Dynamic Modeling and Energy Consumption Analysis of Crab Walking of a Six-legged Robot

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Introduction and Objective of the Work

The superior terrain adaptability and maneuverability characteristics of multi-legged robots compared to wheeled or tracked vehicles for off-road locomotion motivated the development of six-legged walking robots [1]. Six-legged robot might be used for locating and disarming bombs, extinguishing fires, underground mining to recover natural resources, explorations of ocean floors and planets, and others, where a human cannot sustain or which would be dangerous for him/her. However, with today's technologies, the legged systems have the disadvantages of pay load to weight ratio, and poor energy efficiency. An autonomous walking robot cannot function satisfactorily with a poor energy efficiency, due to the fact that it has to carry all driving and control units in addition to payload and trunk body. Long duration missions are also subjected to power supply constraints. The minimization of energy consumption plays a key role in the design of an autonomous multi-legged robot. Various approaches are available in the literature to obtain energy-efficient gaits of multi-legged robots [2-8]. The previous work focused on walking along straight-forward path only. Moreover, most of the studies on walking robot dynamics were conducted with simplified models of legs and body. But, in order to have a better understanding of its walking, dynamics and other important issues of walking, such as dynamic stability, energy efficiency and its on-line control; kinematics and dynamic models based on a realistic walking robot design are necessary to build. During locomotion of a multi-legged robot on flat terrain, different types of gaits, namely straight forward gait, crab gaits and turning gaits etc. have to be used to avoid obstacles in its path. Out of many possible gait patterns, the present study concentrates on dynamic modeling and energy efficiency analysis of crab gaits, as crab walking is very important to an omni-directional locomotion. To the best of the authors' knowledge, no significant study has been reported on dynamic modeling and energy efficiency analysis of crab walking of a realistic six-legged robot.

In the present study, an attempt has been made to derive a detailed model based on both a dynamic model of mechanical systems and an actuator model, for crab walking of six-legged robot. An attempt is also made to study the effects of gait parameters on energy consumption of a realistic six-legged robot.

Mathematical Formulation and Results

In order to develop the detailed dynamic and energy consumption model of a six-legged robot while negotiating crab walking on flat terrain, the following assumptions are made:

(a) The trunk body moves at a constant velocity along a straight line, which makes a constant angle (called crab angle, α) with the longitudinal axis of the trunk body.

(b) The robot is assumed to describe a wave-crab gaits with two duty factors equal to 1/2 (tripod gait) and 2/3 (tetrapod gait).

(c) The trunk body is kept at a constant height from the level ground during locomotion.

(d) The joint actuators are DC geared motors, which cannot store negative energy. Therefore, any negative energy, i.e., gain in energy supplied by external forces, is lost.

Fig. 1 shows a 3-D model of a six-legged walking robot considered in the present study. Denavit-Hartenberg (D-H) notations have been used in kinematic modeling of each leg.

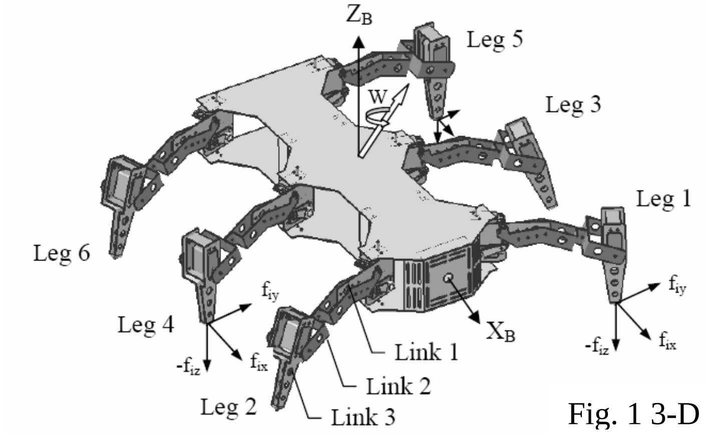

Fig. 1 3-D model of a six-legged robot

For deriving the dynamic equations and finding joint torques' variations over the locomotion cycle, Lagrange-Euler formulation has been used. A systematic derivation of Lagrange-Euler equations yields a dynamic expression that can be written in the vector-matrix form as given below.

$$\boldsymbol{\tau}_{\mathbf{i}} = [\mathbf{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{H}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \mathbf{G}(\boldsymbol{\theta})]_{\mathbf{i}} - \mathbf{J}_{\mathbf{i}}^{\mathbf{T}} \mathbf{F}_{\mathbf{i}} , \qquad (1)$$

where $M(\theta)$ is the 3×3 mass matrix of the leg, H is a 3×1 vector of centrifugal and Coriolis terms, $G(\theta)$ is a 3×1 vector of gravity terms, τ_i is the 3×1 vector of joint torques and F_i is the 3×1 vector of ground reaction forces of foot 'i'. During the leg's swing phase, there is no foot-terrain interaction, and F_i becomes equal to zero. However, during the support phase, ground contact exists and equation (1) becomes undetermined, which has to be solved using an optimization criterion, e.g., minimization of norm of foot forces (approach 1) and minimization of norm of joint torques (approach 2).

In this simulation, crab angle and body height are assumed to be equal to 20^0 and 0.13 m, respectively. Table I shows the average values of the squares of joint torques of the robot negotiating crab walking with tripod and tetrapod gaits, as obtained by approaches 1 and 2. Simulation results indicate that the average of the squares of joint torques during one complete locomotion cycle for tripod gait has turned out to be higher than that of tetrapod gait for both the approaches.

TABLE I
Average values of the Squares of Joint Torques versus Duty Factor

Duty factor (β)	Average of the squares of joint torques $(\text{N-m})^2$	
	Approach 1	Approach 2
1/2	3.9733	2.03943
2/3	2.7582	1.51999

Crab angle=20°, Velocity = 0.02m/sec, Stroke = 0.1m, Height of trunk body = 0.13 m

The average value of the squares of joint torques of the robot as obtained by approach 1 is seen to be higher than that yielded by approach 2 for both tripod and tetrapod gaits. Since the average of the squares of joint torques is considered to be proportional to average dissipated power (average heat loss) of the joint motor, it can be concluded that approach 2 is more energy efficient than approach 1. This happens due to forces required to support the body is distributed more evenly among the legs, in case of tetrapod gait than tripod gait and thereby, the contribution (in terms of torque and power) of each support leg is reduced.

The effects of velocity on average power consumption over one locomotion cycle of the robot for two different duty factors are displayed in Table II. For a particular value of duty factor, average power consumption is found to increase with the increase in velocity, as expected. Thus, the velocity should be as low as possible to minimize power consumption for a particular duty factor. However, traveling with a low velocity takes more time to cover a fixed distance, and consequently, total energy consumption may be increased. The energy required to travel a fixed distance can be quantified using a parameter called specific resistance, that is, energy consumed per unit weight and per unit traveled length. Table III displays the effects of variation of velocity on specific resistance during crab walking over a flat terrain. Specific resistance is found to decrease with the increase of velocity for a particular value of duty factor.

TABLE II
Average Power Consumption versus Velocity

Velocity, V_α (m/sec)	Average power consumption (in Watts)			
	Tripod gait (β=1/2)		Tetrapod gait (β=2/3)	
	Approach 1	Approach 2	Approach 1	Approach 2
0.020	0.2704	0.2229	0.2071	0.1999
0.025	0.2875	0.2521	0.2309	0.2246
0.030	0.3049	0.2817	0.2622	0.2424
0.035	0.3227	0.3115	0.2937	0.2606
0.040	0.3414	0.3407	0.3256	0.2791
0.045	0.3715	0.3590	0.3577	0.2980
0.050	0.4018	0.3774	0.3901	0.3173

Crab angle=20°, Stroke = 0.1m, Height of trunk body = 0.13 m

TABLE III
Specific Resistance versus Velocity

Velocity, V_α (m/sec)	Specific resistance			
	Tripod gait (β=1/2)		Tetrapod gait (β=2/3)	
	Approach 1	Approach 2	Approach 1	Approach 2
0.020	0.3937	0.3246	0.3016	0.2911
0.025	0.3349	0.2937	0.2690	0.2617
0.030	0.2960	0.2735	0.2545	0.2354
0.035	0.2685	0.2592	0.2444	0.2169
0.040	0.2486	0.2481	0.2370	0.2033
0.045	0.2405	0.2323	0.2315	0.1929
0.050	0.2341	0.2198	0.2272	0.1848

Crab angle=20°, Stroke = 0.1m, Height of trunk body = 0.13 m

Approach 2 is seen to yield more efficient gaits compared to approach 1 for both tripod and tetrapod gaits. Results related to the effects of stroke on average power consumption and specific resistance during crab walking of the robot with wave gaits of two different duty factors are presented in Tables IV and V, respectively.

TABLE IV
Average Power Consumption versus Stroke

Stroke, R_α (m)	Average power consumption (in Watts)			
	Tripod gait (β=1/2)		Tetrapod gait (β=2/3)	
	Approach 1	Approach 2	Approach 1	Approach 2
0.120	0.2875	0.2468	0.2212	0.2167
0.115	0.2821	0.2398	0.2169	0.2117
0.110	0.2776	0.2337	0.2132	0.2074
0.105	0.2738	0.2281	0.2100	0.2034
0.100	0.2704	0.2229	0.2071	0.1999
0.095	0.2674	0.2180	0.2045	0.1967
0.090	0.2647	0.2134	0.2022	0.1937
0.085	0.2624	0.2090	0.2001	0.1909
0.080	0.2604	0.2048	0.1982	0.1882

Crab angle=20°, Velocity = 0.02m/sec, Height of trunk body = 0.13 m

TABLE V
Specific Resistance versus Stroke

Stroke, R_α (m)	Specific resistance			
	Tripod gait (β=1/2)		Tetrapod gait (β=2/3)	
	Approach 1	Approach 2	Approach 1	Approach 2
0.120	0.4186	0.3593	0.3221	0.3156
0.115	0.4109	0.3493	0.3158	0.3083
0.110	0.4043	0.3403	0.3105	0.302
0.105	0.3987	0.3322	0.3058	0.2963
0.100	0.3937	0.3246	0.3016	0.2911
0.095	0.3894	0.3175	0.2978	0.2864
0.090	0.3855	0.3108	0.2945	0.282
0.085	0.3821	0.3044	0.2914	0.2779
0.080	0.3792	0.2983	0.2886	0.2741

Crab angle=20°, Velocity = 0.02m/sec, Height of trunk body = 0.13 m

For a given velocity, both average power consumption and specific resistance are found to increase with stroke for both tripod and tetrapod gaits. Moreover, for a particular stroke, average power consumption and specific resistance are seen to be higher for tripod gait than that of tetrapod gait for both approaches 1 and 2. It is interesting to observe that approach 2 has provided more energy efficient solutions compared to approach 1 for all strokes. Tetrapod gaits are found to be more energy-efficient compared to that of tripod gaits. Moreover, in order to minimize total energy consumption, the velocity should be as high as possible and stroke should be as low as possible, but without violating dynamic constraints of the joint motors.

References

[1] S. M. Song, and K. J. Waldron, *Machines That Walk: The Adaptive Suspension Vehicle*. The MIT Press, Cambridge, Massachusetts, USA, 1989.

[2] V. V. Lapshin, "Energy consumption of a walking machine: model estimations and optimization," in *Proc. 7th Conf. Advanced Robotics*, San Feliu de Guixols, 1995, pp. 420-425.

[3] M. A. Nahon, and J. Angeles, "Minimization of power losses in cooperating manipulators," *ASME Journal of Dynamic, Systems, Measurement and Control*, vol. 114, pp. 213-219, 1992.

[4] D. W. Marhefka, and D. E. Orin, "Quadratic optimization of force distribution in walking machines," in *Proc. IEEE Int. Conf. Robotics and Automation*, Belgium, 1998, pp. 477–483.

[5] D. C. Kar, K. K. Issac and K. Jayarajan, "Minimum energy force distribution for a walking robot," *Journal of Robotic Systems*, vol. 18, no. 2, pp. 47–54, 2001.

[6] B. S. Lin, and S. M. Song, "Dynamic modeling, stability and energy efficiency of a quadrupedal walking machine," *Journal of Robotic Systems*, vol. 18, no. 11, pp. 657–670, 2001.

[7] J. Nishii, "Gait pattern and energetic cost in hexapods," in *Proc. 20th Annu. Int. Conf. IEEE Engineering in Medicine and Biology Society*, 20, 1998, pp. 2430–2433.

[8] T. Zelinska, "Efficiency analysis in the design of walking machine," *J. Theor. Appl. Mech.*, vol. 38, pp. 693-708, 2000.