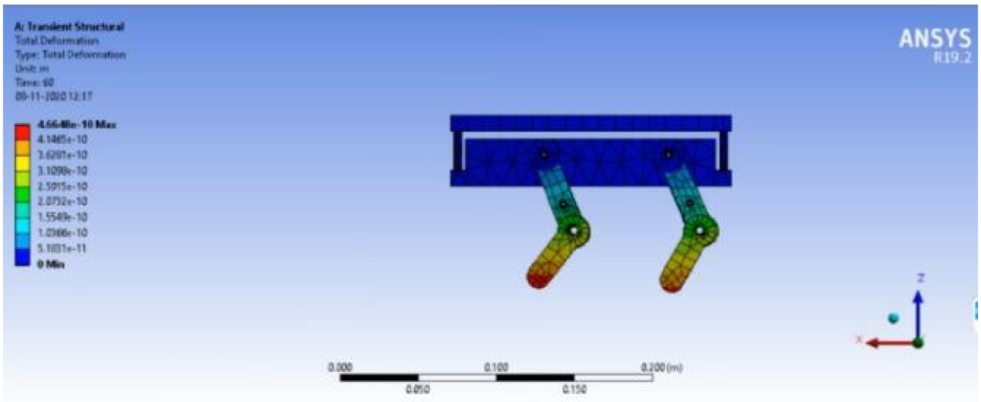

Figure 8(a). Transient Total Deformation at an initial position

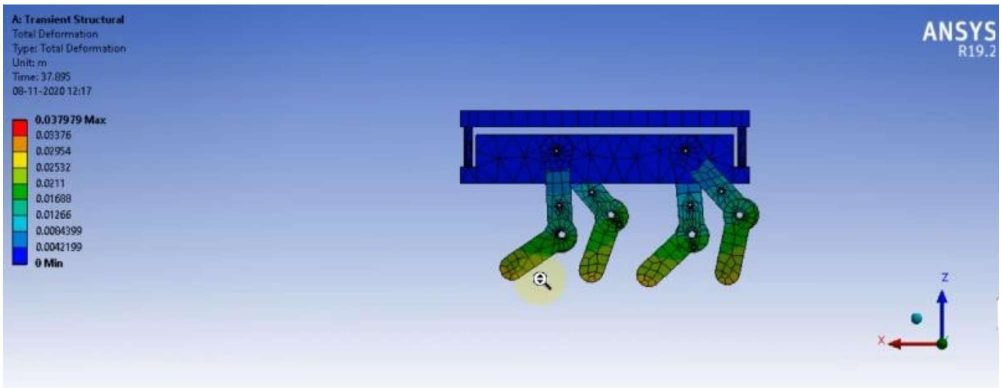

Figure 8(b). Transient Total Deformation during movement

The final prototype uses NVIDIA Jetson Nano as the brain of the robot and eight MG996R servo motors for each link of the robot. Table 2 shows the list of the components used in the final prototype. The robot's body was 3D printed using Polyethylene terephthalate (PET) material and the legs were fabricated from a 10 mm thickness clear acrylic sheet using a CO_2 Laser Cutting Machine. The foot of the legs is made using a combination of a rubber bush for more added grip and 3D printed material for fastening the foot to the leg. Figure 5 will show the final assembled prototype.

Table 4. Components used for the final prototype

S.NO	COMPONENT NAME	SPECIFICATION	QUANTITY
1	NVIDIA Jetson Nano	4GB RAM, Quad-core ARM cortex processor	1
2	MG996R Servo motor	180° Rotation Metal gear train	8
3	PCA 9685 Servo driver	16 Channel Driver	1
4	CS270 Logitech Web Camera	720P, 30 FPS	1
5	SMPS Power Supply	Input – 220V AC Output – 5V DC	1

Figure 9. Components of the Prototype before assembly

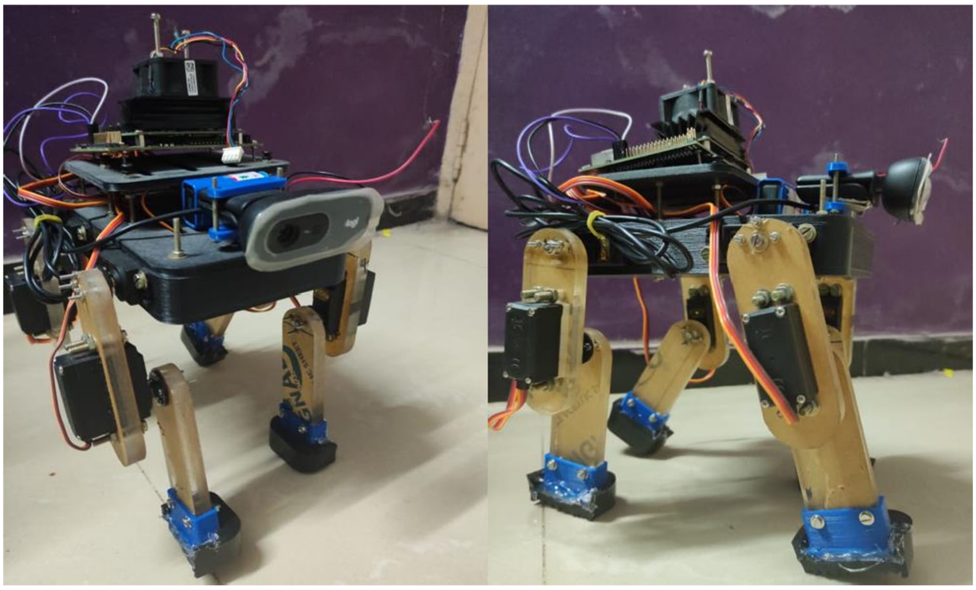

Figure 10. Final Assembled Prototype

3 Conclusion

The quadruped robot has been designed, developed and a final prototype has been successfully made. Various design parameters have been considered and have resulted in various design approaches in the project. The prototype design has been made based on inference obtained in the design study and the gait movements required. Presently the robot is designed to undertake four gait motions- crawl, walk, trot and pace. The kinematic calculations for the forward and inverse kinematics of the robot have yet to be derived along with support polygon calculations which determine the stability of the robot. The prototype design has undergone static and transient structural analysis in the ANSYS workbench. The prototype has been made using 3D printed PET material and an acrylic sheet of 10 mm thickness and it has eight servo motors and an Arduino UNO for the first phase of the project to check the gait movements.

References

1. S.Kim and PM. Wensing. *Foundations and Trends in Robotics*, *now*. **5-2**. (2017)
2. MH. Raibert. *Legged robots that balance*. *MIT Press.* (1985)
3. R. Khusainov, A. Klimchik and E. Magid. I*n Informatics in Control, Automation and Robotics. Springer, Cham*. (2018)
4. X.Meng, S. Wang, Z. Cao and L. Zhang. *35th Chinese Control Conference (CCC), IEEE*. (2016).
5. B. Li, Y. Li Y and X. Rong. *IEEE International Conference on Robotics and Biomimetics*. (2010).
6. BJ. Smith and JR. Usherwood. *Bio-inspiration & Biomimetics*. **15(2):**026004. (2020)
7. S. Oak and V. Narwane. *Int.J.of Inno. Sci., Engg. & Tech.* **1(6)**:340-5. (2014)
8. S. Kitano, S. Hirose, G. Endo and EF. Fukushima. *IEEE / RSJ International Conference on Intelligent Robots and Systems.* 6025-6030. (2013).
9. C.Y. Chan and Y.C. Liu. *IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*. pp. 614-620. (2016).
10. A.K. Mishra. *IIT Patna*. (2014)
11. A.T. Sprowitz, A. Tuleu and AJ. Ijspeert. *Front. in comp. Neuroscience*. **8**, 27. (2014).
12. RM.K. Chetty, D. Ganapathy, A. Joshuva and M. Manju. *Int. J. Rob. and Auto*. **36 - 1**. (2021).
13. M. Khorram. and S.A.A.Moosavian. *Robotica.* **35 - 8.** 1670-1689. (2017).
14. A. Globisz, D. and Krawczyk. *11th France - Japan & 9th Europe - Asia Congress on Mechatronics / 17th International Conference on Research and Education in Mechatronics (REM)*. (2016).
15. T. Chanthasopeephan, A. Jarakorn A, P. Polchankajorn and T. Maneewarn. ***Rob. and Aut. Sys***. 62-1:38-45, (2014).
16. Gp. Jung, JS. Kim, JS. Koh, SP. Jung and KJ. Cho. *IEEE/RSJ International Conference on Intelligent Robots and Systems*. (2014)