

Dynamic Gaits and Control in Flexible Body Quadruped Robot

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Abstract—Legged robots are highly attractive for military purposes such as carrying heavy loads on uneven terrain for long durations because of the higher mobility they give on rough terrain compared to wheeled vehicles/robots. Existing state-of-the-art quadruped robots developed by Boston Dynamics such as LittleDog and BigDog do not have flexible bodies. It can be easily seen that the agility of quadruped animals such as dogs, cats, and deer etc. depend to a large extent on their ability to flex their bodies. However, simulation study on step climbing in 3D terrain quadruped robot locomotion with flexible body has not been reported in literature. This paper aims to study the effect of body flexibility on stability and energy efficiency in walking mode, trot mode and running (bounding) mode on step climbing.

Keywords— *Simulation, stability margin, flexible body, dynamic gait*

I. INTRODUCTION

Legged robots are preferred to wheeled mobile robots for locomotion in environments which generally contain uneven terrain. In such an environment, legged robots offer better mobility than their wheeled mobile robots [1]. A legged robot can easily overcome obstacles by stepping on/over them if it is at a lower level than its maximum ground clearance, whereas a wheeled mobile robot cannot overcome obstacles of height greater than the radius of its wheels even if its ground clearance is large enough. Legged robots can isolate the payload by providing active suspension through leg actuators while traversing on rough terrain. They are also less prone to slipping and jamming when moving over soft terrain [2]. Further, they are capable of maintaining their average speed on rough terrain, whereas average speed of wheeled robots is quite low on a similar terrain.

Multi-legged robots are comparatively more stable than one and two-legged robots because of the larger stability margin they are capable of. However, robots with large number of legs require more complex mechanisms and higher number of actuators, adding weight and energy required for locomotion. Three legged robots cannot maintain static stability when one of the legs is in swing phase, whereas a four-legged robot can. This makes quadruped robot the right choice considering simplicity and stability. Quadruped robots can be broadly classified

into two types based on the kinematic structure of their legs. These are quadruped robots with insect-type 3-Degree-of-Freedom (DoF) legs and those with mammal-type 3- or 4-DoF legs. Numerous quadruped walking and running robots have been developed to date.

Trot is one of the most widely used gaits in quadruped robots [3, 6] in which the robot is supported on diagonally opposite legs during support phase. Trot gait is preferred where lower energy consumption is desirable [4]. Trot being a symmetric gait, there exists a similarity between biped walking and quadruped trotting where the quadruped can be viewed as two bipeds connected one behind the other [5].

The bounding gait is a form of fast running legged locomotion in which a quadruped animal uses front legs as a pair (LF-RF) and rear legs as a pair (LR-RR) [7]. In this gait, the quadruped lands with both of its front legs and moves the rear legs forward, lands, and swings the front leg pair further to the next step. Existing state-of-the-art quadruped robots developed by Boston Dynamics such as Little Dog [8] and Big Dog [9] do not have flexible bodies. In case of four legged animals like dogs, cats, and deer etc. mobility depends to a large extent on flexibility of the body. Kwon and Yoo [10] report a simulation study on energy efficiency of a quadruped robot in sagittal plane. A fuzzy control strategy for 3D quadruped trot to execute high-speed turns over a range of speeds and turning rates were presented [11]. A quasi-static step climbing behavior for a minimal sensing wheel-legged quadruped robot PAW [12] uses wheel traction and its legs to reconfigure itself with respect to the step during the climb. MHT [13] makes use of velocity model for inverse kinematics of the vehicle and incorporates optimization technique to minimize joint torques. The Static Stability Margin used is as defined by Papadopoulos and Rey [14].

However, simulation study on step climbing in 3D terrain quadruped robot locomotion with flexible body has not been reported in literature till date. This paper aims to study the effect of body flexibility on stability and energy efficiency in walking mode, trot mode and running mode on step climbing. This paper includes mathematical modelling, creating solid model, importing to simulation software (ADAMS) where the physics engine based

simulation is carried out. Finally interfacing with Simulink based on MATLAB programmes will completely execute the quadruped robot gaits mechanism with flexible body. Validity of the algorithm has been extensively tested via simulations using MSC ADAMS and MATLAB/SIMULINK interface.

II. SYSTEM DESCRIPTION

The flexible body quadruped robot (FBQR) has a total of 14 DoF with 3 DoF per leg and 2 DoF for the body. The legs will have mammal type configuration with two DoF hip joint, and one DoF knee joint. The schematic diagram of the proposed kinematic structure is shown in Fig. 1. The first leg is lifted for the walking to be initialized. At this point of time the other three legs will form the polygon pattern of three sides and the projection of the Centre of Mass (CoM) lies within this pattern forming stable walking. Flexing of the body in pitch and roll is effected by body joints 1 and 2 respectively. The length of the obstacle that can be overcome depends on the distance between the knee joints of the front and rear legs. The knee bending direction of the legs will be outward in order to allow overcoming obstacles of larger length. The knee bending direction of legs will be inward in order to get better stability at faster speed.

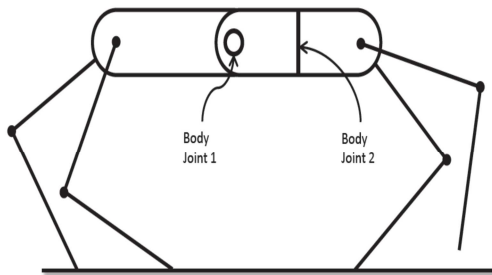


Fig. 1: Schematic diagram of the FBQR

Fig. 2 shows the mechanical structure of the proposed model of the vehicle (FBQR). The system has been designed as a legged robot. It consists of four leg connected to the chassis. Each leg has three degrees of freedom consisting of 2-DoF hip joint and a knee joint. The leg tip has a Semi-circular foot to provide proper traction for the leg placement. Next we derive the forward kinematics of each leg. The leg is considered from the hip joint to the semicircular foot attached to last link.

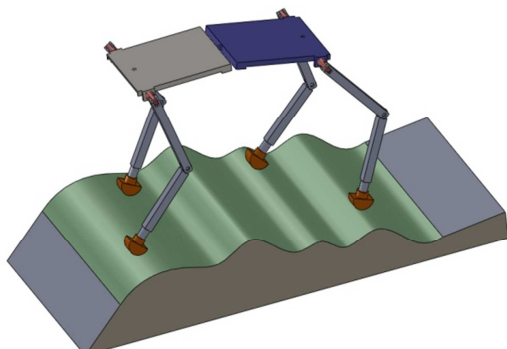


Fig. 2: Mechanical Structure of the FBQR

A. Leg Forward Kinematics

Fig. 3 shows the kinematics of the single leg with the corresponding frame assignments at various joints. The frame {0} is the frame attached to fixed end of the hip joint and frames {1}, {2} and {3} are the frames attached to each of the rotary joints. Frame {4} is attached to the ankle joint where the semicircular foot is placed. {R} is the reference frame at the center of the chassis with the Z-axis aligned to gravity. {B} is the body frame with origin coincident with {R}. Yaw angle between these frames is always zero.

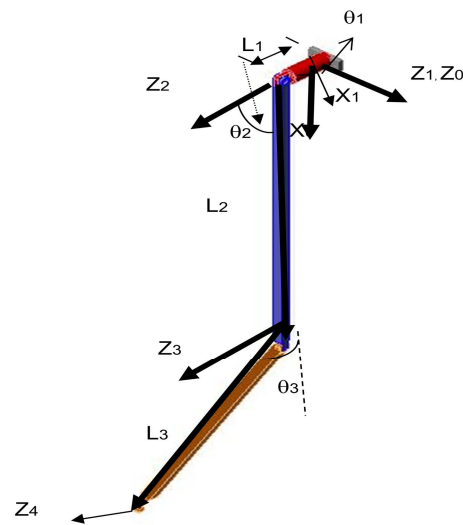


Fig 3: Leg Kinematics configuration

The DH parameters of this leg are shown in Table I.

TABLE-I.

DH PARAMETERS

Axis, i	DH Parameters			
	a_{i-1}	a_{i-1}	θ_i	d_i
1	0	0	θ_1	0
2	$\pi/2$	0	θ_2	L_1
3	0	L_2	θ_3	0
4	0	L_3	0	0

$$L_1 = \pm 80\text{mm, +ve for leg1, leg3 and -ve for leg2 and leg4}$$

$$L_2 = 400\text{mm}$$

$$L_3 = 400\text{mm}$$

Based on the DH parameters transformation matrix from frame {0} to frame {4} of the leg can be calculated and represented by 0_4T . Transformation from frame {0} of leg to frame {B} at center of the body is calculated by the

transformation matrix B_0T . The forward kinematics of the leg tip pose in the body frame is given by

$$P_{leg} = {}^B_0T {}^0_4T$$

TABLE -II

QUADRUPED ROBOT PARAMETERS	
Mass, m	40 Kg
Body length, L_b	1.0 m
Body width, w	0.5 m
Height of Trotting, h	0.9m
Stride length (Max), L_s	1.0m

B. Leg Jacobian

If Jacobian of the leg assembly in the frame $\{0\}$ is given by 0J , the Cartesian velocity of leg ankle therefore given by

$$[v_x \ v_y \ v_z]^T = {}^0J[\dot{\theta}_1 \ \dot{\theta}_2 \ \dot{\theta}_3]$$

Where,

$\dot{\theta}_1, \ \dot{\theta}_2, \ \dot{\theta}_3$ are angular velocities of the joints of leg.

C. Simulation model of FBQR

3D design software (Solidworks) is used to design FBQR. The simulation model is a mammalian type FBQR with 3 DoF each leg and 2Dof (Roll and Pitch) flexible body. Robot modeled is as shown in Fig.4. The solidworks model file was imported to ADAMS software and then the input/output variables of the plant were assigned by the joints, motors, and constraints. The material was assumed to be Aluminum alloy for all the components for simulation. A dummy mass was attached to the body of the quadruped to imitate the payload carrying capability. The quadruped robot parameters as shown in TABLE –II, have been used for the simulation of the robot. The frictional coefficient between the ground and the leg foot was considered to be 0.7.

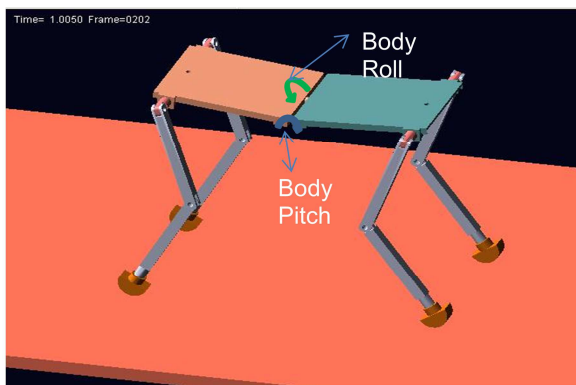


Fig 4. Simulation model of FBQR

Using this model, physical simulations were carried out for walking (crawling) gait, trot gait and bounding gait with flexible body.

III. CONTROL SYSTEM

The MATLAB Simulink was used along with the physics engine based MSC ADAMS plant. The complete quadruped robot with flexible body can be controlled using this tool. Fig. 5 shows the simulation control plant. The ADAMS_PLANT provides the angular positions of the each joint. The MATLAB function programme consists of various control algorithms depending on the requirement for the leg placement. This function program supplies the angular velocity control commands to the plant.

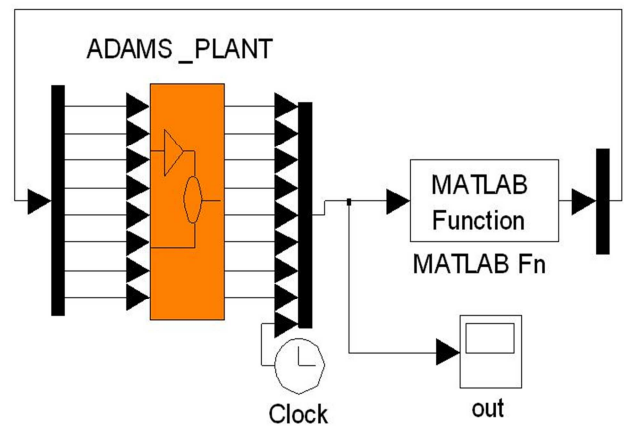


Fig 5. Simulation Control Plant

A hierarchical control system was implemented for the FBQR. The lowest level control is the angular position/velocity control of all joints. The joint position controller uses PD/PID control law. Next level is the leg tip velocity/position control. The leg controller is responsible for coordinating all three joints in a leg to perform coordinated motions by using the direct and inverse kinematic functions of a leg.

The trajectory controller is responsible for coordinating the simultaneous motion of all four legs to perform straight line or circular motions. The individual leg trajectory is based on cubic polynomial with via point. This trajectory plan is used for normal walking and trot gaits, where as circular motion for individual legs will be performed for the gallop and bounding gaits. The gallop gait can be achieved by providing small phase difference in pair of front legs and pair of back legs.

The force control processes the terrain adaptation with attitude control. The static stability controller determines whether a given foot placement configuration is stable or not. The gait generator scheme generates the sequence of leg lifting and foot placement to move the robot in stable manner and foot placements are based on the particular gait sequence for walking, trot and bounding or galloping.

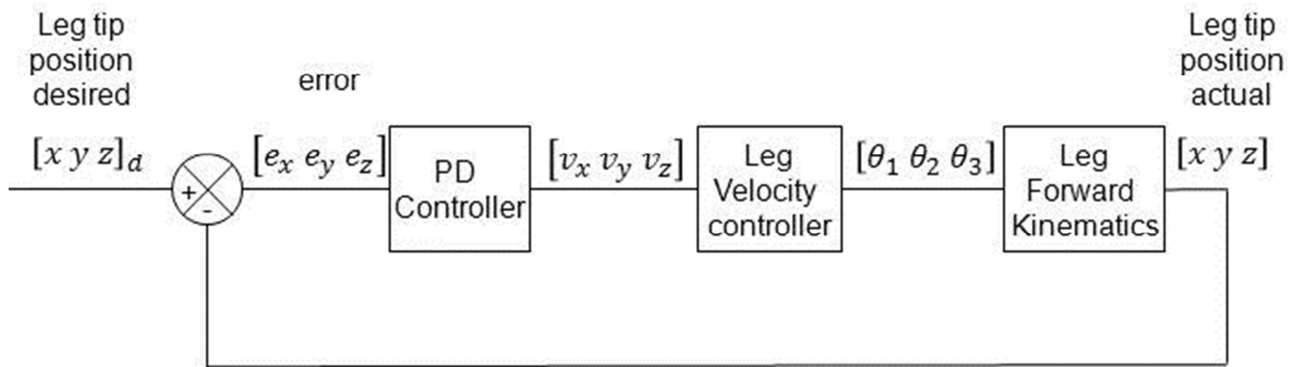


Fig. 6. Leg Controller block diagram

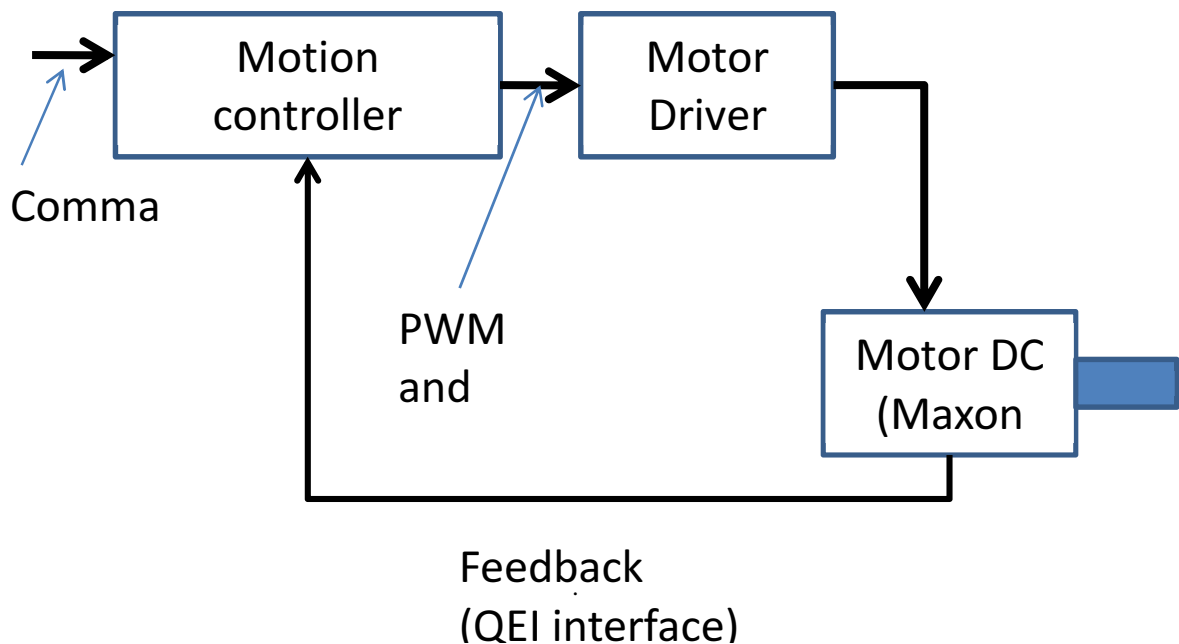


Fig. 7. Actuator control scheme

Leg tip velocity controller uses the leg Jacobian to determine the joint angular velocities which are controlled by joint velocity controller as shown in Fig.6. Leg tip position control is achieved by driving the leg velocities based on the error in leg tip position.

The actuator controls are analysed for different configurations of the applied torque and the relative angular velocity of each actuator. The actuator control scheme is as shown in Fig.7

IV. SIMULATION

Gait planning for the uneven terrain is simulated for two different configurations of the robot legs. The two configurations refers to one with 2DoF leg and other with 3DoF leg. A gait refers to a walking or running pattern, the walking gaits (walk, trot) and running gait (bound,

gallop) are produced by the gait planner. The gait planner algorithms are supplied through MATLAB function program. Continuous and discontinuous periodic gaits for quadruped robot have been simulated and compared. The continuous gaits are characterized by the simultaneous motion of the legs and body motion; whereas discontinuous gaits are characterized by the sequence motion of the legs and body motion. One leg is transferred with other three legs in support and halted. In discontinuous gaits the body is propelled with all legs in support and moving simultaneously, maintaining their footprints. Simulations were carried out on fixed body and flexible body quadruped robot.

Using the control scheme described above simulation was carried out using MSC ADAMS for multi-body dynamics simulation and MATLAB SIMULINK for control. All the quadruped robot joint motors are modeled as velocity control rotary actuators. Simulation is carried out with 3D

model of the robot for step height of 0.05m, 0.1m and 0.16m. From the simulation, it has been found that the body bends outward on the flight phase because of the free angle. This is the motion like the galloping motion of animal. Due to flexibility of the body the stride length has been increased and the robot speed has also been increased. On the other hand, the robot bends inward during the stance phase and it helps to accelerate the robot.

All simulations were performed using MSC ADAMS with a MATLAB/SIMULINK interface. In Fig.8 the snapshots of the gait sequence for climbing the step during the bounding gait are shown.

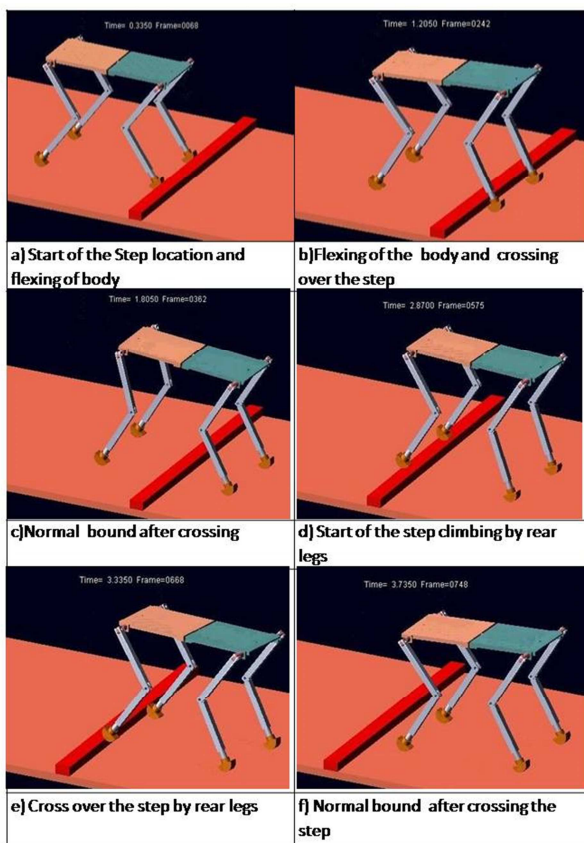


Fig 8. Snap shot of simulation of Step climbing of quadruped robot.

V. RESULTS AND DISCUSSION

Statically stable walking quadruped robot is achieved, if the horizontal projection of its CoM lies inside the support pattern. The Static Stability Margin (SSM) was defined for a given support polygon as the smallest of the distances from the CoM projection to the edges of the support polygon. SSM is the optimum stability margin for an ideal machine on horizontal, even terrain.

SSM has been computed while the robot was walking using a two-phase discontinuous gait. SSM measured over

time is plotted in Fig. 9. The two-phase discontinuous gait used in the simulations is characterized by a sequence of leg and body motions. The leg sequence is performed by transferring one leg at a time, while the body is supported on the other three legs. The body is moved forward with all four legs on the ground (body motion). When the body is in motion, at that time the SSM is not measured because all the four legs are in contact with the ground and it has maximum stability. A maximum of 80mm has been measured as the SSM during the leg motion. The complete SSM is plotted in Fig. 9

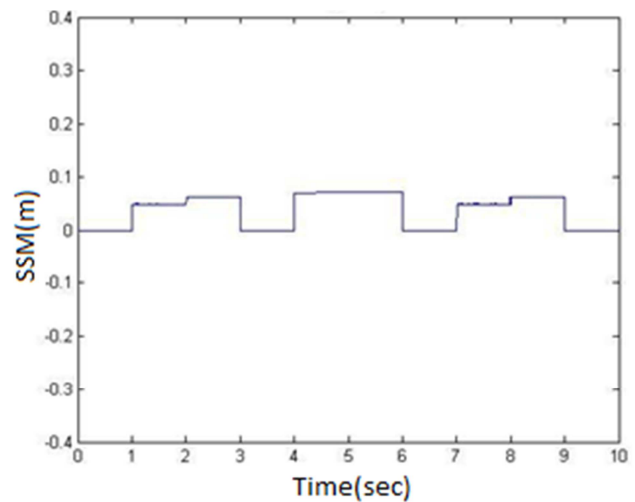


Fig. 9. Static Stability Margin during walking gait

Next, simulations were carried for the bounding gait and step climbing during this gait. During the simulation of step climbing the reaction forces have been measured and used for the step climbing control. Fig. 10 shows the forces measured by the force sensors on rear legs. For the flat terrain in bounding gait the forces are normal. During the step climbing, the reaction forces are increased as shown in Fig. 10. Similarly for the trot gait, the graphs can be plotted for all the 4 legs and the reaction forces can also be measured from the simulation. From this figure, it can also be found that beginning of the step is detected when horizontal force F_x is more than 200N in negative direction.

Fig. 11 shows the forces measured by the force sensors on front legs. For the flat terrain in bounding gait, the forces are normal. While climbing the steps, the reaction forces are found to be increased and the same has been shown in this figure.

Variation of CoM for front base and back base were plotted in Fig.12. A sudden variation can also be observed during the step climbing sequence.

Similarly, the variation of velocity of the front base and back base were plotted in Fig. 13. During the step climbing, it can be noticed that the velocity of the robot has decreased.

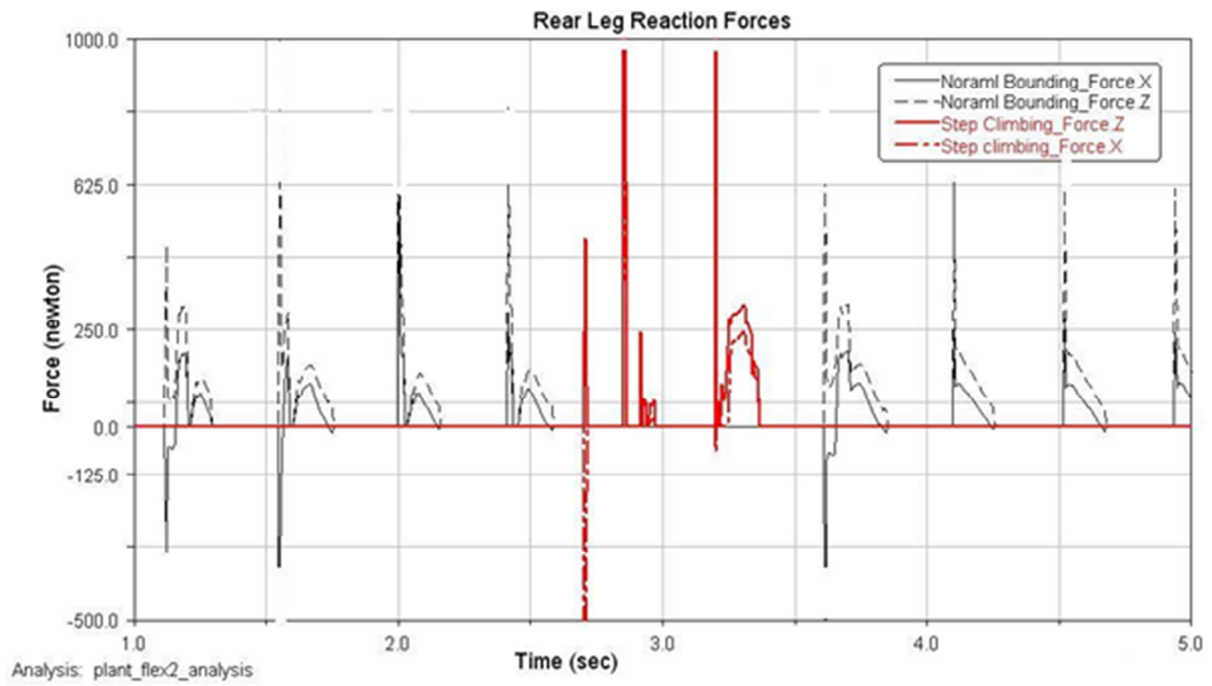


Fig.10. Rear Leg Reaction forces of FBQR

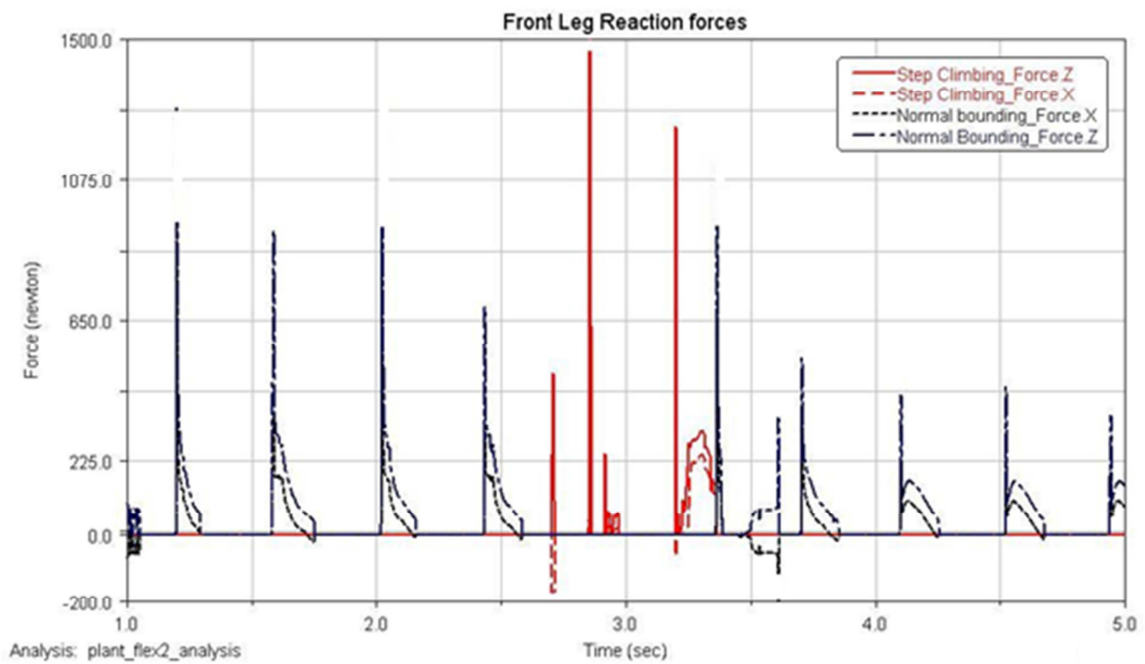


Fig.11. Front Leg Reaction forces of FBQR

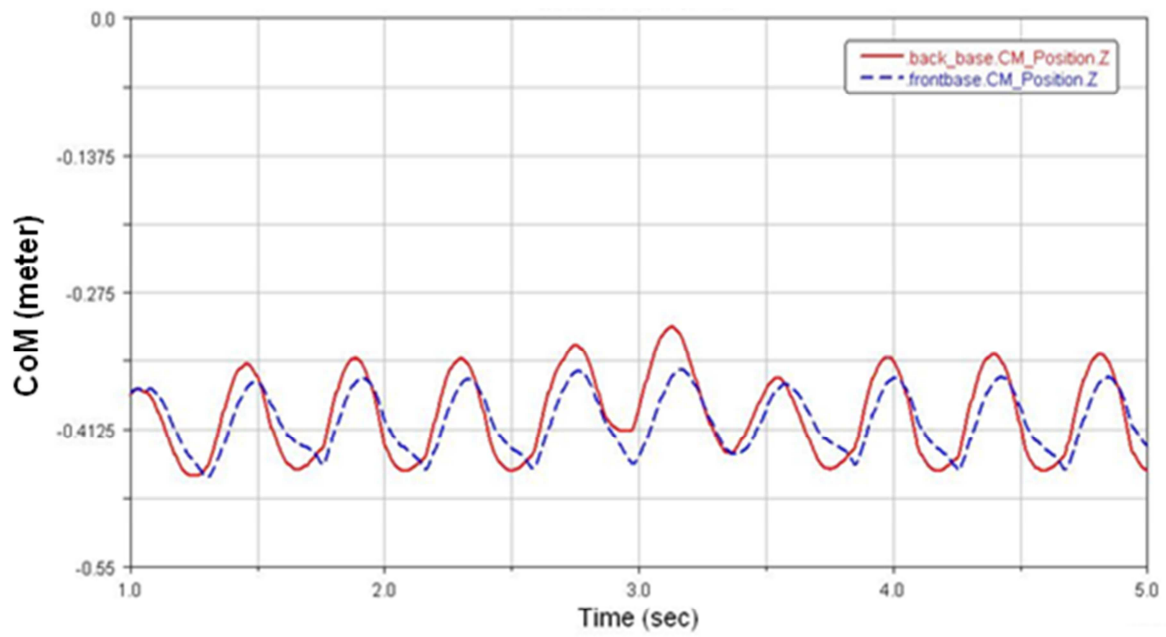


Fig. 12 Variation of Centre of Mass (CoM) for front body base and rear body base.

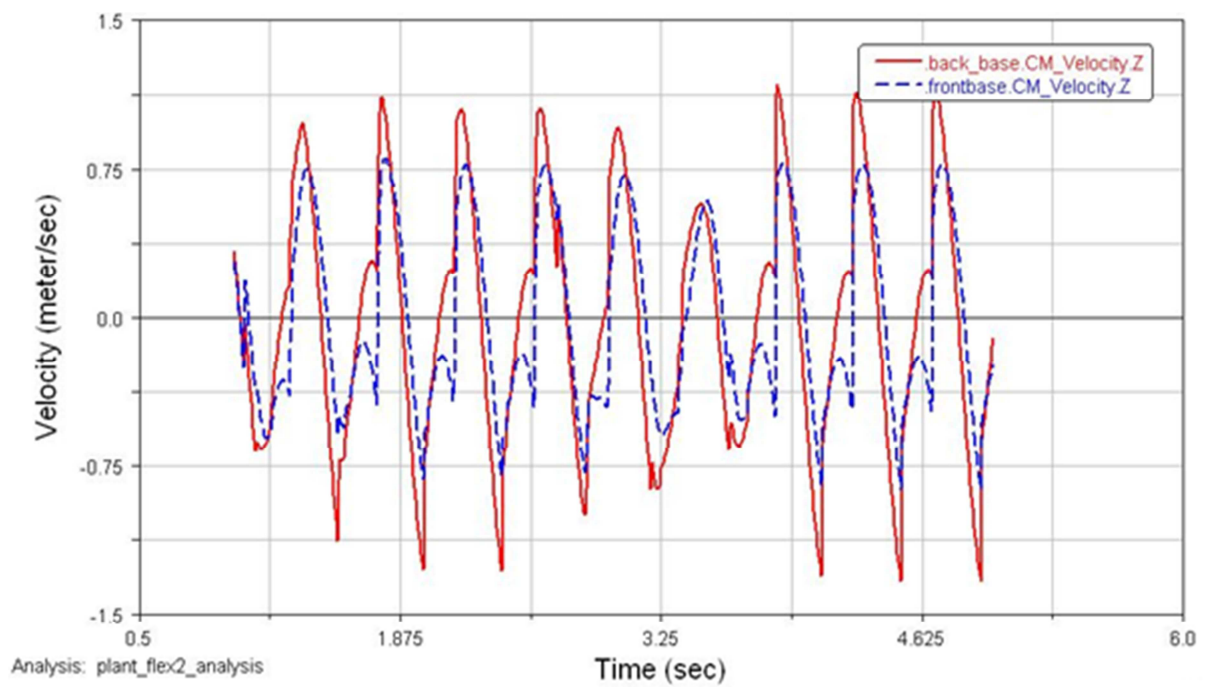


Fig. 13 Variation of Velocity for front body base and rear body base.

The simulation results are presented in Table 3. The parameters of stride length, hopping height, average speed and foot clearance were mentioned for both the flexible body quadruped robot and fixed body quadruped robot.

TABLE -III

COMPARISON OF FIXED AND FLEXIBLE BODY QUADRUPED ROBOT

Parameter	Fixed Body Quadruped	Flexible Body Quadruped
Stride length	0.58m	0.98m
Hopping height	0.68m	0.78m
Average Speed	1.7m/s	2.05m/s
Foot clearance	0.035m	0.16m

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, the forces acting on step climbing in bounding and trot gaits have been investigated in flexible body quadruped robot. Simulations were carried out on step climbing in 3D terrain quadruped robot locomotion with flexible body. This paper also includes the effect of body flexibility on stability and energy efficiency in walking mode, trot mode and running (bounding) mode on step climbing. The flexible body quadruped saves much energy compared to fixed body quadruped. The stride length, hopping height, average speed and foot clearance has increased with flexible body quadruped compared to fixed body quadruped robot. Hence flexible body provides higher speed and enhanced mobility. As future work, we wish to develop the prototype of flexible body quadruped robot that will validate the results obtained from this simulation.

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