

PAPER • OPEN ACCESS

Design and Development of an Autonomous Quadruped Robot

To cite this article: B Sandeep and P Tamil Selvan 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1012** 012016

View the [article online](#) for updates and enhancements.

You may also like

- [Static Gait Scheme for Horizontal Posture Slope Climbing with Quadruped Robot](#)
Ashish Majithiya and Jatin Dave
- [Control strategy of optimal distribution of feet forces for quadruped robots based on virtual model](#)
Xinjie Chen, Yuegang Tan, Ruiya Li et al.
- [Balance control of quadruped robot based on model predictive control](#)
ChengYe Wu, Qing Wei, Cong Zhang et al.



The Electrochemical Society
Advancing solid state & electrochemical science & technology

242nd ECS Meeting

Oct 9 – 13, 2022 • Atlanta, GA, US

Early hotel & registration pricing
ends September 12

Presenting more than 2,400
technical abstracts in 50 symposia

The meeting for industry & researchers in

BATTERIES
ENERGY TECHNOLOGY
SENSORS AND MORE!



Register now!



**ECS Plenary Lecture featuring
M. Stanley Whittingham,**
Binghamton University
Nobel Laureate –
2019 Nobel Prize in Chemistry



Design and Development of an Autonomous Quadruped Robot

Sandeep B ¹, Tamil Selvan P ^{1*}

¹ School of Mechanical Engineering, Vellore Institute of Technology, Chennai

E-mail: tamilselvan.p@vit.ac.in

Abstract This research paper contains the work done on the ‘*Design and development of an Autonomous quadruped robot*’ – a system engineered to complete tasks like carrying weaponry and materials for military applications. The primary aim of the project was to design a quadruped that works successfully in harsh conditions and irregular terrain where human intervention is impossible or hard. Initially, individual components of the design were designed and modifications were made according to the requirements. The development was carried out in five major steps including frame assignment, DH parameter analysis, Kinematic and dynamic analysis, Multibody simulation, Stability analysis and execution of gaits. The average time taken for the device to complete one cycle was found to be 10 seconds in crawl gait and around 8 seconds in trot gait. Further tests on the final device also directed a consistent results in its functionality and time taken for the quadruped to complete one gait cycle.

As such, the performance of the quadruped is found to be successful and also open to further modification for better performance and varied usage requirements since the research on autonomous quadruped is at its early stages of development.

Keywords Autonomous quadruped, gait patterns and implementation, DH parameters, Multibody simulation, Stability criterion, SSM,

1. Introduction

Locomotion on legs is one of the foremost and reliable type of movement patterns around us in the environment. Proof of first use of movement among biologically apt beings are found around 585 million years ago. Nature helped the evolution of legs as a source of movement than use of wheels because more than half of the world cannot be travelled by use of wheels. Mammals exhibit “erect” locomotion posture (ELP)[14]. Humans show ELP in their movement too. Here, limbs are held right under the torso. Designing a robot with inspiration from their biological counterparts can lead us to provide very critical ethical and logical functions for the robots. Also, it has been seen from various studies that artificial intelligence is more efficiently developed in bio-inspired compliant designs. Here, the focus is on quadruped robots, which belongs to a broader class of robotic system with legs. Quadruped robots have four legs with each leg consisting of two or more degrees of freedom.

The first design for a legged robot system was developed by Chebyshev in 1870[1]. It was a simple 4 link system with a dual axis leg motion. Further improvements on the legged robotics systems came with the development of mechanical horse by researcher Rygg in 1893[1]. This was a purely mechanical model with a pedal to help in movement. Further along 1965, Ralph Moshier along with



General Electric developed a Walking Tuck. It was an electro mechanical model which could follow mechanical motion with electrical inputs, but was huge in size[1]. MH Raibert [5] in 1986, with his study on Legged Robots that Balance, opened the doors to new developments in the field of robots. This was further supported by an extensive study on Dynamic effects of static stability in 1998 [25] by Gonzalez de Santos, Jimenez and Armada. The further improvements on quadruped robots came with the incorporation of biological inspiration to robotic design [11,15,20]. This boom was followed by Tekken[13], Boston dynamics spot mini[27] and MITs Cheetah cub[29] with impeccable stability and smooth gait patterns. Further development lead to BigDog[23] which was discontinued due to its loud noise of hydraulics and heavy weight. In this research, the focus is on developing a quadruped robot from initial design to final gait stability stage which is highly stable in maneuverability and can carry substantial amount of load while also being economically feasible.

2. Design of Quadruped Robot

The overall design process of the robot is compliantly based on the interdisciplinary design approach. This approach lends its focus on CAD, kinematic and dynamic models, MSA and FEA. This is an existing engineering approach to do research for R&D requirements for modelling of a prototype (shown in Figure 2).

In this approach a CAD drawing is designed based on the quadruped model according to the given criteria or robot requirement. The designed quadruped is then validated using multibody dynamics (MBD) mechanism. The simulation parameters are set such that it is in close proximity to the real-world conditions. For this the material properties and characteristics are set according to the real robot and also the conditions of the environment are taken into consideration.

The step by step process is as follows (See Fig 1) :

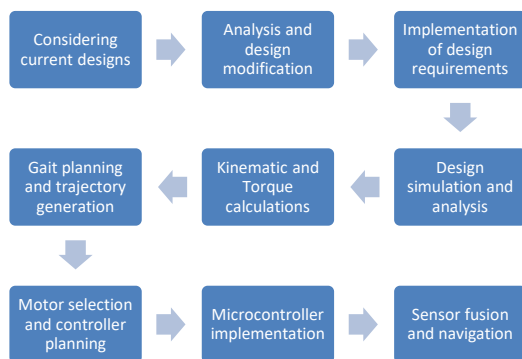


Figure 1 Development approach

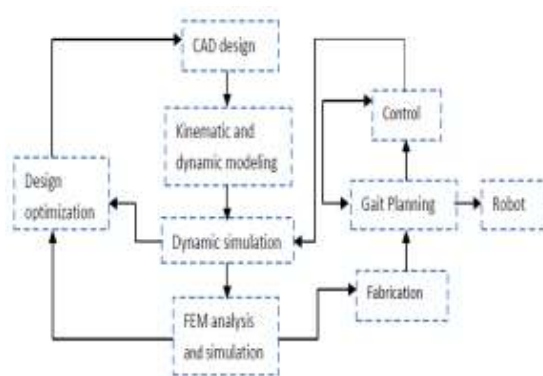


Figure 2 Design Approach

The overall simulation is based on kinematic and dynamic analysis. The trajectory and gait planning is done considering the feedback and stability of the quadruped.

To understand the biological inspiration behind the quadruped robot, consider the locomotion and limb arrangement of a dog. A dog has mainly two bones in their hind legs, Femur and Tibia which helps in the movement of legs. Here, each leg of a dog gives 3 DOF and contains mainly 2 parts ignoring the feet as it doesn't help in the degrees of movement. This 3 DOF movement of the legs help it traverse in all terrains in all direction with proper gait patterns and also provides us with a better agility and maneuverability compared to other quadruped designs. This led us to developing a similar design for the quadruped with 4 legs with 2 main segments providing 3 degrees of freedom.

The structure of leg design in dogs by the nature was rather complex and hard to achieve with perfection, which directed us to developing a similar, simpler structure with the capability and structural nature to follow the maneuverability requirement of the robot. Considering the leg of a dog in robotic terms a structure in which all 4 legs are symmetrical is developed in nature where, the upper hip joint provides the robot with the ability to turn in the lateral plane, helping in direction change. Whereas the lower hip and knee joints help in locomotion of the robots according to gait patterns.

The basic design of this mammal inspired quadruped robot consists of 4 limbs to hold the torso and assist in its movement. Each leg is a rigid 2 link mechanism with each of it offering 3 DOF. Hence, the overall degrees of freedom of the robot is 12. All the legs consists of 3 DC motors with one motor acting on the upper hip for lateral movements in the XY plain, and other 2 motors in the lower hip and knee joints respectively. The total weight of the robot is around 60 kg with each leg carrying a wait of approximately 10 kg. The structure of the robot is developed in aluminum with a modular and flexible design consisting of no permanent joints. Each motor of the robot is controlled using 12 slave micro controllers controlled by a master. The upper hip helps in roll movement and lower hip and knee helps in the pitch of the robot respectively.

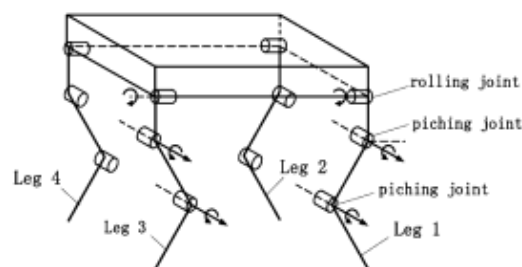


Figure 3 Joint types (with ref. to *Quadruped locomotion* by Gonzalez de Santos)

The torso of the robot helps in stabilizing the movements with each motor housed in its on casing. The casing works as a support to carry additional axial load during the lateral movement. The four legs provide a stable state at its initial homing position where the legs support the entire body at static state. The stability is maintained at motion using stability criterions. The lower hip and knee motors helps in vertical movement with knee motor carrying the maximum load and hence requiring maximum torque, whereas the upper hip joint helps in horizontal rotation so as to help change the direction of the robot.

Table 1. Design description of quadruped

S. No.	Characteristics	Value
1	M_{robot}	20kg (torso) + 10kg (each leg)
2	$M_{\text{motor}} + M_{\text{extra}}$	3.5 kg (each)
5	Width	360 mm
6	Length	720 mm
7	Length of link 1	80 mm
8	Length of link 2	400mm
9	Length of link 3	400mm
10	Centroid coordinate	(-360,-180,-720)mm
12	Maximum speed V_{max}	4 m/s
13	Gait	Trot , crawl

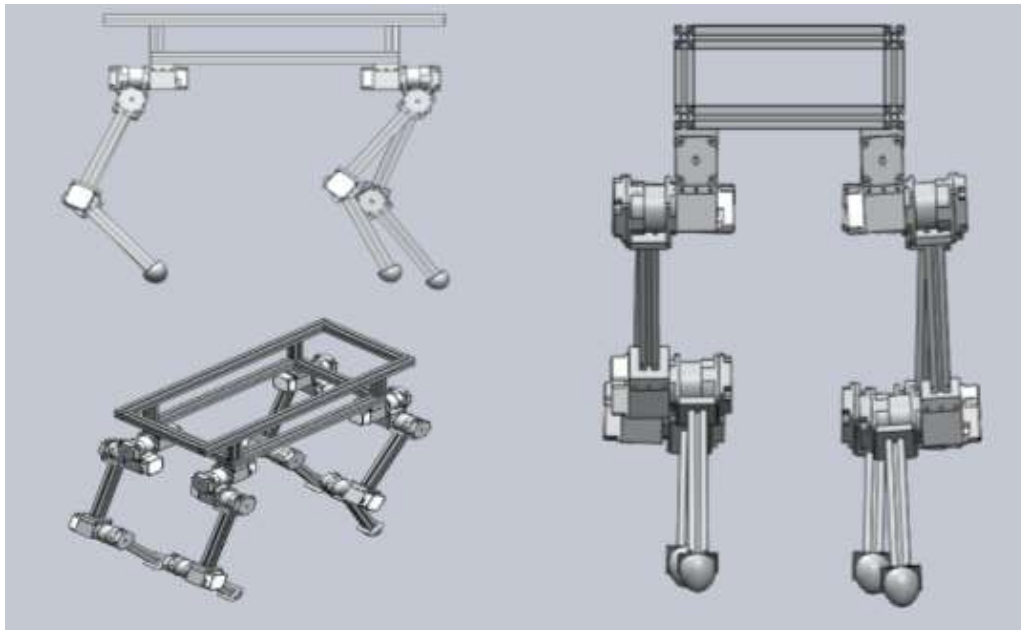


Figure 4 CAD Model of Quadruped

2.1 Torque Calculation

For calculation of motor torque, the quadruped is considered to be statically stable with all the weight concentrated towards the centre of the body. The entire robot is considered to be in a maximum torque condition with reaction force acting vertically opposite to the ground surface.

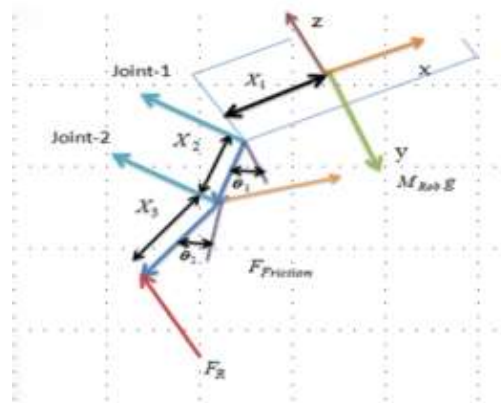


Figure 5 Free body diagram

$$W_{\text{rob}} = M_{\text{rob}}g \quad (1)$$

Considering the torque at joint1

Here, only the friction acting on the body is taken into consideration, hence the net torque at joint1 will be

$$\tau_1 = F_{\text{Friction}} * X_2 \quad (2)$$

$$F_{\text{Friction}} = \mu F_R \quad (3)$$

$$\text{Net torque at joint1} = \tau_1 / \eta \quad (4)$$

$$\eta = \text{Motor efficiency} * \text{gear efficiency}$$

Now, Considering torque at joint2

Only the reaction force from ground is taken into picture, so the overall net torque at joint2 can be given as,

$$\tau_2 = F_r \sin(\theta_2) * X_3 \quad (5)$$

$$\text{Net torque at joint2} = \tau_2 / \eta \quad (6)$$

$$\eta = \text{Motor efficiency} * \text{gear efficiency}$$

Here,

$$X_2, X_3 = 40 \text{ cm}$$

$$\mu = 0.25 \text{ (flat surface)}$$

From MBD simulation, The maximum approximate reaction force $F_R = 60\text{N}$,

From equation (3.2)

$$\tau_1 = (0.25 * 60) * 40 = 600 \text{ N-cm}$$

ie, From (3.4)

$$\text{Net torque } \tau'_1 = 600 / 61.88 = 9.69 \text{ Kgcm}$$

Similarly, Considering equation ,
when $\theta_2 = 45^\circ$

$$\tau_2 = 60 * 0.71 * 40 = 1704 \text{ kgcm}$$

$$\text{Net torque } \tau'_2 = 1704 / 61.88 = 27.53 \text{ Kgcm}$$

at $\theta_2 = 90^\circ$

$$\tau_2 = 60 * 40 = 2400 \text{ kgcm}$$

$$\text{Net torque } \tau'_2 = 2400 / 61.88 = 38.74 \text{ Kgcm}$$

2.2 Motor Selection

The maximum torque requirement of the robot is at its knee and is around 38 kgcm. Hence the motor is coupled with a planetary gearhead to give sufficient output torque. The gear head offers a gear ratio of 230:1 so as to be able to produce a high torque for joint torque requirements.



Figure 6 Maxon RE 40 motor

(ref : Maxon.com)



Figure 7 Planetary gearhead GP 52C

Table 2 Specifications of motor

Nominal Voltage	V	24
Nominal speed	rpm	6940
Nominal torque	Kgcm	1.804
Nominal current	mA	6
Stall torque	Kgcm	24.677
Max. efficiency	%	91
Terminal resistance	ohm	0.299
Torque constant	Kgcm/A	0.30
Weight	kg	0.48

Table 3 Specifications of gearhead

Reduction		230:1
Max. motor shaft diameter	m	0.008
Max. continuous torque	kgcm	305.94
Max. efficiency	%	68
Weight	kg	0.92

3. Kinematic analysis

Frame assignment of the robot is based on an arbitrary reference in both joint and cartesian space. The torso of the robot is defined to be in a global reference frame with each legs defined in its on local reference frames. Each joint of the leg is taken in separate frames and hence referenced to the DH parameters. The convention is taken such that the Z axis is pointed in the direction of the shaft ie, outwards and X and Y axis as mutually perpendicular to the direction of Z.

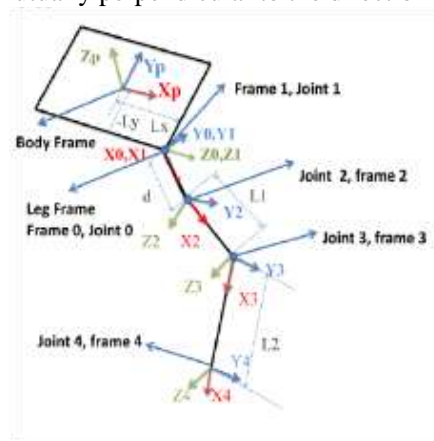


Figure 8 Frame assignment of the quadruped

DH parameters of the quadruped robot is defined with reference to the frame assignment and geometrical configuration considering the movement parameters of the quadruped.

Table 4 DH Parameters

S.No	Angle of Twist (α_{i-1})	Length of link (a_{i-1})	Link offset (d_i)	Joint angle (θ_i)
1	0	0	0	θ_1
2	$\pi/2$	$-l_1$	0	θ_2
3	π	$-l_2$	0	θ_3

3.1. Forward kinematics

The forward kinematics of the quadruped is calculated using the DH parameters in the above table. The total transformation is calculated by summing the transformations from individual frames. The end effector frame is then added to the final transformation.

Considering the transformation from 0th frame to 1st frame,

$${}^0_1T = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & 0 \\ \sin(\theta_1) & \cos(\theta_1) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

Transformation from frame 1 to 2,

$${}^1_2T = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & l_1 \\ 0 & 0 & -1 & 0 \\ \sin(\theta_2) & \cos(\theta_2) & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

Transformation from frame 2 to 3,

$${}^2_3T = \begin{bmatrix} 1 & 0 & 0 & -l_2 \\ 0 & \cos(\theta_3) & -\sin(\theta_3) & 0 \\ 0 & \sin(\theta_3) & \cos(\theta_3) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

Hence, the transformation from frame 0 to 3 implies,

$${}^0_3T = \begin{bmatrix} C_{23}C_1 & S_{23}C_1 & -S_1 & -C_1(l_1+l_2C_2) \\ C_{23}S_1 & S_{23}S_1 & C_1 & -S_1(l_1+l_2C_2) \\ S_{23} & -C_{23} & 0 & -l_2S_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Now, considering the end effector and completing the final transformation

$${}^3_4T = \begin{bmatrix} 1 & 0 & 0 & -l_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

$${}^0_4T = [{}^0_1T {}^1_2T {}^2_3T {}^3_4T]$$

$${}^0_4T = \begin{bmatrix} C_{23}C_1 & S_{23}C_1 & -S_1 & -C_1(l_1+l_2C_2+l_3C_{23}) \\ C_{23}S_1 & S_{23}S_1 & C_1 & -S_1(l_1+l_2C_2+l_3C_{23}) \\ S_{23} & -C_{23} & 0 & -l_2S_2 - l_3C_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Similarly, transformation for the remaining legs are found to be same as they are similar in nature and their frame assignment are taken to be same. This also helps in reducing the complexity of the calculation

$$P_x = x = -\cos(\theta_1) (l_1 + l_2\cos(\theta_2) + l_3\cos(\theta_2)\cos(\theta_3)) \quad (11)$$

$$P_y = y = -\sin(\theta_1) (l_1 + l_2\cos(\theta_2) + l_3\cos(\theta_2)\cos(\theta_3)) \quad (12)$$

$$P_z = z = -l_2 \sin(\theta_2) - l_3\cos(\theta_2)\cos(\theta_3) \quad (13)$$

3.2. Inverse kinematics

For calculation of inverse kinematics of the leg frame, it should be noted that each end position has more than a one unique way of achieving success and hence they have more than one result. That is in each case there are multiple sets of joint angles for the end effector to reach the desired position. But in a legged robot, all these solutions may not be equally desirable due to factors like say stability and motion type. This is when inverse kinematics comes into picture.

There are various methods used for the calculation of inverse kinematics, like graphical, algebraic and pseudo-inverse methods. Now, consider the algebraic method for inverse kinematic calculation.

Assuming a new 4*4 matrix that is similar to a transformation from frame 0 to frame 4

$${}^0_4T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & x \\ r_{21} & r_{22} & r_{23} & y \\ r_{31} & r_{32} & r_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

By multiplying the inverse of first transformation matrix with transformation equation,

$${}^0_1T^{-1} {}^0_4T = [{}^1_2T {}^2_3T {}^3_4T] \quad (15)$$

By comparing the value on both sides, three sets of independent equations with r_{ij} are obtained,

$$x\cos(\theta_1) + y\sin(\theta_1) = (L_2 \cos(\theta_2 + \theta_3) + (L_1 \cos(\theta_2) + d))$$

$$x\sin(\theta_1) - y\cos(\theta_1) = 0$$

$$Z = L_2 \sin(\theta_2 + \theta_3) + L_1 \sin(\theta_2)$$

Solving these equations, joint angles of leg 1 are found,

$$\theta_1 = \tan^{-1}(y/x) \quad (16)$$

$$x\cos(\theta_1) + y\sin(\theta_1) - d = k \quad (17)$$

By taking the square of equation 16 and 17 and adding them, the third joint angle is obtained,

$$\theta_3 = \cos^{-1} \{(z^2 + k^2 - l_1^2 - l_2^2) / (2l_1l_2)\} \quad (18)$$

$$P_1 = l_1 + l_2 \cos(\theta_3) \quad (19)$$

$$P_2 = l_2 \cos(\theta_3) \quad (20)$$

By multiplying the equation 19 and 20 with position equation 17 and 15 second joint angle is found,

$$\theta_2 = \cos^{-1} \{(k * P_1 * z * P_2) / (P_1^2 + P_2^2)\} \quad (20)$$

Hence, leading to all the required solutions for the joint angles. But, this joint angles are with the respect to the leg frame where the frame of reference is with respect to the leg. Now, considering the torso as global frame of reference, the velocity analysis is carried out.

3.3. Jacobian Velocity analysis

The jacobian associates with the angular velocity of the robot body and helps in defining the linear velocity at points of the defined modular structure. So, considering joint 0 as the global point of reference the angular velocity of the arbitrary link [i] is calculated.

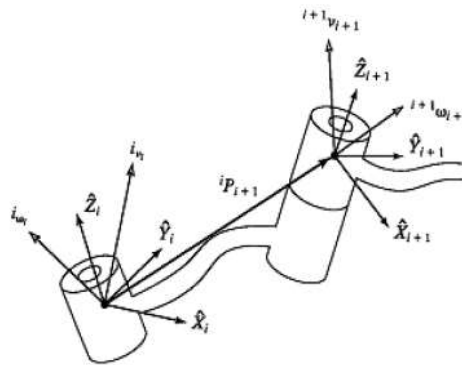


Figure 9 Velocity vector of referencing link (courtesy Quadruped locomotion by Gonzalez de Santos)

Therefore, angular and linear velocity can be given as,

$${}^{i+1}\omega = {}^{i+1}R_i^i \omega + \dot{\theta}_{i+1} {}^{i+1}Z \quad (21)$$

$${}^{i+1}V = {}^{i+1}R_i ({}^iV + {}^i\omega \times {}^{i+1}P) \quad (22)$$

Eq.1 (courtesy Quadruped locomotion by Gonzalez de Santos)

Now, differentiating the position equation with respect to the transformation matrix, the transformation of velocity from 0 to 4 can be defined as,

$${}^0_4V = \begin{bmatrix} S_1(l_1+l_2C_2+l_3C_{23}) & -C_1l_2S_2 \\ -C_1(l_1+l_2C_2+l_3C_{23}) & S_1l_2S_2 \\ 0 & -l_2S_2+l_3C_{23} \end{bmatrix} \quad (23)$$

3.3.1. linear and angular velocity from leg frame

From equation 21 and 22,

For Link 0

$${}^0_0\omega = [0] \quad (24)$$

$${}^0_0v = [0] \quad (25)$$

For Link 1

$${}^1_1\omega = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix} \quad (26)$$

$${}^1_1v = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (27)$$

For Link 2

$${}^2_2\omega = \begin{bmatrix} \sin\theta_2\dot{\theta}_1 \\ \cos\theta_2\dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \quad (28)$$

$${}^2_2v = \begin{bmatrix} 0 \\ 0 \\ -d\dot{\theta}_1 \end{bmatrix} \quad (29)$$

For Link 3

$${}^3_3\omega = \begin{bmatrix} \sin(\theta_2 + \theta_3)\dot{\theta}_1 \\ \cos(\theta_2 + \theta_3)\dot{\theta}_1 \\ \dot{\theta}_2 + \dot{\theta}_3 \end{bmatrix} \quad (30)$$

$${}^3_3v = \begin{bmatrix} l_1\sin(\theta_3)\dot{\theta}_2 \\ l_1\cos(\theta_3)\dot{\theta}_2 \\ -l_1\cos(\theta_3)\dot{\theta}_2 + -d\dot{\theta}_2 \end{bmatrix} \quad (31)$$

Since the end effector is in the end of the frame let us consider the change to be negligible.

Now, comparing it with the body frame,

3.3.2. Linear and angular velocities from the torso

There will not be any change in linear velocities even if the change is considered from the torso. The only evident change will be seen in the joint velocities from the body. This can be calculated by a multiplication factor of rotation from the body frame. Hence,

$${}^3_3 v = \begin{bmatrix} l_1 \sin(\theta_3) \dot{\theta}_2 \\ l_1 \cos(\theta_3) \dot{\theta}_2 \\ -l_1 \cos(\theta_3) \dot{\theta}_2 + -d \dot{\theta}_2 \end{bmatrix}$$

This is further multiplied by the end effector and in turn multiplied by the rotation matrix so as to receive the final joint velocity matrix

$${}^4_4 Jv = \begin{bmatrix} 0 & P_1 & l_2 \cos(\theta_{23}) \\ -k \cos(\theta_1) & -P_2 \sin(\theta_1) & -P_3 \sin(\theta_1) \\ -k \sin(\theta_1) & -P_2 \cos(\theta_1) & -P_3 \cos(\theta_1) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \quad (32)$$

4. Trajectory planning of quadruped robot

Leg movement is basically described by the motion of a robot based on its trajectory. Here, trajectory is the time history of the position, its velocity and acceleration of each degree of freedom. When simulation is done without a proper trajectory planning, the robot movement is found to be random and irregular and the robot lacks balance. This is due to the sudden change in velocity in the cartesian space.

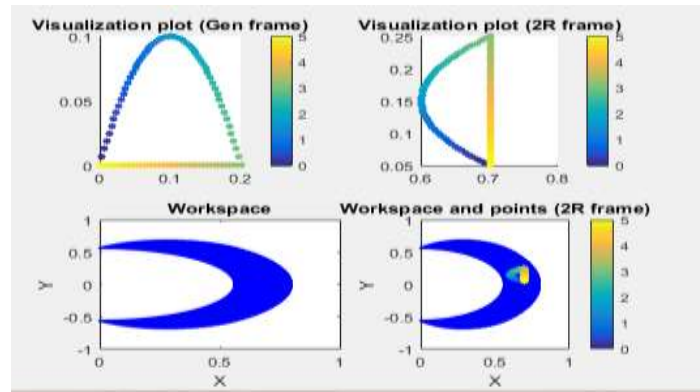


Figure 10 Point visualization in leg workspace

Trajectory planning is necessary for kinematic based motion analysis. Hence, the trajectory is generated with the help of probable via points so as to maintain smooth profile. Since the quadruped has 3 degrees of freedom. The robot shows a variation in all 3 axes of the cartesian space.

Considering the values of a function and its respective derivatives at two of the points, there is exactly one function of third degree that has the same four values, this is called a Cubic Hermite spline. There are two common ways of using the following method.

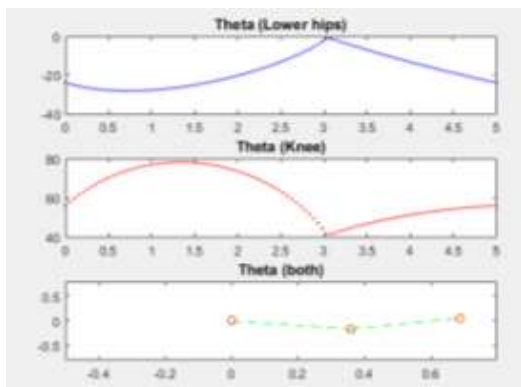


Figure 11 Joint angle generation

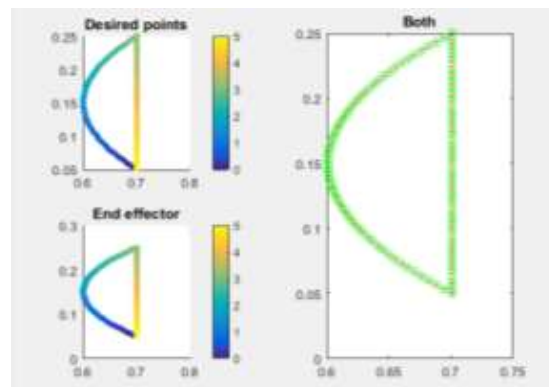


Figure 12 Trajectory generation

$$f(x) = ax^3 + bx^2 + cx + d \quad (33)$$

If the value of the said function is known at various data points, cubic interpolating the curve helps in approximating the function and its value by a continuously differentiable function, which is piecewise cubic. So, since the via points are already defined by the inverse kinematic function, using those points in MATLAB to validate a cubic spline and hence a cubic profiling of the robot motion is generated.

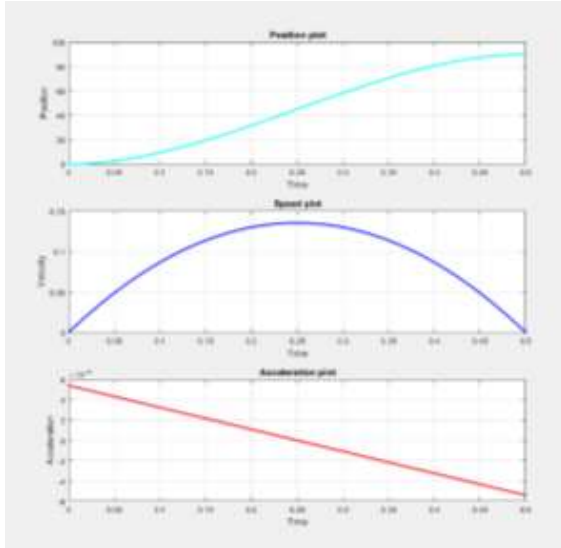


Figure 13 cubic profiling curves

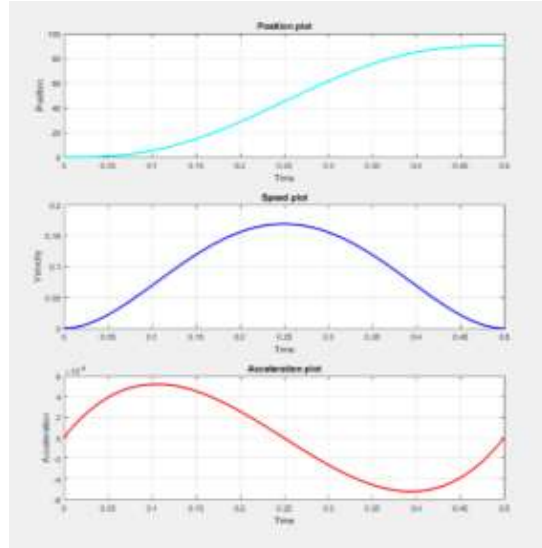


Figure 14 Fifth degree profiling curve

The given cubic polynomial is further intrapolated to the fifth degree with the help of MATLAB. The curve is then further smoothened to generate a fifth degree curve. This curve follows a softer curve where even the critical points in the third degree curve is further intrapolated to return smoother curve points

5. Gait Planning and stability analysis

A centroid based analysis of a quadruped is done considering a foot polygon. In a four legged robot, the foot polygon is basically referred in rectangular and triangular bases. This section helps in finding a computational method to find the centroid of the foot polygons formed by the robotic leg.

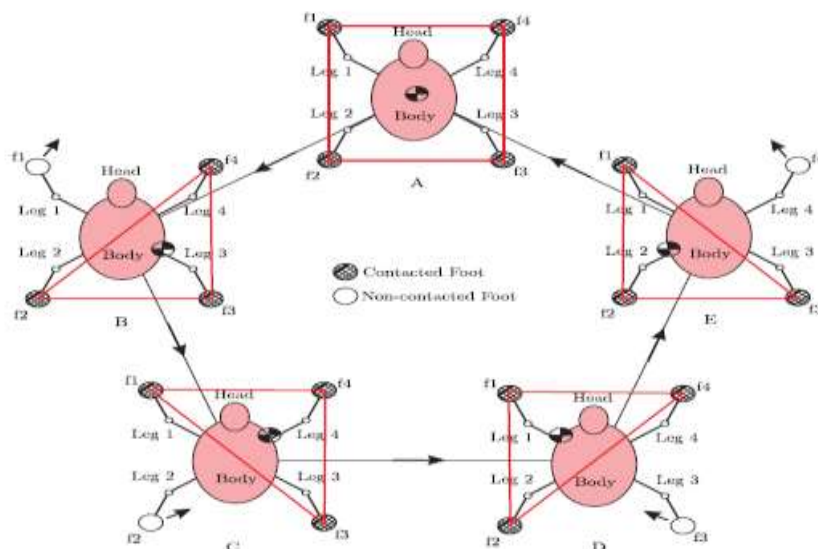


Figure 15 Step sequence of the feet (courtesy to semanticscholar.org)

During a quadruped walking, a triangular foot configuration is made the moment the first leg is lifted of the ground. For example, figure 5.3(d) shows the triangular foot of a polygon and its centroid coordinate ($C_g(x_g(t), y_g(t))$) position can be represented by,

$$x_g(t) = \{x_1(t) + x_2(t) + x_3(t)\}/3 \quad (34)$$

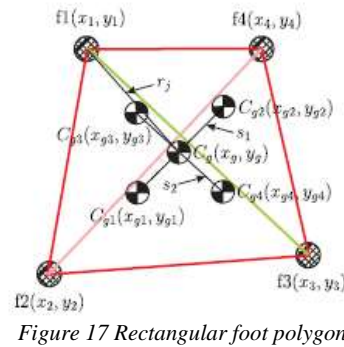
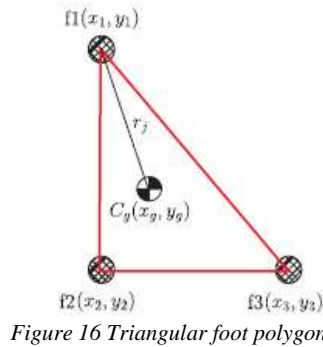
$$y_g(t) = \{y_1(t) + y_2(t) + y_3(t)\}/3 \quad (35)$$

where, $x_i(t)(i= 1, 2, 3)$ and $y_i(t)(i= 1, 2, 3)$ are the positions of each foot in the x - and y -direction correspondingly. At the straight state of the quadruped, a rectangular foot pattern similar to Fig. 17 is made. The centroid point of rectangular polygon can be found using the equation,

$$x_g(t) = I/(s_1(t) - s_2(t)) \{s_1(t)x_{g1}(t) - s_2(t)x_{g3}(t) + y_{g3}(t) - y_{g1}(t)\} \quad (36)$$

$$y_g(t) = \begin{cases} s_1(t)\{x_g(t) - x_{g1}(t)\} + y_{g1}(t), \text{ or} \\ s_2(t)\{x_g(t) - x_{g3}(t)\} + y_{g3}(t) \end{cases} \quad (37)$$

where $x_i(t)(i= 1, 2, 3, 4)$ and $y_i(t)(i= 1, 2, 3, 4)$ are the positions of each end effector duly. The parameter $s_1(t)$ shows the slope character of the line passing through the centre point of the triangle $f1f2f3$, $C_{g1}(t)$, and also the centre of triangle $f1f3f4$, $C_{g2}(t)$. The point $s_2(t)$ represents the slope of the line segment travelling along the centroid of triangle $f1f2f4$, $C_{g3}(t)$, also the centroid of triangle $f2f3f4$, $C_{g4}(t)$. See the step configuration in Fig 15.



The centroid of all the foot polygons formed during the motion of the robot was noted and the walking balance is analyzed. Also, the balance of the quadruped robot during motion is found by using a simple index of its movement. Through various simulations, it is confirmed that the movement of a quad robot on legs requires a waddling in its motion to walk with is stable balance.

5.1 Walking balance index

Even if the overall center of mass is directed towards the centre, the balance of the configuration maybe slightly different depending on the shape of the foot polygon. It is usually considered that, as the polygon is more spacious so is the balance leading to a increased walking balance. Hence, this helps in generation of a simple performance index.

$$I_B = \min(r_j(t)), j = 1, \dots, n \quad (38)$$

Here, $\min(r_j(t))$ is the minimum value that can be attained by $r_j(t)$. The n is 3 for a triangular polygon and 4 in the case of a rectangular foot polygon. That is, the total distance between the proper centroid and the vertex ' j ' of a polygon in (Fig.16 and Fig.17), $r_j(t)$, is calculated by

$$r_j(t) = \sqrt{\{x_g(t) - x_j(t)\}^2 + \{y_g(t) - y_j(t)\}^2}. \quad (39)$$

Practically, the value I_B in (38) represents the lowest distance between the centroid of the support polygon and position of each foot in a walking balance. It is then inferred that the case with a rather large I_B in study by referring to many walking patterns with better potential of smooth walking. The walking starts with the initial step of the quadruped as follows,

Table 5 Initial position of four legs

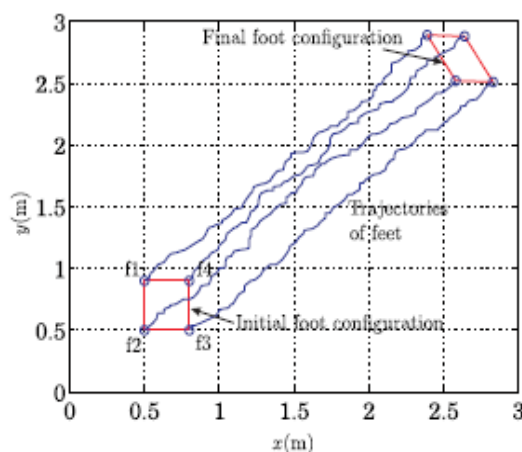
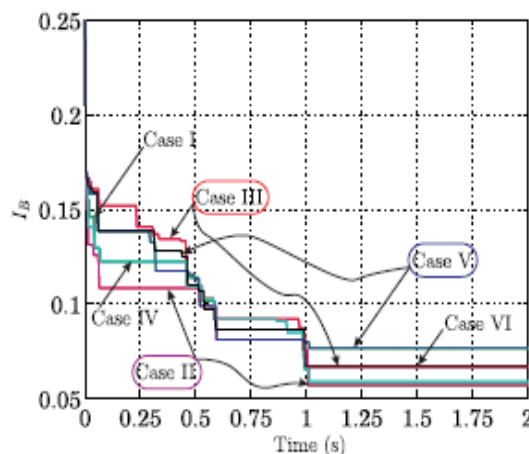
Foot	X (m)	Y (m)	Further remarks
$f1$	0.2	0.5	Rectangular posture as shown in figure 17.
$f2$	0.2	0.2	
$f3$	0.4	0.2	
$f4$	0.4	0.2	

After going to the initial homing position, there are multiple sequence of steps so as to maintain a stable dynamic and static posture. The steps are followed in such a fashion with reference to the centroid based balancing criteria so as to make the robot traverse in a stable position.

Table 6 Example cases for step by step walking

Case	Order of footsteps	Further remarks
1	$f1\ f2\ f3\ f4\ f1$	See Figure 15
2	$f1\ f2\ f4\ f3\ f1$	
3	$f1\ f3\ f4\ f2\ f1$	
4	$f1\ f3\ f2\ f4\ f1$	
5	$f1\ f4\ f2\ f3\ f1$	
6	$f1\ f4\ f3\ f2\ f1$	

On managing the step criteria with respect to the timing parameters a stable walking method is obtained. The walking is maintained such that the robot is stable and without tendency to slack during motion. The motion parameters for uneven and irregular terrain is obtained similarly. (refer Figure 18)

Figure 18 Reference foot trajectory for walking
(courtesy Centroid based analysis of quadruped robot walking balance)Figure 19 Balance index
(courtesy Centroid based analysis of quadruped robot walking balance)

As the robot starts its motion, all the designed centroid trajectories are being moved in another form. This implies that the centroid position trajectory of the bot depends on the order of foot movement during motion. In theory, the wriggling trajectories directs our attention to the idea that the four-legged walking robot walks with a waddle like movement similar to a duck during movement. Considering the facts, it is not a strange behaviour, and such a wriggle like motion is naturally occurring for the structural balance of the robot. This is because it is necessary for the quadruped to adjust its motion during walking so as to prevent itself from falling while in motion. But these motions are rather

unstable and undesirable. That is why sudden changes in centroid trajectories are not allowed for dextrous walking and such characteristics requires the need for an excessive walking. Furthermore, it is noted from the trend of that the walking behaviour of the robot that the movement can be more balanced by properly scheduling the entire walking order.

Next, to understand what style helps in better walking balance, look at the performance index defined in (18) for the walking task. Fig. 19 shows the indices of walking balance for all the legs as assigned in Table 6. From Fig.19, it is to be confirmed that walking style case 3 defined in Table 6 maintains the best balance is the front part of the quadruped, but Case 5 is better than the others for the rear. Also, the overall walking balance of the Case 2 is found to be the lowest of all for the walking task. In a four-legged task, the idea for the walking motion of the robot is to be controlled by removing any unwanted waddle like motion. One major reason for this is that waddling tends to disturb the overall control performance of the quadruped. In theory, if the COM of the quadruped vehicle is to be directed to the centroid of foot polygon in all the steps during motion, it is really easy to guarantee the overall walking balance in each step taken during the process. So, in order to identify a characteristic of waddling in a quad robot movement, it is useful to check the trajectory of the centroid of the foot polygon formed in every step of its motion.

6. Experimental Results

6.1 Multibody simulation of the quadruped leg

Leg of the quadruped robot shows 3 DOF which includes one roll and two pitch motion. This simulation helps in the calculation of joint torque and joint motion for proper selection of actuators. The variation in torque and joint motion is observed. This simulation helps in understanding the leg ratio requirements to achieve required output torque and also joint angles for the projection.

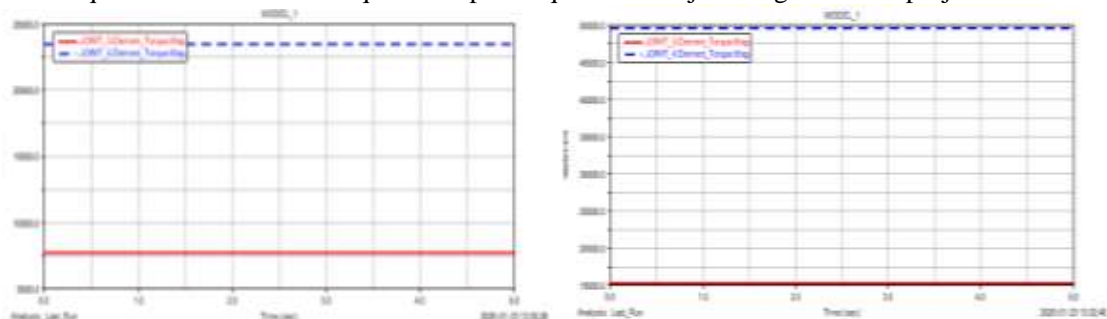


Figure 20 Torque requirement at medium and maximum load condition

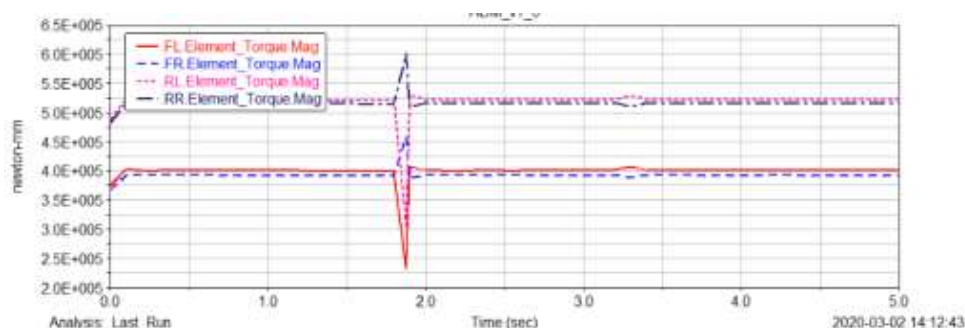


Figure 21 Torque change in the leg during one action cycle

6.2 Multi-body simulation of the robot

This section shows the whole-body simulation of the quadruped robot. This simulation was carried out in an Adams – MATLAB embedded atmosphere. The quadruped simulation carries out a proper analysis of the robot motion. The joint characteristics are observed along with motion analysis for

smooth motion planning. The simulation also helps in observing the stability criterion and making necessary changes to make the quadruped stable. Crawl and Trot gaits were implemented in simulation and the crawl gait is found to be the most stable and also requires the most torque for its movements

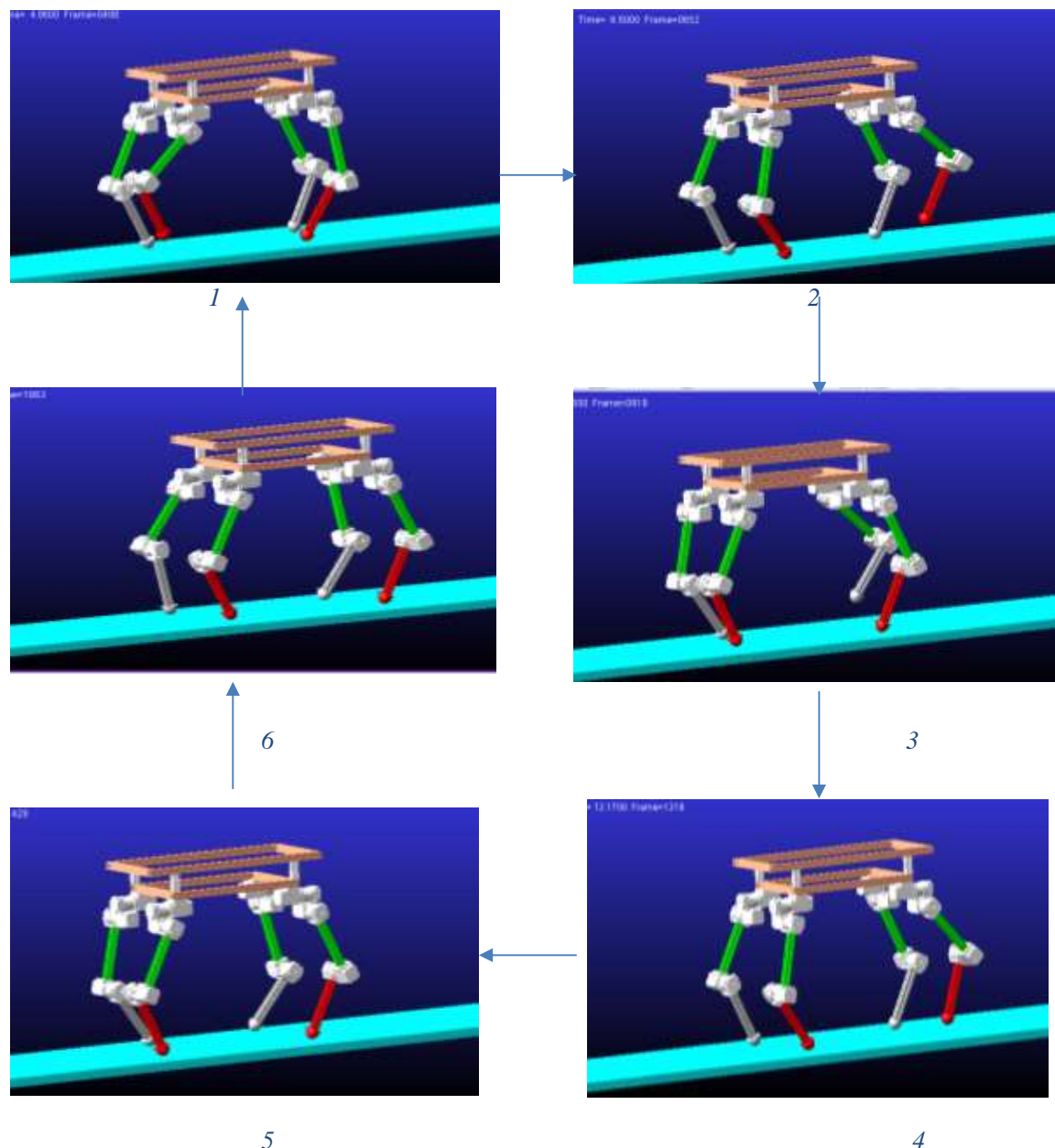


Figure 22 Gait simulation

The simulation cycle returned the following results ,

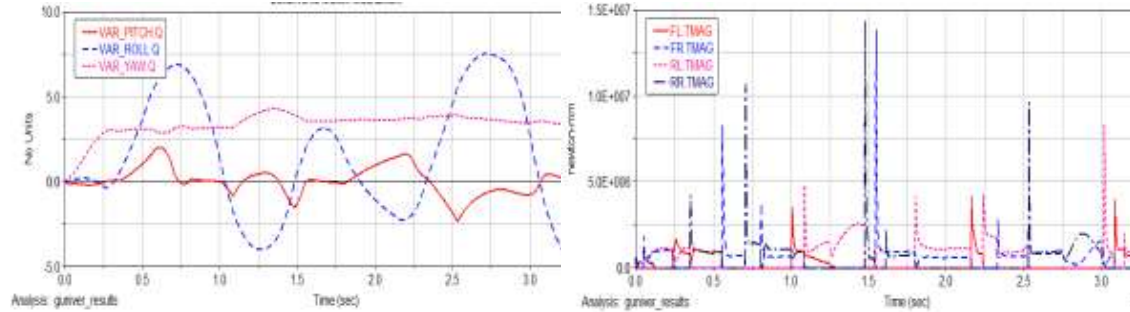
CRAWL GAIT :

Figure 23(a) Roll, pitch and yaw acting on the quadruped (b) Torque

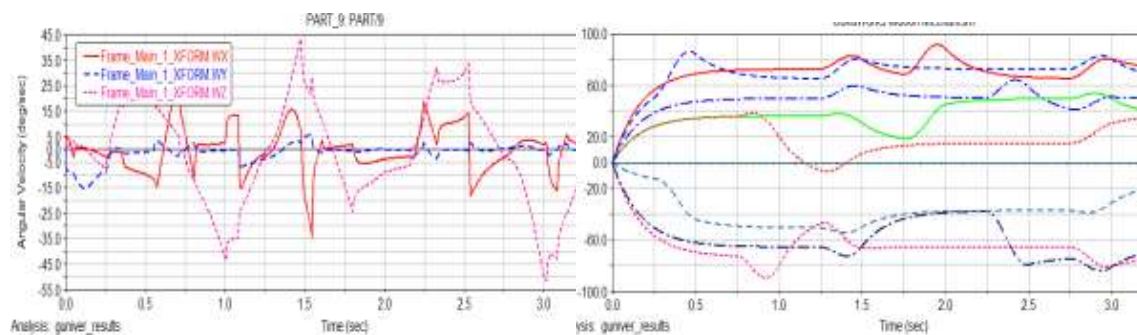


Figure 24(a) Angular velocity variation in x, y and z axis during crawl gait (b) angular change

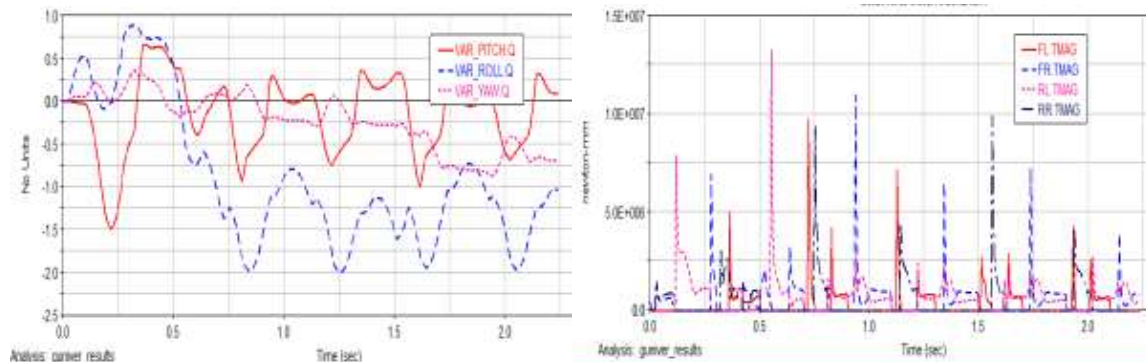
TROT GAIT :

Figure 25(a) Roll, Pitch and Yaw of the robot during Trot gait (b) Torque variation

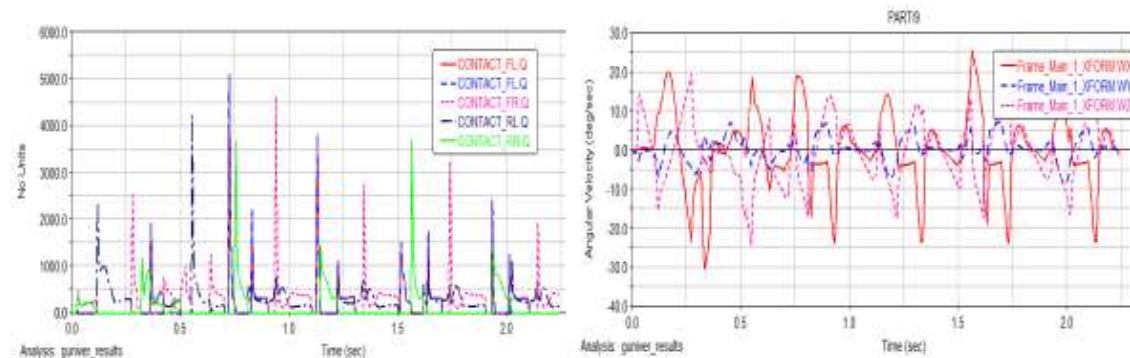


Figure 26(a) Contact force on each leg during trot gait (b) Angular variation

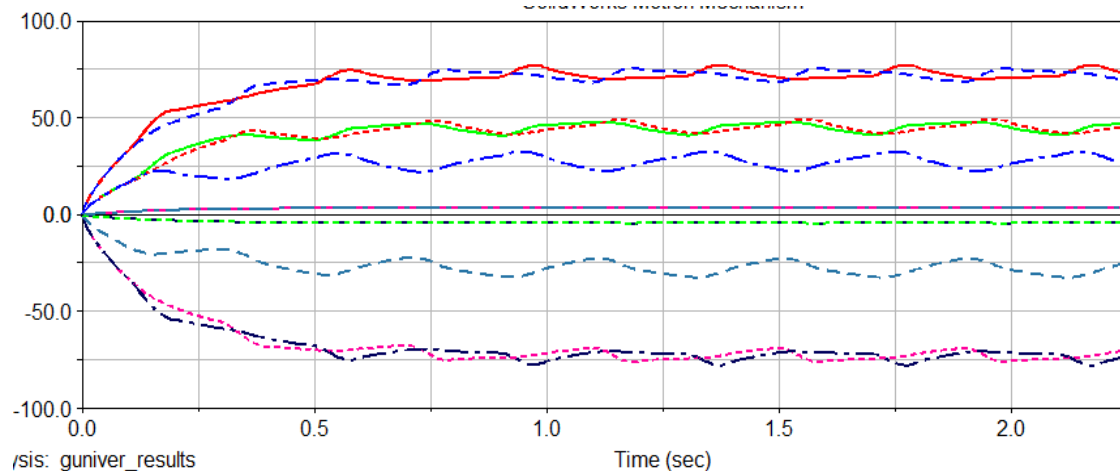


Figure 27 Angular change in all 12 joints during trot gait

7. Overview of Control Architecture

The motion control of quadruped is based on a 3 Channel Input capture (IC) method consisting of slave and master controls. The controllers are connected serially to the PC with the master controller controlling the entire structure through the CAN bus.

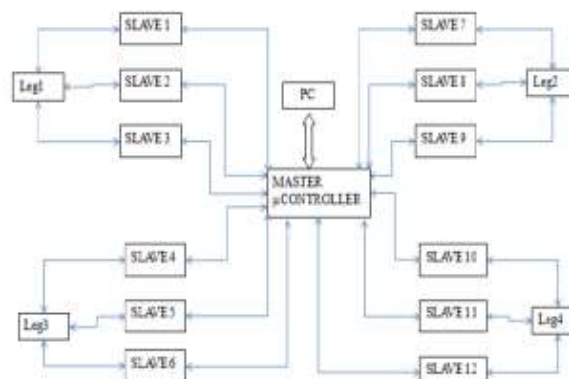


Figure 28 Control structure of the quadruped

A well-defined single axis motion control is tested, where the slave card is connected to the motor at joints and master card for the connection of all the slave cards and interface to the host computer. The master and slave cards are connected through CAN bus and a distribution control is used to split one control into 12 different signals according to movement requirements. The host communication is carried out through a RS232 serial bus. The motor is tested in various frequency ranges of PWM and the movement speed is considered according to the stability of motion.

Motion will be controlled and tested in both open loop and close loop circuits. In the open loop motion control, the control will be based on PWM signal and interrupt timer and in the closed loop control, it will be focused on the error percentage of servo loop. The motion will follow a particular motion trajectory according to requirement of movement smoothness (cubic, quadratic or fifth degree). The closed loop control will direct to us the positional feedback of motor with each instantaneous change.

8. Conclusion

Steps were taken to make the system rugged and rough with an ability to traverse in all terrains. The entire system is based on a closed PID controller loop with one master controller which transfers information to 12 slaves so as to control the joint movement. The micro controller used is PIC18F4011 micro-controller. The P-control algorithm is what helps us in achieving the control of speed at a point

of the robot. The basic concept of servo loop is to calculate the total error and subtract it incrementally whereby achieving the point value of the PWM duty cycle. The error can be found by removing the final point from the given initial or target point. This helps in calculating the final position whereby the multiplying the error with the proportionality gives us the absolute value of its absolute position. This duty cycle directs us in generating the PWM which is then directed to the motor as its input. A feedback control loop is used to overcome the absence of an absolute encoder.

The quadruped was controlled using proper gait patterns with the help of kinematic analysis. The gaits were extrapolated using trajectory parameters to achieve a smooth profile and hence completing the proper gait patterns and stabilizing the overall movement. The research is hence concluded to be successful in terms of functionality and open to further necessary improvements.

References

- [1] Pablo Gonzalez de Santos, Elena Garcia and Joaquin Estremera "Quadrupedal Locomotion An Introduction to the Control of Four legged Robots" by Springer-Verlag London Limited 2006
- [2] F.E. Fish, P.B. Frappell, R. V. Baudinette, P.M. Macfarlane, "Energetics of Terrestrial Locomotion of the Platypus *Ornithorhynchus Anatinus*", The Journal of Experimental Biology, 2001, 204, pp.797–803.
- [3] R.W. Blob, A.A. Biewener "Mechanics of limb bone loading during terrestrial locomotion in the green iguana (*Iguana iguana*) and American alligator (*Alligator Mississippiensis*)", The Journal of Experimental Biology, (2001), 204, pp.1099–1122.
- [4] J.M. Parrish, "The Origin of Crocodilian Locomotion, Paleobiology", 1987, Vol. 13, No. 4, pp. 396-414.
- [5] M.H. Raibert "Legged Robots That Balance" MIT Press, 1986.
- [6] Stable Stair-Climbing of a Quadruped Robot. <https://arxiv.org/pdf/1809.02891>
- [7] J. F. Vincent, O. A. Bogatyreva, N. R. Bogatyrev, A. Bowyer, A. K. Pahl, "Biomimetics: its practice and theory". Journal of the Royal Society Interface, 2006, 3(9), 471-482.
- [8] A.E. Rawlings, P.J. Bramble, S.S. Staniland, "Innovation through imitation: biomimetic, bioinspired and biokleptic research". Soft Matter, 2012, 8, 6675-6679.
- [9] B. Webb, T. Consilvio, "Biorobotics" 2001 Mit Press.
- [10] Stoeter, Sascha A., Ian T. Burt, and N. Papanikolopoulos. "Scout robot motion model." In Robotics and Automation, 2003. Proceedings.2003.
- [11] Harada, Kanako, Sheila Russo, Tommaso Ranzani, Arianna Menciassi, and Paolo Dario. "Design of Scout Robot as a robotic module for symbiotic multi-robot organisms." In Micro-Nano Mechatronics and Human Science (MHS), 2011 International Symposium on, 2011 pp. 511-513.
- [12] Kimura, H., Fukuoka, Y., and Cohen, A. H. (2007). Adaptive dynamic walking of a quadruped robot on natural ground based on biological concepts. International Conference on, 2003, vol. 1, pp. 90-95
- [13] Fukuoka, Y., and H. Kimura. "Dynamic locomotion of a biomorphic quadruped 'Tekken' robot using various gaits: walk, trot, free-gait and bound." Applied Bionics and Biomechanics 6, 2009, no. 1, pp 63-71.
- [14] Li, Yibin, Bin Li, Jiahong Ruan, and Xuwen Rong. "Research of mammal bionic quadruped robots: a review." In Robotics, Automation and Mechatronics (RAM), 2011 IEEE Conference on, 2011 pp. 166-171.
- [15] Zhou, Xiaodong, and Shusheng Bi. "A survey of bio-inspired compliant legged robot designs." Bioinspiration & biomimetics 7, 2012: no. 4.
- [16] Chen, Xianbao, Feng Gao, Chenkun Qi, and Xianchao Zhao. "Spring parameters design to increase the loading capability of a hydraulic quadruped robot." In Advanced Mechatronic Systems (ICAMEchS), 2013 International Conference on, 2013, pp. 535-540.
- [17] Estremera, Joaquin, and Kenneth J. Waldron. "Leg Thrust Control for Stabilization of Dynamic Gaits in a Quadruped Robot." In Romansy 16, 2006, pp. 213-220. Springer Vienna.
- [18] Vivian Allen, Ruth M. Elsey, Nicola Jones, Jordon Wright and John R. Hutchinson, "Functional specialization and ontogenetic scaling of limb anatomy in *Alligator mississippiensis*, Journal of anatomy, 2009, pp 423-445

- [19] T. McGeer “Passive dynamic walking”. *Int. J. Rob. Res.* 9, 2 (March 1990), pp. 62-82. [31] Anand Kumar Mishra, “Design, Simulation, Fabrication and Planning of Bio- Inspired Quadruped Robot”, 2014 May
- [20] Li, Yibin, Bin Li, JiuHongRuan, and Xuewen Rong. "Research of mammal bionic quadruped robots: a review." In *Robotics, Automation and Mechatronics (RAM)*, 2011 IEEE Conference on, 2011, pp. 166-171. IEEE, 2011.
International Journal of Robotics Research, 26:475–490.
- [21] Q. Huang, K. Yokoi, S. Kajita, K. Kaneko, H. Arai, N. Koyachi, K. Tanie, "Planning walking patterns for a biped robot," *Robotics and Automation, IEEE Transactions on* , vol.17, 2001, no.3, pp.280,289.
- [22] Mori, Makoto, and Shigeo Hirose. "Development of active cord mechanism ACM-R3 with agile 3D mobility." In *Intelligent Robots and Systems*, 2001. Proceedings. 2001 IEEE/RSJ International Conference on, 2001, vol. 3, pp. 1552-1557.
- [23] Boston Dynamics Corp. (2008). Bigdog overview. (Online) <http://www.bostondynamics.com/img/BigDogOverview.pdf>.
- [24] JJ craig “Introduction to Robotics Mechanics and Control” 3rd edition, 2004, by Pearson publication
- [25] Gonzalez de Santos, P., Jimenez, M., and Armada, M. “Dynamic effects in statically stable walking machines” *Journal of Intelligent and Robotic Systems*, 1998, 23(1), pp 71–85.
- [26] A. Crespi and A.J. Ijspeert: *AmphiBot II: an amphibious snake robot that crawls and swims using a central pattern generator*, Proceedings of the 9th International Conference on Climbing and Walking Robots, 2006, pp 19-27.
- [27] Boston Dynamics Corp. (2010). <http://www.bostondynamics.com>.
- [28] Harada, Kanako, Sheila Russo, Tommaso Ranzani, Arianna Menciassi, and Paolo Dario. "Design of Scout Robot as a robotic module for symbiotic multi-robot organisms." In *Micro-NanoMechatronics and Human Science (MHS)*, 2011 International Symposium on, 2011, pp. 511-513.
- [29] Drenner, Andrew, Ian Burt, Tom Dahlin, Bradley Kratochvil, Colin McMillen, Brad Nelson, Nikolaos Papanikolopoulos et al. "Mobility enhancements to the scout robot platform." In *Robotics and Automation*, 2002. Proceedings. ICRA'02. IEEE International Conference on, vol. 1, 2002, pp. 1069-1074.
- [30] Walking Truck - Wikipedia. https://en.wikipedia.org/wiki/Walking_truck