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Analysis of Six-Legged Walking Robots

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Abstract

In the present paper, an attempt has been made to carryout kinematic and dynamic examination of a six-legged robot. A three-revolute (3R) kinematic chain has been chosen for each leg instrument with a particular ultimate objective to imitate the leg structure of a bug. Denavit–Hartenberg (D-H) conventions are used to perform kinematic examination of the six-legged robot. The prompt and invert kinematic examination for each leg has been considered remembering the ultimate objective to develop a general kinematic model of a six-legged robot, when it takes after a straight way. The issues related to heading time of legs have been settled for both the swing and support times of the robot. Specify that heading period issue in the midst of the support organize has been nitty gritty as a change issue and comprehended using the base squared method. Lagrange-Euler arrange has been utilized to choose the joint torques. The made kinematic and element models have been examined for tripod step time of the six-legged robot.

Keywords: *Kinematic analysis, Dynamic analysis, Tripod gait, Six-legged robot*

1 Introduction

A multi-legged robot has a huge potential for mobility over unpleasant territory, especially in contrast with customary wheeled or followed portable robot. It presents more adaptability and territory flexibility at the cost of low speed and expanded control many-sided quality [1]. Keeping in mind the end goal to create dynamic model and control calculation of legged robots, it is vital to have great models depicting the kinematic conduct of the complex multi-legged automated component. The component of a legged robot can be considered as an in part parallel instrument. Waldron et al. [2] dissected the kinematics of a half and half series–parallel control framework. In spite of the fact that the work on parallel components [3] frames a reason for legged-robot kinematic investigation, legged strolling robots vary from parallel instruments in some imperative regards. As Lee and Song [4] brought up, the kinematics of a mobile machine is confounded because of its numerous degrees of opportunity. Normally legs of strolling machines, amid strolling are lifted and put by a step, so that the topology of a mobile machine component changes. Promote, the control issue of a mobile machine is fundamentally more mind boggling than that of a parallel system in light of the fact that a mobile machine for the most part has more determined joints than that of a parallel controller. Howard et al. [5] examines the kinematics of a mobile machine utilizing vector and screw polynomial math. Barreto et al. [6] built up the free-body outline technique for kinematic and element displaying of a six-legged machine. Erden [7] researched the flow of a hexapod strolling robot in a level tripod stride in view of Newton-Euler detailing. Koo and Yoon [8] got a scientific model for quadruped strolling robot to examine the elements in the wake of considering all the inertial impacts in the framework. A dynamic model of strolling machine was determined by Lin and Song [9] to concentrate the dynamic solidness and vitality productivity amid strolling. Pfeiffer et al. [10] examined the elements of a stick bug strolling on level landscape. Freeman and Orin [11] built up a productive element reenactment of a quadruped utilizing a decoupled tree-structure approach. Because of the intricacy of a sensible strolling robot, it is not a simple assignment to incorporate the inertial terms in the displaying. The a large portion of the takes a shot at strolling progression were directed with a streamlined model of legs and body. In any case, keeping in mind the end goal to have a superior comprehension of strolling, elements and other essential issues of strolling, for example, dynamic strength, vitality proficiency and online control, kinematic and dynamic models in view of a practical strolling robot configuration are important. Here, an endeavor has been made to do kinematic and dynamic examination of a genuine six-legged robot.

2 Kinematics of Three Joint Leg

The kinematic and element investigation of strolling robot can be isolated into six primary parts. Given position, introduction, speed, increasing speed of the storage compartment body, introductory feet positions and walk design, compute the (i) joint relocations in view of reasonable foot direction, (ii) jointvelocities and (iii) joint increasing velocities, (iv) bolster feet strengths, and (vi) torques estimations of every joint amid exchange and bolster stages.

To derive the kinematic model, the following assumptions are made:

(a) The robot moves forward in a straight path on flat surface with alternating tripod gait.
(b) The trunk body is held at a constant height and parallel to the ground plane during locomotion.
(c) The center of gravity of the trunk body is assumed to be at the geometric center of the body.

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Fig. 1 demonstrates a 3-D model of a six-legged strolling robot considered in the present review. It comprises of a trunk of rectangular cross-area and six legs, which are comparative and deliberately dispersed around the storage compartment body on two sides. Every leg has three degrees of opportunity and is made out of three connections associated by the three turning joints. The Denavit-Hartenberg (D-H) documentations [12] have been utilized as a part of kinematic displaying of every leg (allude to Fig. 2).

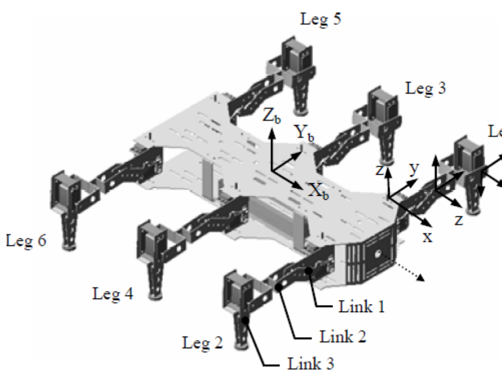
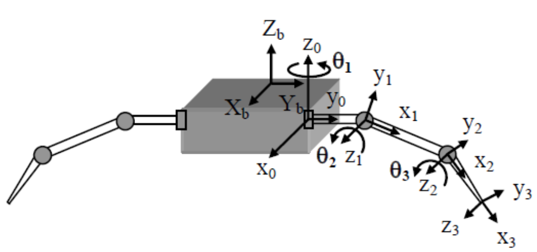


Fig. 1 CAD model of six-legged robot



Tables 1 and 2 show four D-H parameters, namely linklength (a_i), link twist (α_i), joint distance (d_i), and joint angle (θ_i), required to completely describe the three joint legs.

Table 1: D-H parameters for left legs

Link	a_i	α_i	d_i	θ_i
1	L_1	90°	0	θ_1
2	L_2	0	0	θ_2
3	L_3	0	0	θ_3

Table 2: D-H parameters for right legs

Link	a_i	α_i	d_i	θ_i
1	L_1	-90°	0	θ_1
2	L_2	0	0	θ_2
3	L_3	0	0	θ_3

The links' homogeneous transformation matrices have been presented as given below.

$$^{0}\mathbf{T}_1 = \begin{bmatrix} c\theta_1 & 0 & s\theta_1 & L_1 c\theta_1 \\ s\theta_1 & 0 & -c\theta_1 & L_1 s\theta_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}\mathbf{T}_2 = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & L_2 c\theta_2 \\ s\theta_2 & c\theta_2 & 0 & L_2 s\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{2}\mathbf{T}_3 = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & L_3 c\theta_3 \\ s\theta_3 & c\theta_3 & 0 & L_3 s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The resulting change grid between foot tip reference layout {3} and leg or hip reference plot {0} is given as:

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$$ {}^{0}\mathbf{T}_3 = {}^{0}\mathbf{T}_1\,{}^{1}\mathbf{T}_2\,{}^{2}\mathbf{T}_3 \qquad (1)$$

$$ {}^{0}\mathbf{T}_3 = \begin{bmatrix} c\theta_1 c(\theta_2+\theta_3) & -c\theta_1 s(\theta_2+\theta_3) & s\theta_1 & (L_1+L_2c\theta_2+L_3c(\theta_2+\theta_3))c\theta_1 \\ s\theta_1 c(\theta_2+\theta_3) & -s\theta_1 s(\theta_2+\theta_3) & -c\theta_1 & (L_1+L_2c\theta_2+L_3c(\theta_2+\theta_3))s\theta_1 \\ s(\theta_2+\theta_3) & c(\theta_2+\theta_3) & 0 & L_2s\theta_2+L_3s(\theta_2+\theta_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The six legs and the capacity compartment body must be facilitated to deal with the kinematic issue of the robot. Consider the body associated reference edge is arranged at the geometric point of convergence of the capacity compartment body. Leg "i" organizes in body reference packaging are gotten using change cross section as given underneath.

$$ {}^{b}\mathbf{T}_{0,i} = \begin{bmatrix} 1 & 0 & 0 & L_{xi} \\ 0 & 1 & 0 & L_{yi} \\ 0 & 0 & 1 & L_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The x, y and z bearings of the foot tip demonstrate with reverence leg reference diagram {0} can be settled for given the joint elements: θ1, θ2 and θ3. The position of the foot is given by the going with expressions:

$$[L_1+L_2\cos\theta_2+L_3\cos(\theta_2+\theta_3)]\cos\theta_1 = p_x \qquad (2)$$
$$[L_1+L_2\cos\theta_2+L_3\cos(\theta_2+\theta_3)]\sin\theta_1 = p_y \qquad (3)$$
$$L_2\sin\theta_2+L_3\sin(\theta_2+\theta_3) = p_z \qquad (4)$$

By unwinding conditions (2), (3) and (4), the joint edges : θ1, θ2 and θ3 have been settled as given underneath.

$$\theta_2=\mathrm{atan2}\left(c,\pm\sqrt{a^2+b^2-c^2}\right)-\mathrm{atan2}(a,b) \qquad (6)$$

$$\text{where } a=2L_2\left(\sqrt{p_x^2+p_y^2}-L_1\right);$$

$$b=2p_zL_2;\ c=\left[\left(\sqrt{p_x^2+p_y^2}-L_1\right)^2+p_z^2+L_2^2-L_3^2\right].$$

$$\theta_3=\cos^{-1}\left[\frac{\left(\sqrt{p_x^2+p_y^2}-L_1\right)^2+p_z^2-L_2^2-L_3^2}{2L_2L_3}\right] \qquad (7)$$

3 Foot Trajectory Planning

The robot is relied upon to depict a constant substituting tripod step (imply Fig. 3) that contains two standard stages. In the key stage, legs: 1, 4, and 5 are in support and moving backward at a foreordained trapezoidal speed profile, while legs: 2, 3, and 6 are in their swing stage, pushing ahead to their next reliable adjust. Each supporting foot tip takes after a straight-line bearing on the ground parallel to the heading of other supporting feet.

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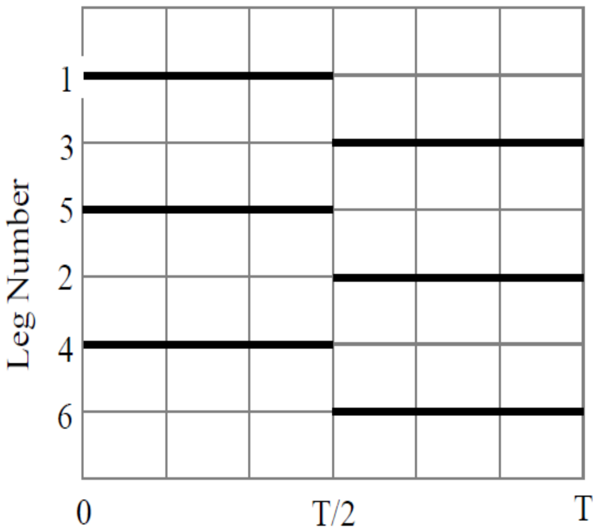

Fig. 3 Gait Diagram (duty factor=0.5)

3.1 Swing Foot Trajectory

To ensure a smooth working, each joint heading of swing legs is relied upon to take after a polynomial of fifth degree in time (t). In case θj is the edge of jth joint of a swing leg, fifth demand polynomial can be conveyed as takes after:

$$\theta j = a_{j0}+a_{j1}t+a_{j2}t^2+a_{j3}t^3+a_{j4}t^4+a_{j5}t^5, \quad (8)$$

where a_{j0}, a_{j1}, a_{j2}, a_{j3}, a_{j4}, and a_{j5} are coefficients, whose qualities are settled using a course of action of point of confinement conditions described over the swing stage and j=1, 2, 3 joints. θj is thought to be sure in counterclockwise direction.The restrain conditions of exact dislodging and dapper speed at starting, focus and last motivations behind the bearing are associated with find the six coefficients for each joint as showed up in Table 3.

Table-3: Coefficient values of joint trajectory

Joint no. (j)	Coefficient values					
	a_{j0}	a_{j1}	a_{j2}	a_{j3}	a_{j4}	a_{j5}
1	110	0	-2.667	-11.259	5.296	-0.790
2	-20.8	0	3.004	8.663	-6.777	1.185
3	-61.8	0	0.116	0.367	-0.283	0.0494

3.2 Support Foot Trajectory

Fig. 4 demonstrates the trapezoidal speed profile of point of convergence of mass of the capacity compartment body for each half cycle. The procedure term and most noteworthy speed of trunk body are thought to be proportional to 6 sec and 0.056 m/sec, independently.

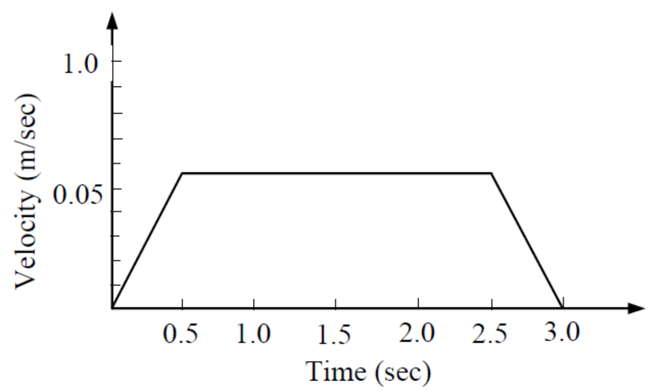

Fig. 4 Velocity profile of the trunk body of the robot

For smooth variety of the joint edges, their directions are accepted to take after the fifth request polynomial as demonstrated as follows.

$$\theta_j = c_{j0}+c_{j1}t+c_{j2}t^2+c_{j3}t^3+c_{j4}t^4+c_{j5}t^5, \quad (9)$$

where c_{j0}, c_{j1}, c_{j2}, c_{j3}, c_{j4}, and c_{j5} are the coefficients. It is to be seen that the half procedure length (3 sec) has been correspondingly secluded into thirty

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between times. The smallest squared procedure has been used to find six coefficients from thirty known estimations of θj. The enhanced coefficients are plot in Table 4.

Table-4: Optimized coefficient values of joint trajectory

Joint no. (j)	Coefficient values						
	c_{j0}	c_{j1}	c_{j2}	c_{j3}	c_{j4}	c_{j5}	c_{j6}
1	70.16	-2.66	28.82	-20.8	7.17	-0.95	0.0
2	-20.80	-0.24	3.19	-4.79	3.06	-0.91	0.10
3	-62.03	3.50	-33.19	39.92	-22.1	6.19	-0.69

4 Dynamics of Six-legged Robot

For deriving the dynamic conditions and finding joint torques' assortments over the movement cycle, Lagrange-Euler itemizing has been used. The quick utilization of Lagrangian components definition together with Denavit-Hartenberg's association orchestrate representation achieves a worthwhile, decreased, effective algorithmic portrayal of the states of development. A proficient enlistment of Lagrange-Euler conditions yields a dynamic expression that can be made in the vector-structure shape as given underneath.

$$\tau = M(\theta)\theta + H(\theta,\theta) + G(\theta) + J^T F, \qquad (10)$$

where M(θ) is the 3×3 lethargy system of the leg, H is a 3×1 vector of diffusive and Coriolis terms, G(θ) is a 3×1 vector of gravity terms, τ is the 3×1 vector of joint torques and F is the 3×1 vector of ground contact powers. In the midst of the leg's swing stage, there is no foot-scene correspondence, and F gets the chance to be particularly equal to zero. Regardless, in the midst of the support organize, ground contact exists and condition (10) gets the opportunity to be unmistakably undetermined. For handling footforce movements, the going with doubts are made:

(i) The ground legs are thought to support the capacity compartment body with no slippage on their tip focuses.

(ii) The contacts of the tip of the feet with ground can be shown as hard point contacts with friction, which demonstrates that the relationship between the tip of the leg and ground is limited to three sections of compel: one regular and two diverting to the surface.

Give us a chance to expect that Fpqr=[Fp, Fq, Fr]T is the footforce vector, when the legs: p, q and r are in bolster stage, where Fi=[fix, fiy, fiz]T is the ground-response constrain by walking i, where i=p, q, r. In the main period of tripod walk, p, q and r are the legs: 1, 4, and 5, individually, and amid the following stage, the legs: 2, 3, and 6 will be in the bolster stage. The torque W=[Fx, Fy, Fz, Mx, My, Mz]T contains the strengths (Fx, Fy, Fz) and minutes (Mx, My, Mz) following up on the robot's focal point of gravity and speaks to the robot's payload, including the impact of surface angle, any remotely connected powers and inertial impacts of the robot's body. Be that as it may, the inertial impacts of the legs have been fail to improve the review. Underthese conditions, six balance conditions that adjust strengths and minutes, when three legs, in particular p, q,and r are in their bolster stage, can be gotten as takes after:

$$\sum_{i=p,q,r} f_{ix} + F_x = 0$$

$$\sum_{i=p,q,r} f_{iy} + F_y = 0$$

$$\sum_{i=p,q,r} f_{iz} + F_z = 0$$

$$\sum_{i=p,q,r} y_i f_{iz} - \sum_{i=p,q,r} z_i f_{iy} + y_c F_z - z_c F_y + M_x = 0$$

$$\sum_{i=p,q,r} z_i f_{ix} - \sum_{i=p,q,r} x_i f_{iz} + z_c F_x - x_c F_z + M_y = 0$$

$$\sum_{i=p,q,r} x_i f_{iy} - \sum_{i=p,q,r} y_i f_{ix} + x_c F_y - y_c F_x + M_z = 0$$

These conditions are regularly composed in a grid shape as takes after:

$$\mathbf{A}_{pqr}.\mathbf{F}_{pqr} = (-\,\mathbf{B}.\mathbf{W}) \qquad (11)$$

where

$$\mathbf{A}_{pqr} = \begin{bmatrix} \mathbf{I}_3 & \mathbf{I}_3 & \mathbf{I}_3 \\ \mathbf{R}_p & \mathbf{R}_q & \mathbf{R}_r \end{bmatrix}; \text{ and } \mathbf{B} = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0}_3 \\ \mathbf{R}_c & \mathbf{I}_3 \end{bmatrix}$$

I3 is the (3×3) identity matrix, **0**3 is the (3×3) null matrix and **R**i is the (3×3) skew symmetric matrix of vector [xi,yi, zi]T.

$$\mathbf{R}_i = \begin{bmatrix} 0 & -z_i & y_i \\ z_i & 0 & -x_i \\ -y_i & x_i & 0 \end{bmatrix} \text{ and } \mathbf{I}_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

This matrix describes the position of tip of a foot i (i=p, q, r) or that of center of gravity (i=c) with respect to body reference layout. The bearings of ith foot-ground contact show with respect body reference diagram, arranged at the body's geometric concentration, are meant by (xi, yi, zi). With the known feet positions, the feet powers in the midst of a whole progress cycle can be figured using condition (11), which is unclear, since it contains six conditions however there are nine inquiries. The game plan of condition (11) has been procured using the base squared system.

5 Simulation Results

In this portion, diversion outcomes of the above numerical model have been discussed in detail. Table 5 shows the physical parameters of each leg of the sixlegged robot used as a piece of PC reenactments. The leg stroke of the tripod walk and body stature are thought to be proportional to 0.14 m and 0.13 m, separately. Fig. 5 exhibits the assignments of foot reaction forces of legs: 1, 4 and 6 in the midst of their support arrange over half movement cycle. It is to be seen that similar assignments of foot reaction forces of legs: 2, 3 and 5 in the midst of their reinforce organize over half movement cycle have been gotten. Furthermore, the front and back legs supplement each other in urge, with the true objective that entire of the vertical qualities of all the ground legs at any given snapshot of time gets the opportunity to be particularly identical to the greatness of the robot. It has been watched that the inside legs are subjected to most noteworthy drive of up to 19.7 N, while the most outrageous propel acting at corner legs are seen to be identical to 15.9 N. It has occurred thusly, as a result of the way that the foot urge depends on upon that leg's foot position in regard to center of mass of the capacity

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compartment. Joint torques are included three sections, specifically inertial term (M-term), spiral and Coriolis term (H-term) and gravity term (G-term).

Table- 5: Physical parameters of each leg

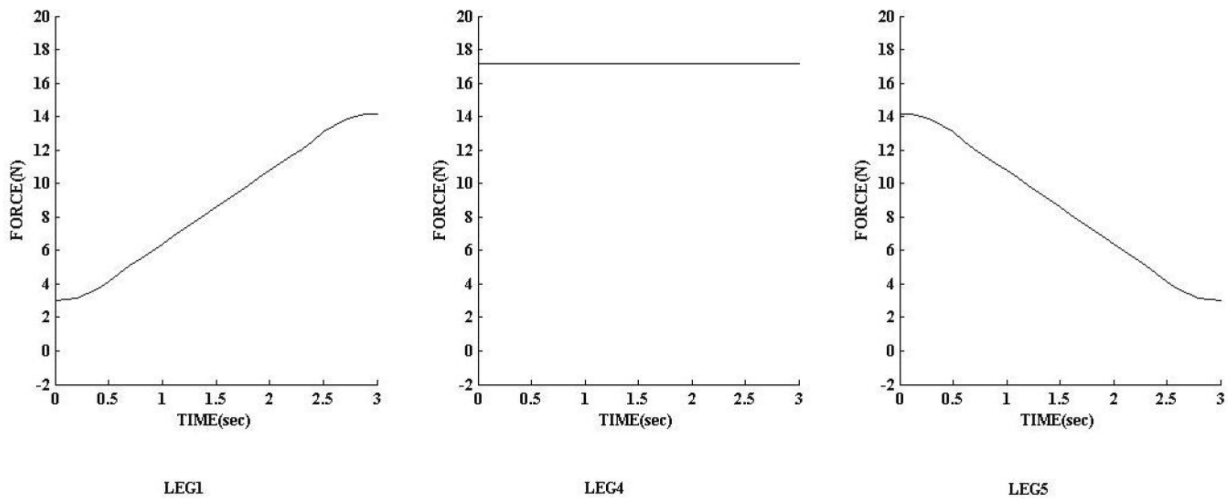

Fig. 5: Foot reaction forces for half cycle (when legs 1, 4 and 5 are on ground)

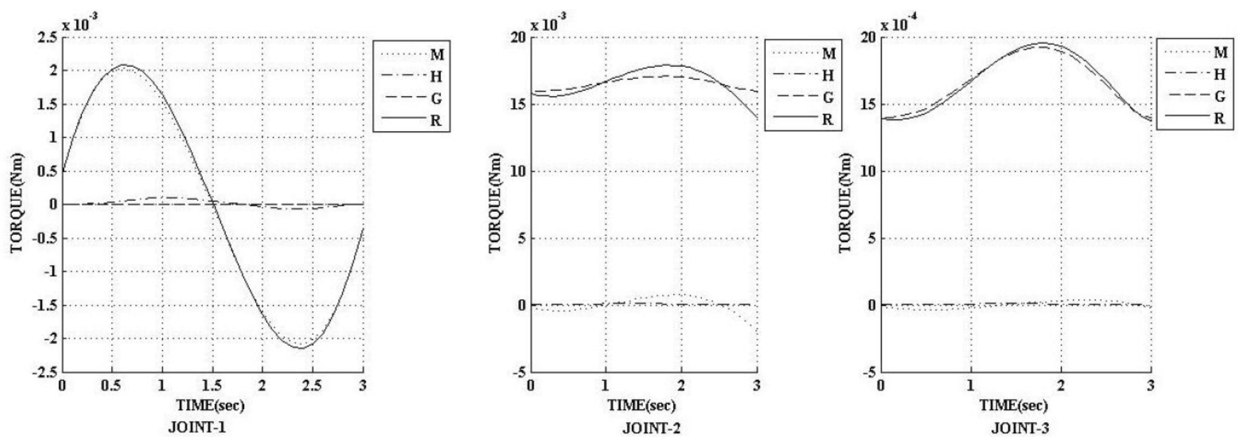

Fig. 6: Contribution of M, H and G terms on torques at joint 1, 2 and 3 during swing phase of left side legs

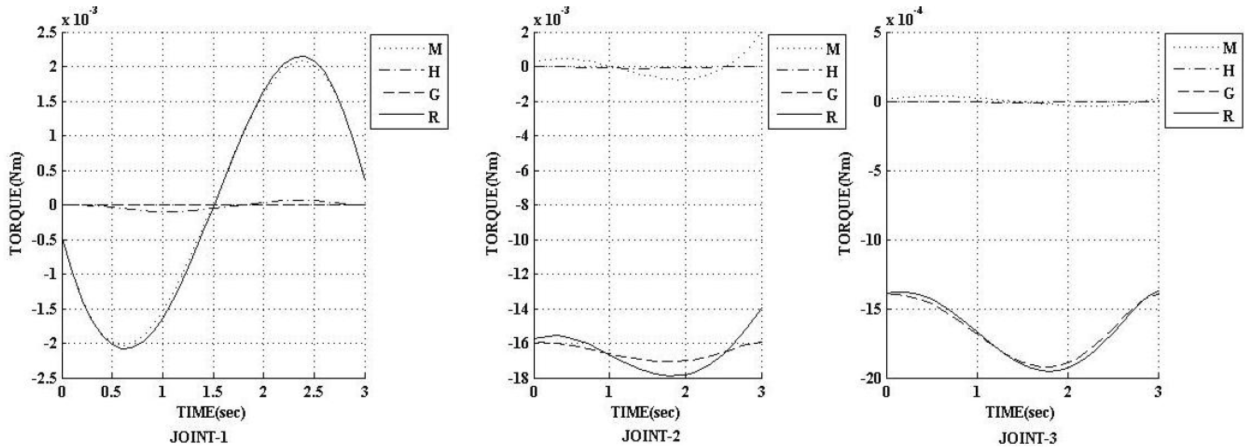

Fig. 7: Contribution of M, H and G terms on torques at joint 1, 2 and 3 during swing phase of right side legs

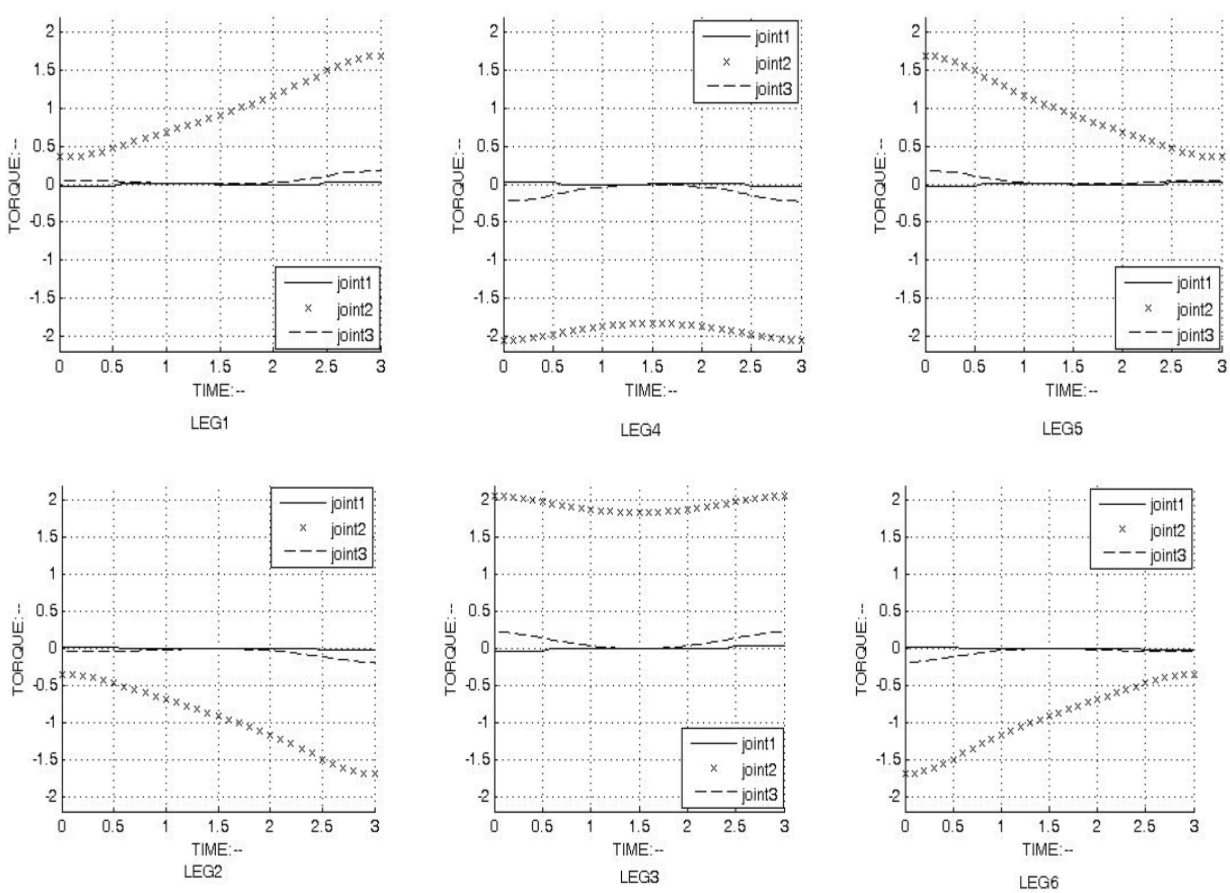

Fig. 8: Variations of joint torques of each leg during their support phase

Figs. 6 and 7 exhibit the duties of inaction, unique/Coriolis and gravity terms on torque of joints: 1, 2 and 3 in the midst of swing time of left side legs and right side legs, independently. Take note of that the gravity has recently irrelevant effect on torque of joint 1, on which the inaction has imperative duty. Torques of joints: 2 and 3 are essentially dependent on the gravity, and the effect of idleness and dissimilar/Coriolis terms are seen to be inconsequential. Fig. 8 addresses the assortments of joint torques in each joint of the legs in the midst of their reinforce arrange. It is captivating to note that for a particular ground leg, the most outrageous torque made at joint 2 is more appeared differently in relation to that at other two joints. The torque estimations of joint 2 contrast in the extent of 1.830 Nm to 2.055 Nm for the inside legs and those for various legs are accepted to lie in the extent of 0.35 Nm to 1.69 Nm. It is moreover interesting to note that the most outrageous torque required at joints: 1 and 3 of the significant number of legs is seen to be identical to 0.22 Nm. In this way, the best torque required at joint 2 evidently is around 8 to 9 times of that at various joints (to be particular joints: 1 and 3). Likewise, joint torques of the legs in the midst of the reinforce organize (suggest Fig. 8) have ended up being significantly more than those in the midst of the swing stage (as showed up in Figs. 6 and 7), obviously.

6 Conclusions

Both the kinematic and also dynamic breaks down of a sixlegged robot have been completed in the present review. The immediate and converse kinematic examination for every leg has been led with a specific end goal to build up the general kinematic model of a six-legged robot. The issues identified with direction era of legs have been explained for both the swing and bolster periods of the robot. Mention that direction arranging issue amid the bolster stage has been explained utilizing the slightest squared strategy. An endeavor has been made in present review to acquire ideal disseminations of feet powers. It has been watched that the center legs are subjected to more compel than corner legs. Joint torques have been computed utilizing Lagrange-Euler plan of the inflexible multi-body framework. The created kinematic and dynamic models have been inspected for tripod step era of the six-legged robot. This work can be reached out to handle the issues identified with tetrapod and non-intermittent stride of the strolling robot.

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