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Modeling and Simulation of Wave Gait of a Hexapod Walking Robot: A CAD/CAE Approach

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ABSTRACT

In the present paper, an attempt has been made to carry out dynamic analysis of a hexapod robot using the concept of multibody dynamics. A CAD (Computer Aided Design) model of a realistic hexapod robot has been made for dynamic simulation of its locomotion using ADAMS (Automatic Dynamic Analysis of Mechanical Systems) multibody dynamics solver. The kinematic model for each leg of three degrees of freedom has been designed using CATIA (Computer Aided Three Dimensional Interactive Application) and SimDesigner package in order to develop its overall model, when it follows a straight path. The variations of joint torque and aggregate center of mass of the robot were analyzed for the wave tetrapod gait. Simulation results provide the basis for developing the control algorithm and an intelligent decision making system for the robot, while in motion.

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1. INTRODUCTION

Walking robots are very complex mechatronics systems, where their multi-degrees of freedom legs are connected to one another through the trunk body. Moreover, a hexapod robot in motion, at any moment, is a complex combination of open and closed loop kinematic chains. The robot's legs that are in contact with the ground form closed loops with the trunk body and ground, whereas non-contacting legs represent individual, branching open loop kinematic chains. To design algorithms for the control of multilegged walking robots, it is important to have good models, which describe the dynamic behavior of the robot [1]. Several methods exist for open and closed chain simulation of legged robots. The algorithm of Rodriguez and Kreutz [2] used linear operator methods to derive simple forms of dynamic equations. Yet in another method, Lilly and Orin [3] treated a legged robot as a system of multiple manipulators (i.e. legs) contacting an object (i.e. trunk body), with ground contact modeled as a manipulator joint. However, both the models are approximate model of the complex legged robot. In order to design more efficient control algorithm for a six-legged robot, it is very much essential to develop more accurate dynamic model of the real legged robots. In this connection, work of Song and Waldron [1], Shih et al. [4], Pfeiffer et al. [5], Lin and Song [6], Kimura et al. [7], and Silva et al. [8-9] are important to mention. Barreto et al. [10] developed the free body diagram method for kinematic and dynamic modeling of a six-legged machine. Erden [11] investigated the dynamics of a hexapod walking robot in a level wave gait based on Newton-Euler formulation. Koo and Yoon [12] obtained a mathematical model for quadruped walking robot to investigate the dynamics after considering all the inertial effects in the system. Li et al. [13] developed a dynamic model and obtained a torque index to optimize the configuration of the legs and operation for consuming the minimum power. Many more analytical dynamic models had been developed by the previous researchers and most of them were derived based on Newton-Euler equation. Due to the complexity of a realistic walking robot, it is not an easy task to include the inertial terms in the modeling. Most of the studies on walking dynamics were conducted with a simplified model of legs and body as well as foot/ground interaction [14], [15]. Therefore, the developed dynamic models were far from actual dynamic behavior of the system. But, in order to have a better understanding of walking, dynamics and other important issues of walking, such as dynamic stability, energy efficiency and on-line control, kinematic and dynamic models based on a realistic walking robot design using the concept of virtual prototyping are necessary.

Here, an attempt has been made to develop a more accurate dynamic model of the hexapod robot using Lagrange-Euler formulation and simulate the CAD model of the real robot in ADAMS solver using the concept of rigid multibody dynamics and analyze its dynamic performance. The variations of the aggregate Center of Mass (CM) at any instant of time and joint torques for tetrapod gait walking on flat terrain have also been discussed.

2. MODELING OF THE HEXAPOD ROBOT

A CAD model of the hexapod robot is built in CATIA CAD/CAE software [16] as shown in Figure 1. The robot trunk body is 495mm in length, 205mm in width and 89mm in height and made of aluminium alloy (density= 2.7e-6 Kg/mm^3). The legs are identical and symmetrically distributed on either side of the trunk body. Each leg consists of three links, namely link i1 (coxa), link i2 (femur) and link i3 (tibia) with effective lengths 83.5mm, 119.34mm, 98.79mm respectively (i=1 to 6). All the joints are motorized rotary joints with rotational axis configuration Z-Y-Y (θ_{i1}-β_{i2}-β_{i3}) for the three joints respectively as shown in Figure 1. Total number of DOF of the system is 24 (6 DOF of the trunk body and 18 DOF of the legs). The robot consists of 19 main parts along with 18 servomotors. A flow-chart shown in Figure 2 shows the CAD/CAE approach undertaken in order to model and simulate the robot.

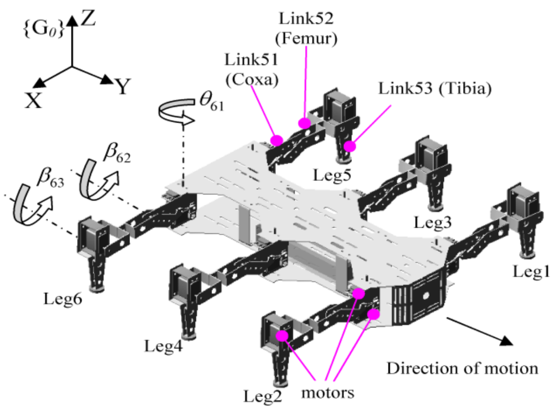

Figure 1. 3D CAD model of a hexapod robot

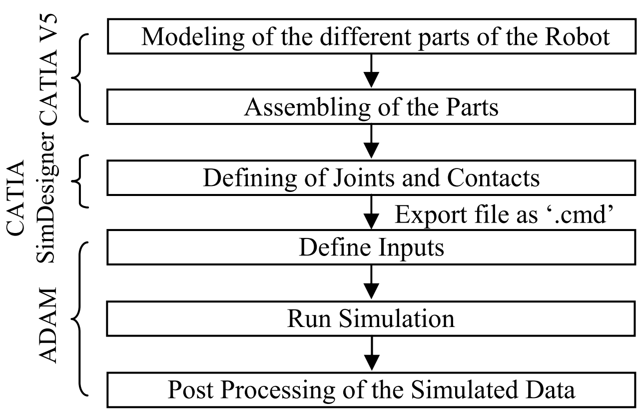

Figure 2. Flowchart for modeling and simulation of the

The kinematic and dynamic parameters of the robot obtained from CAD model are listed in Table 1.

Table 1. Kinematic and dynamic parameters of the robot

Parameters		Trunk body	Link i1 (i=1 to 6)	Linki 2 (i=1 to 6)	Link i3 (i=1 to 6)
Mass (Kg)		0.65	0.15	0.041	0.11
Mass Moment of Inertia (Kg-mm^2)	J_{0x}	16652.9	70.827	20.188	98.446
	J_{0y}	2518.5	108.377	86.698	87.515
	J_{0z}	16897.2	56.745	100.265	20.777
Length (mm)		495	83.50	119.34	98.79

Total mass of the six legged robot (including additional parts) = 3.08746 Kg.

In order to develop more accurate dynamic model, computer aided simulation tools based on rigid multibody dynamics called ADAMS has been used. A virtual prototype of the hexapod robot has been developed and simulated in ADAMS/Solver [17]. The following assumptions are made to simplify the rigid multibody dynamic analysis of robot.

(a) The robot moves forward in a straight path on flat surface with wave tetrapod gait.
(b) The trunk body is held at a constant height and parallel to the ground plane during locomotion.
(c) Swing legs are considered not to cross the supporting legs so that forthcoming support polygon is convex.

In the present work, following two aspects with respect to dynamic stability of tetrapod gait of the robot over perfectly flat terrain have been checked for, namely,

a. Variation of torque with stroke at each step
b. Variation of torque with cycle time at each step

The input motions for each of the rotary joints are defined through *Step Math Function* in ADAMS. As an example, the velocity input motion of leg 2 having stroke=0.14m and cycle time =2.4s is as shown in Figure 3. For all types of simulations, maximum variation of joint angle $\theta_{i1} = \pm 20^0, \beta_{i2} = 0^0$ to 6^0 & joint angle β_{i3} is kept constant at 90^0. Impact-based contact parameters have been defined between the legs and the ground to make the simulation more realistic (Figure 4).

The simulation is evaluated for 10s and 600 time steps to study at most three complete cycles. In the simulation, each time step represents an integration step in which the new positions, orientations, velocities and accelerations of the robot's body parts are computed based on the forces acting on them.

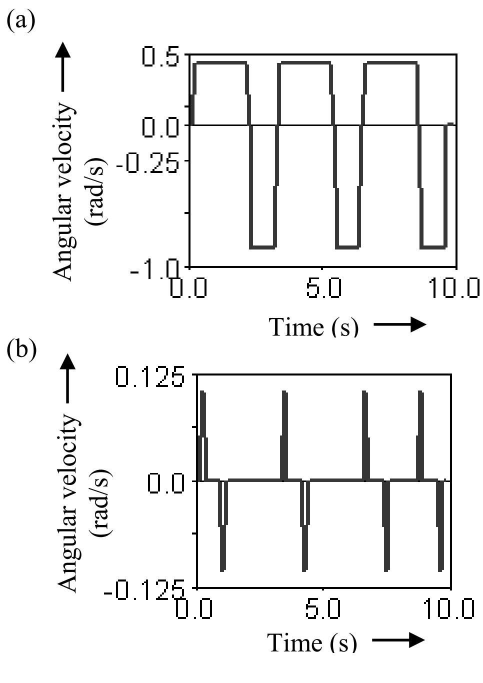

Figure 3. Velocity Step Functions for stroke = 0.14m, Cycle time=2.4s for the tetrapod gait (a) L_{21} (b) L_{22}

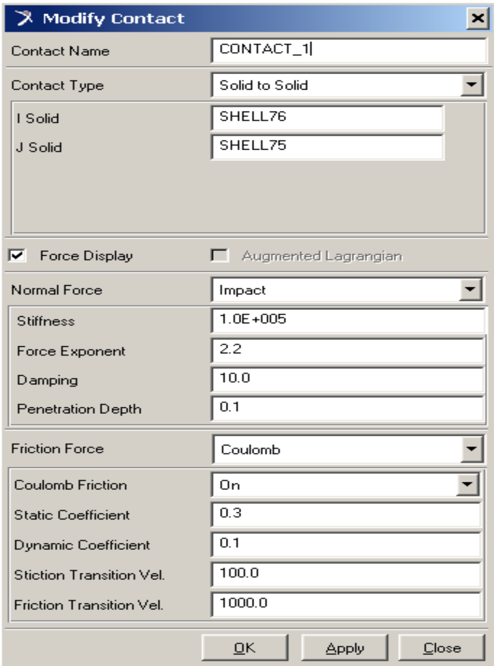

Figure 4. Contact parameters used during simulation

3. RESULTS AND DISCUSSION

Simulation of the six legged robot has been done to investigate the generation of statically stable gait patterns for various stroke and cycle time of the walking robot. In this section, the results of the aggregate CM and torque-distribution in the different joints of the links while the robot is in motion on a flat terrain are discussed.

3.1. Aggregate Center of Mass of the walking robot

To determine the position of the aggregate CM of the walking robot at any instant of time in order to check its dynamic stability is a very essential part of our investigation. The variation of aggregate CM is investigated in ADAMS using a user written subroutine. The user written subroutine centroid .cmd file is imported to the ADAMS workbench and the simulation is run.

For visualization of the variation of the aggregate CM at any instant of time, the user written subroutine AGG_CM_STATE_VARIABLE_IMPORT.cmd file is imported. Figure 5 shows that there is no such off bit path variation of the CM and the trace is more or less a straight line. Thus, the system is stable.

3.2. Joint Torques for Tetrapod Gait Walking on Flat Terrain

Dynamic simulation of the hexapod is done to study the torque requirement in the joints of the legs. The objective is to minimize the torque in the joints so as to make the drive more easily controllable. The torques at all the joints are calculated by varying the gait parameters. The torque required at the joints, to achieve system motion are simulated in ADAMS environment based on the virtual model in Figure 1 and dynamic torque equations as mentioned in APPENDIX A. The tetrapod gait is composed of the following sequences: i) legs 1-6 retracting, legs 2-3 protracting and legs 4-5 in the middle; ii) legs 1-6 protracting, legs 2-3 in the middle and legs 4-5 retracting iii) legs 1-6 in the middle, legs 2-3 retracting and legs 4-5 protracting. The walk is repeated for torque-distribution calculations. Figure 6 shows the torque distribution in the joints of all the links for two cycles (Duty factor= 2/3, Stroke=0.14m, Cycle time= 2.4s). In Figure 6, one can easily observe that for all the legs, the joint torques in retraction take significant values, while the joint torqueses in protraction are very less. Again, the torque in joint 1 seems to be higher than the torque in other joints. Since these are considered to be proportional to the average dissipated power on the motors, the motor selection has to be based on the maximum torque obtained from the simulation.

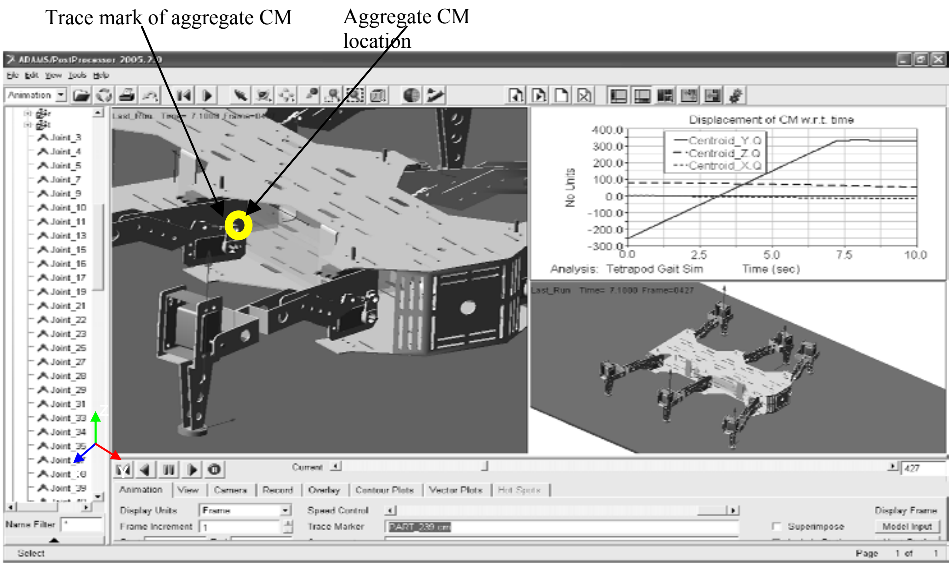

Figure 5. Aggregate CM variation of the hexapod robot during simulation

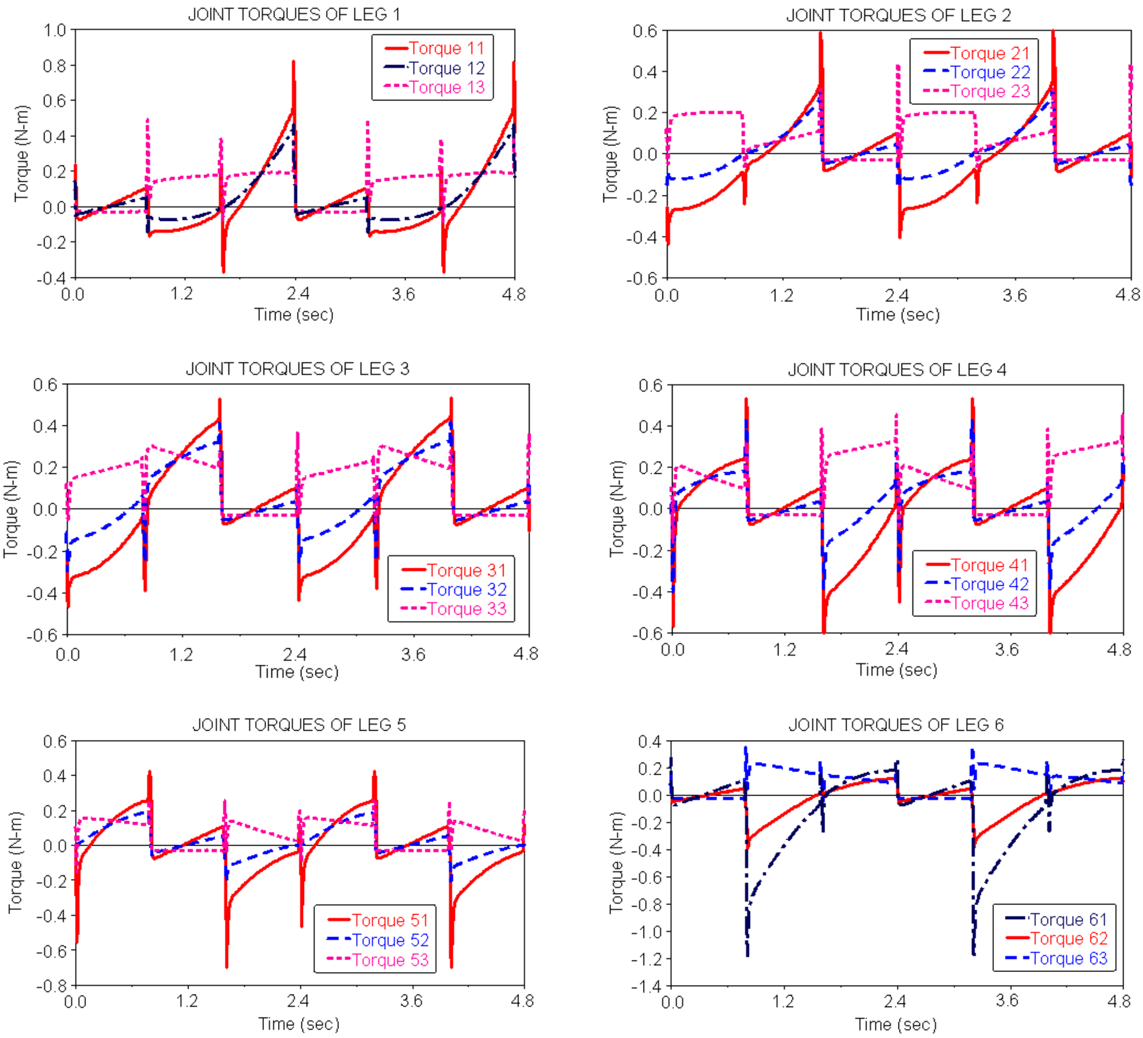

Figure 6. Variation of joint torques for tetrapod gait walking on flat terrain (Duty factor= 2/3, Stroke= 0.14m,

Cycle time= 2.4s)

4. CONCLUSION

A 3D virtual prototype of the robot system is created in CATIA V5 workbench and exported to ADAMS using CATIA SimDesigner and simulated in real time. The variations of aggregate CM of the system and torques at different joints have been studied. The results show that the torque required during retraction phase is much higher than that during protraction phase for all the joints. It is obvious that during the retraction phase, legs are carrying the weight of the trunk body, pay load. For most of the cases, torque in joint 1 is found to be higher than that of the other joints. So, the motor has to be selected based on the maximum torque. This work will allow further benchmarking of the mechanical event simulation of the six legged robot system, such as trajectory planning, kinematic workspace constraints and coordination issues with other system references etc. Future work will focus on the determination of relationships of energy efficiency with different gait patterns for different walking speeds.

Appendix A: Formulation of Mathematical Model of the Dynamic System

The Lagrange's equation of motion for unconstrained system in a matrix-vector form is:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{Q}_{nc}\,, \tag{1}$$

Where $\mathbf{M} \in \mathbf{R}^{24\times24}$ is the mass matrix of the robotic system, $\mathbf{h} \in \mathbf{R}^{24}$ is the force vector containing velocity dependent forces and gravitational forces, $\mathbf{Q}_{nc} \in \mathbf{R}^{24}$ is the non-conservative force/torque vector applied to the robot.

Due to foot contact with the ground for a constrained six-legged robotic system, one may use Lagrange Multipliers and write in the matrix-vector form as follows:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) - \mathbf{\Phi}_{\mathbf{q}}^{T}\lambda = \mathbf{Q}_{nc}\,, \tag{2}$$

Where λ is the vector of Lagrange multipliers, which is identical to the terrain reaction forces of the supporting feet , and $\mathbf{\Phi}_{\mathbf{q}} \in \mathbf{R}^{3n_g\times24}$ is the constraint Jacobian matrix, n_g is the number of feet grounded.

The acceleration constraint equation can be written as follows:

$$\mathbf{\Phi}_{\mathbf{q}}\ddot{\mathbf{q}} - \boldsymbol{\gamma}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{0}\,, \tag{3}$$

Where $\boldsymbol{\gamma} \in \mathbf{R}^{3n_g}$ is the velocity dependent acceleration vector containing the Centripetal and Coriolis accelerations. The constrained equations of motion of the whole system can be written in vector-matrix form as follows:

$$\begin{bmatrix} \mathbf{M} & \mathbf{\Phi}_{\mathbf{q}}^{T} \\ \mathbf{\Phi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}} \\ -\boldsymbol{\lambda} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q}_{nc} - \mathbf{h} \\ \boldsymbol{\gamma} \end{Bmatrix} \tag{4}$$

The colliding phenomena will occur, when the foot strikes the ground. Assuming that the ideally plastic impact occurs between the colliding foot and the ground surface instantaneously, the collision has been modeled as the occurrence of instantaneous velocity change. Here, the ideally plastic impact means that the tip velocity of the colliding foot has been vanished right after the foot strike. Then from Lagrange's impulse equation for a kinematically constrained system with the assumption of ideally plastic input, a differential-algebraic equation is obtained in the following form:

$$\begin{bmatrix} \mathbf{M} & {}^{g}\mathbf{\Phi}_{q}^{T} & {}^{c}\mathbf{\Phi}_{q}^{T} \\ {}^{g}\mathbf{\Phi}_{q} & 0 & 0 \\ {}^{c}\mathbf{\Phi}_{q} & 0 & 0 \end{bmatrix} \begin{Bmatrix} \nabla\dot{q} \\ \lambda^{g} \\ \lambda^{c} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ -\mathbf{v}^{c} \end{Bmatrix}, \tag{5}$$

Where n_c is the number of colliding feet having velocity vector $\mathbf{v}^c \in \mathbf{R}^{3n_c}$, ${}^g\mathbf{\Phi}_q \in \mathbf{R}^{3n_g \times 24}$ and $\lambda^g \in \mathbf{R}^{3n_g}$ are the Jacobian matrices and the impact force vectors of the originally contacted feet respectively, whereas ${}^c\mathbf{\Phi}_q \in \mathbf{R}^{3n_c \times 24}$ and $\lambda^c \in \mathbf{R}^{3n_c}$ are the Jacobian matrices and the impact force vectors of the colliding feet, respectively. The instantaneous change of velocity due to the collision of feet is determined as $\dot{q}^+ = \dot{q}^- + \Delta\dot{q}$, where the superscripts – and + represent the quantities right before and after the collision, respectively.

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