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Gait Efficiency of Walking Robots

Manuel F. Silva, J. A. Tenreiro Machado
Dept. of Electrical Engineering
Institute of Engineering of Porto
Rua Dr. Antonio Bernardino de Almeida,
4200-072 Porto, Portugal
{mfsilva,jtm}@dee.isep.ipp.pt

António M. Lopes
Dept. of Mechanical Engineering
Faculty of Engineering of Porto
Rua Dr. Roberto Frias,
4200-465 Porto, Portugal
aml@fe.up.pt

Abstract - **This paper studies periodic gaits of multi-legged robot locomotion systems based on dynamic models. The purpose is to determine the system performance during walking and the best set of locomotion variables. For that objective the prescribed motion of the robot is completely characterized in terms of several locomotion variables such as gait, duty factor, body height, step length, stroke pitch, foot clearance, legs link lengths, foot-hip offset, body and legs mass and cycle time. In this perspective, we formulate three performance measures of the walking robot namely, the mean absolute power, the mean power lost in the joint actuators and the mean force of the interface body-legs per walking distance. A set of model-based experiments reveals the influence of the locomotion variables in the proposed indices.**

I. INTRODUCTION

Walking machines allow locomotion in terrain inaccessible to other type of vehicles, since they do not need a continuous support surface [1]. On the other hand, the requirements for leg coordination and control impose difficulties beyond those encountered in wheeled robots [2]. Gait selection is a research area requiring an appreciable modeling effort for the improvement of mobility with legs in unstructured environments [3, 4]. Previous studies mainly focused in the structure and selection of locomotion modes [5, 6]. Nevertheless, there are different optimization criteria such as energy efficiency, stability, velocity, comfort, mobility and environmental impact [7–13]. With these facts in mind, a simulation model for multi-leg locomotion systems was developed, for several periodic gaits. This study intends to generalize previous work [14, 15] through the formulation of several dynamic indices measuring the average power during different walking trajectories, the power lost in the joint actuators and the mean force acting on the hips along the space-time walking cycle.

The foot and body trajectories are analyzed in what concerns its variation with the gait, duty factor, step length, maximum foot clearance, body height, legs link lengths and foot trajectory offset. Several simulation experiments reveal the system configuration and the type of the movements that lead to a better mechanical implementation, for a given locomotion mode, from the viewpoint of the proposed indices.

Bearing these facts in mind, the paper is organized as follows. Section two introduces the model for a multi-legged robot and the motion planning algorithms. Section three formulates the optimizing indices and section four develops a set of experiments that reveal the influence of the system parameters in the periodic gaits, respectively. Finally, section five presents the main conclusions and directions towards future developments.

II. A MODEL FOR MULTI-LEGGED LOCOMOTION

We consider a longitudinal walking system with n legs ($n \geq 2$ and n even), with the legs equally distributed along both sides of the robot body, having each one two rotational joints (Fig. 1).

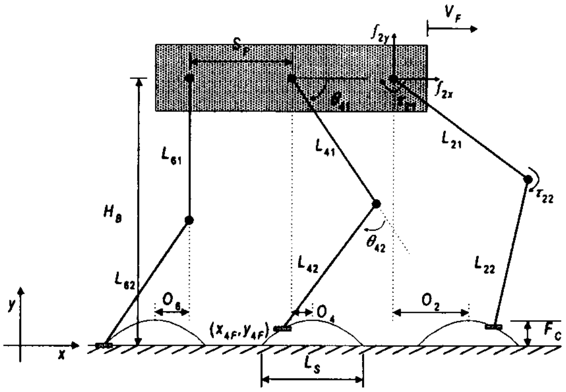

Fig. 1. Coordinate system and variables that characterize the motion trajectories of the multi-legged robot

Motion is described by means of a world coordinate system. The kinematic model comprises: the cycle time T, the duty factor β, the transference time $t_T = (1-\beta)T$, the support time $t_S = \beta T$, the step length L_S, the stroke pitch S_P, the body height H_B, the maximum foot clearance F_C, the i^{th} leg lengths L_{i1} and L_{i2} and the foot trajectory offset O_i ($i=1,\ldots,n$). Moreover, we consider a periodic trajectory for each foot, with body velocity $V_F = L_S / T$.

The algorithm for the forward motion planning accepts the body and i^{th} feet cartesian trajectories $\mathbf{p}_F(t) = [x_{iF}(t), y_{iF}(t)]^T$ as inputs and, by means of an inverse kinematics algorithm, generates the related joint trajectories $\boldsymbol{\theta}(t) = [\theta_{i1}(t), \theta_{i2}(t)]^T$, selecting the solution corresponding to a forward knee.

The body of the robot, and by consequence the legs hips, are assumed to have a horizontal movement with a constant forward speed V_F. Therefore, for leg i the cartesian coordinates of the hip of the legs are given by:

$$\mathbf{p_H}(t)=\begin{bmatrix} x_{iH}(t) \\ y_{iH}(t) \end{bmatrix}=\begin{bmatrix} V_F \cdot t \\ H_B \end{bmatrix}, \tag{1}$$

Given a particular gait and duty factor β, it is possible to calculate for leg i the corresponding phase ϕ_i and the time instant where each leg leaves and returns to contact with the ground [2]. From these results, and knowing T, β and t_S, the cartesian trajectories of the tip of the foots must be completed during t_T.

For each cycle the trajectory of the tip of the swing leg is computed through a cycloid function given by (considering, for example, that the transfer phase starts at $t = 0$ sec for leg 1), with $f = 1/T$:

- during the transfer phase:

$$x_{1F}(t) = V_F\left[t - \frac{1}{2\pi f}\sin(2\pi f t)\right] \tag{2a}$$

$$y_{1F}(t) = \frac{F_C}{2}\left[1 - \cos(2\pi f t)\right] \tag{2b}$$

- during the stance phase:

$$x_{1F}(t) = V_F \cdot T \tag{3a}$$

$$y_{1F}(t) = 0 \tag{3b}$$

From the coordinates of the hip and feet of the robot it is possible to obtain the leg joint positions and velocities using the inverse kinematics:

$$\mathbf{p}(t)=\begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix}=\mathbf{p_H}(t)-\mathbf{p_F}(t) \tag{4a}$$

$$\boldsymbol{\theta}(t) = f[\mathbf{p}(t)] \tag{4b}$$

$$\dot{\boldsymbol{\theta}}(t) = \mathbf{J}^{-1}[\dot{\mathbf{p}}(t)] \tag{4c}$$

Based on this data, the trajectory generator is responsible for producing a motion that synchronises and co-ordinates the legs. In order to avoid the impact and friction effects we impose null velocities of the feet in the instants of landing and taking off, assuring also the velocity continuity. These joint trajectories can also be accomplished either with a step or a polynomial versus time acceleration profile. After planning the joint trajectories we calculate the inverse dynamics in order to 'map' the kinematics into power consumption. The robot inverse dynamic model is:

$$\boldsymbol{\tau} = \mathbf{H}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{c}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \mathbf{g}(\boldsymbol{\theta}) \tag{5}$$

where $\boldsymbol{\tau} = [f_{ix}, f_{iy}, \tau_{i1}, \tau_{i2}]^T$ ($i=1,\ldots,n$) is the vector of forces/torques, $\boldsymbol{\theta} = [x_i, y_i, \theta_{i1}, \theta_{i2}]^T$ is the vector of position coordinates, $\mathbf{H}(\boldsymbol{\theta})$ is the inertia matrix and $\mathbf{c}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$ and $\mathbf{g}(\boldsymbol{\theta})$ are the vectors of centrifugal/Coriolis and gravitational forces/torques, respectively.

III. Measures for Performance Evaluation

In mathematical terms, we provide three global measures of the overall performance of the mechanism in an average sense.

A. Mean Absolute Power

The key measure in this analysis is the mean absolute power per travelling distance. It is computed assuming that power regeneration is not available by actuators doing negative work, that is, by taking the absolute value of the power. At a given joint j (each leg has $m = 2$ joints) and leg i (since we are adopting an hexapod it yields $n = 6$ legs), the mechanical power is the product of the motor torque and angular velocity. The global index is obtained by averaging the mechanical absolute power delivered over a period T and a step L_S:

$$P_{av} = \frac{1}{L_S}\cdot\frac{1}{T}\sum_{i=1}^{n}\sum_{j=1}^{m}\int_0^T\left|\boldsymbol{\tau}_{ij}(t)\cdot\dot{\boldsymbol{\theta}}_{ij}(t)\right|dt \tag{7}$$

The average of the absolute power consumption, per travelling distance, P_{av}, should be minimised.

B. Mean Power Lost

Another optimisation strategy for an actuated system considers the power lost in the joint actuators per cycle T and step length L_S. From this point of view, the index mean power lost per meter can be defined as:

$$P_L = \frac{1}{L_S}\cdot\frac{1}{T}\sum_{i=1}^{n}\sum_{j=1}^{m}\int_0^T\left[\boldsymbol{\tau}_{ij}(t)\right]^2 dt \tag{8}$$

The most suitable trajectory is the one that minimizes P_L.

C. Mean Force at the Interface Body-Legs

A third possible optimisation strategy considers the forces that occur on the hips of the robot per cycle T and step length L_S. The index mean force on the hips per meter is defined as:

$$F_L = \frac{1}{L_S}\cdot\frac{1}{T}\sum_{i=1}^{n}\sum_{j=1}^{m}\int_0^T\left\{[f_{ix}(t)]^2 + [f_{iy}(t)]^2\right\}dt \tag{9}$$

The best trajectory is the one that minimizes F_L.

IV. Simulation Results

To illustrate the use of the preceding concepts, in this section we develop a set of simulation experiments to estimate the influence of several parameters during periodic gaits and to compare the performance measures. Consequently, the multi-legged locomotion was simulated, in order to examine the role of the walking gait versus β, L_S, H_B and F_C, with $V_F = 1$ m/s, $S_P = 1$ m, $L_{i1} = L_{i2} = 1$ m, $O_i = 0$ m, $M_{i1} = M_{i2} = 1$ Kg, $M_b = 36$ Kg and $M_{if} = 0$ Kg.

Due to the high number of parameters and values, in the sequel we capture the optimal values by cross-relating several distinct combinations for the Wave Gait (*WG*):

- Step Length vs. Body Height – Figure 2 shows P_{av}, P_L and F_L versus (L_S, H_B). We verify that P_{av} and P_L decrease slightly with H_B and sharply with L_S, while F_L only varies (decreases) with L_S.
- Step Length vs. Duty Factor – Figure 3 depicts the three indices versus (L_S, β). We conclude that P_{av} and P_L increase monotonically with β and decrease with L_S. F_L decreases with L_S and presents a minimum for $\beta \approx 88\%$.
- Duty Factor vs. Body Height – Figure 4 depicts $P_{av}(\beta, H_B)$. We conclude that P_{av} increases monotonically with β and decrease slightly with H_B. Although not presented $P_L(\beta, H_B)$ and $F_L(\beta, H_B)$ show the same type of variation with β and H_B.
- Duty Factor vs. Foot Clearance – Figure 5 depicts $P_{av}(\beta, F_C)$ revealing that it increases with β and F_C. The charts of $P_L(\beta, F_C)$ and $F_L(\beta, F_C)$ show the same type of variation with β and F_C.

In conclusion, comparing all the previous experiments, we can establish a compromise for optimising the Wave Gait, namely, that the best situation occurs for $\beta \approx 50\%$, $1.5 \le H_B \le 1.8$ m, $3.0 \le L_S \le 5.0$ m and $F_C \approx 0$ m, considering $L_{i1} = L_{i2} = 1$ m, $O_i = 0$ m and $V_F = 1$ m/s.

Once established these optimal values we can study the effect of other parameters, namely:

- Body Forward Velocity – Figure 6 presents the evolution of min[$P_{av}(V_F)$], min[$P_L(V_F)$] and min[$F_L(V_F)$], respectively. This figure reveals that P_{av} increases with V_F. Furthermore, we have $P_{av} \propto V_F^{1.03}$ for low velocities and $P_{av} \propto V_F^{3.00}$ for high velocities, being the "switch" between both behaviours for $V_F \approx 1.15$ m/s.
  Concerning P_L we have a slightly different variation. For low velocities we have $P_L \propto V_F^{-0.03}$ while for high velocities $P_L \propto V_F^{4.06}$. For medium velocities, this chart presents a transition area. The transitions between low to medium and medium to high velocities occur for $V_F \approx 0.45$ m/s and $V_F \approx 2.0$ m/s, respectively.
  The chart for F_L presents a similar variation, being $F_L \propto V_F^{0.20}$ for low velocities and $F_L \propto V_F^{1.90}$ for high velocities. For this index, the transitions between low to medium and medium to high velocities occur for $V_F \approx 1.2$ m/s and $V_F \approx 10.0$ m/s, respectively.
- Body Height and Step Length vs. Body Forward Velocity – Figure 7 presents the evolution of $L_S(V_F)$ and $H_B(V_F)$ for the minimum values of P_{av}. We conclude that for $V_F \le 2$ m/s L_S / H_B increases / decreases with V_F from $L_S = 3.1$ m / $H_B = 1.9$ m up to $L_S = 10.3$ m / $H_B = 1.0$ m. Moreover, $L_S(V_F)$ and $H_B(V_F)$ present the same variation for the minimum values of P_L and F_L.

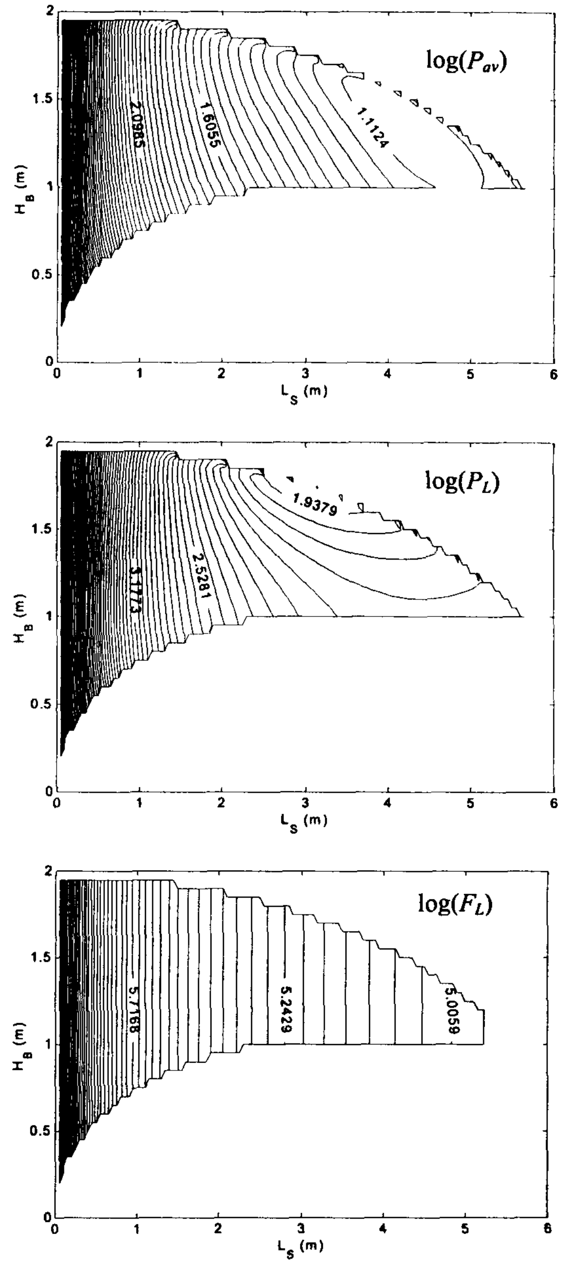

Fig. 2. Plots of $\log(P_{av})$, $\log(P_L)$ and $\log(F_L)$ vs. (L_S, H_B) for $\beta = 50\%$, $F_C = 0.01$ m, $V_F = 1$ m/s, *WG*.

- Number of Legs – if the legs mass is constant, the total mass of the robot (M_{Rt}) varies with the number of legs (n):

$$M_{R_t} = M_b + \sum_{i=1}^{n} (M_{i1} + M_{i2}), \quad M_{i1} = M_{i2} = 1kg \qquad (10)$$

where M_b is the mass of the body. Figure 8 shows that P_{av} increases proportionally with n. We get similar conclusions for P_L while F_L only increases with n for high velocities (Fig. 9).

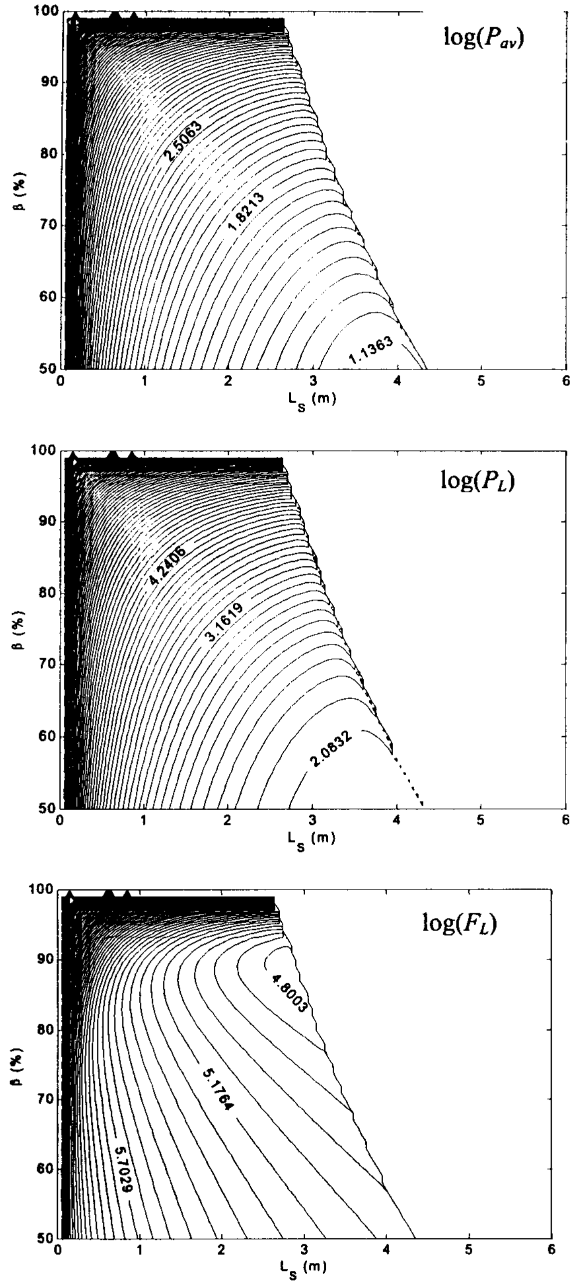

Fig. 3. Plots of $\log(P_{av})$, $\log(P_L)$ and $\log(F_L)$ *vs.* (L_S, β) for $F_C = 0.01$ m, $H_B = 1.5$ m, $V_F = 1$ m/s, *WG*.

- Foot Trajectory Offset vs. Leg Length – In the previous experiments we considered constant link lengths and masses, namely $L_{i1} = L_{i2} = 1$ m and $M_{i1} = M_{i2} = 1$ Kg, for $O_i = 0$ m. Now we study the influence of these factors upon P_{av}, P_L and F_L. Therefore, we establish a total constant leg length and mass of $L_t = L_{i1} + L_{i2} = 2$ m and $M_{Lt} = M_{i1} + M_{i2} = 2$ Kg while varying the relation between the two links, yielding $(i = 1, \ldots, 6; j = 1, 2)$ $M_{ij} = (L_{ij} / L_t).M_{Lt}$.
  Figure 10 shows $P_{av}(O_i, L_{i1})$ for legs link lengths $0.2 < L_{i1} < 1.7$ and for hip–foot offset $-0.5 < O_i < 0.5$.

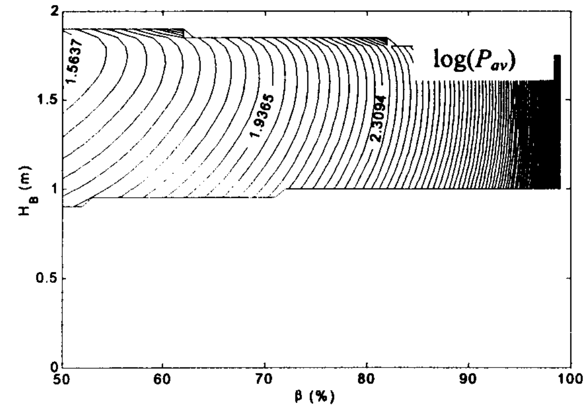

Fig. 4. Plot of $\log(P_{av})$ *vs.* (β, H_B) for $L_S = 4.2$ m, $F_C = 0.01$ m, $V_F = 1$ m/s, *WG*.

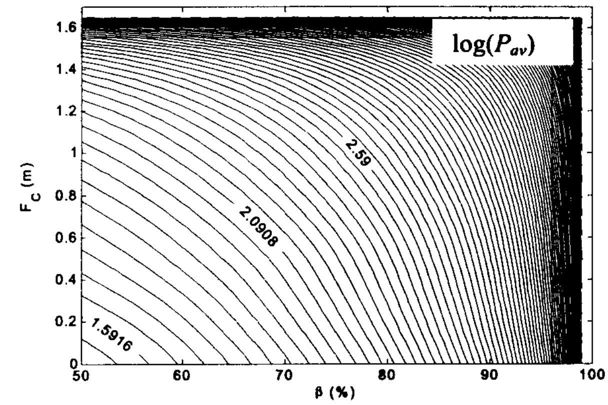

Fig. 5. Plot of $\log(P_{av})$ *vs.* (β, F_C) for $L_S = 1.9$ m, $H_B = 1.7$ m, $V_F = 1$ m/s, *WG*.

We conclude that P_{av} varies slightly with L_{i1} and O_i. For values of O_i and L_{i1} outside this interval P_{av} increases rapidly. $\text{Log}(P_L)$ and $\log(F_L)$ present a similar variation. From these charts we conclude that the locomotion is more efficient with $L_{i1} > 1.6$ m ($L_{i1}+L_{i2} = 2$ m) and $O_i < 0$ m.

V. CONCLUSIONS

In this paper we have compared various dynamic aspects of multi-legged robot locomotion gaits. By implementing different motion patterns, we estimated how the robot responds to a variety of locomotion variables such as duty factor, step length, body height, maximum foot clearance, foot trajectory offset and leg lengths. For analysing the system performance three quantitative measures were defined: the average power consumption, the power expenditure in the actuators and the mean force acting on the hips per walking distance. Analysing the experiments we obtained the best set of locomotion variables and, also, we concluded that the results obtained through the different indices are compatible.

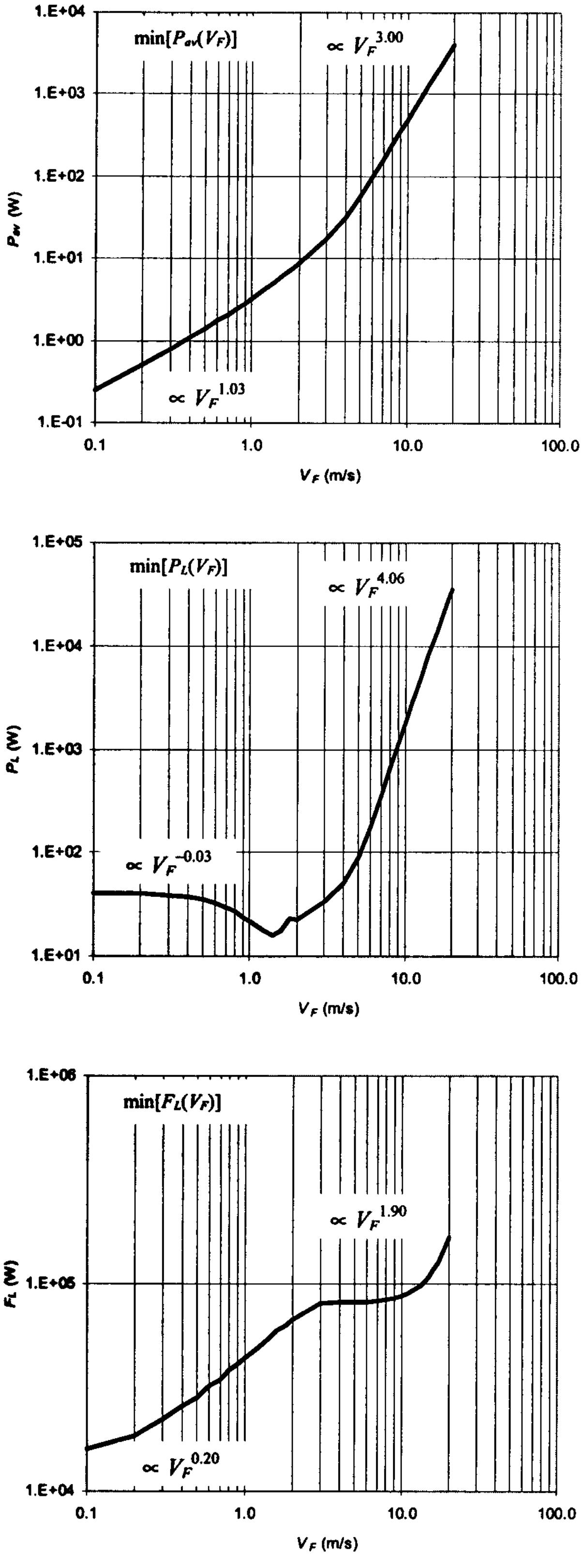

Fig. 6. Plots of min[$P_{av}(V_F)$], min[$P_L(V_F)$] and min[$F_L(V_F)$] for F_C = 0.01 m, *WG*.

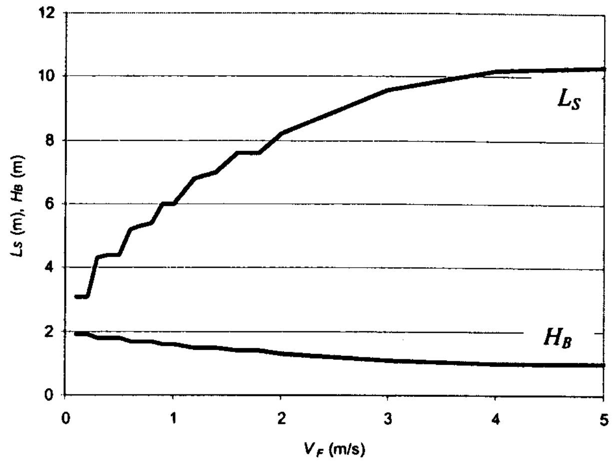

Fig. 7. Plot of $L_S(V_F)$ and $H_B(V_F)$ for min(P_{av}) with F_C = 0.01 m, *WG*.

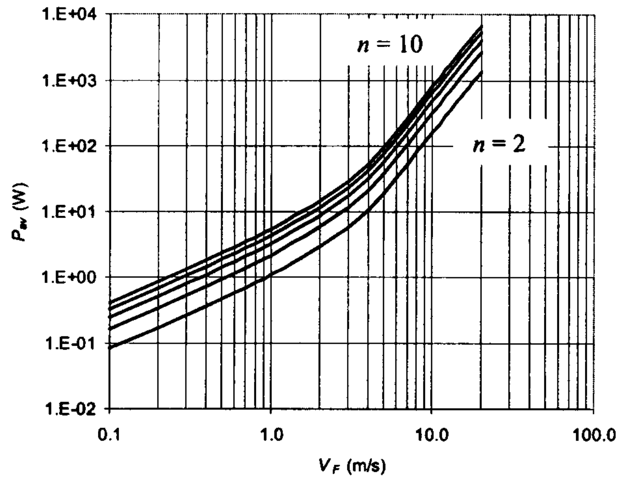

Fig. 8. Plots of min[$P_{av}(V_F)$] vs. n for F_C = 0.01 m, *WG*.

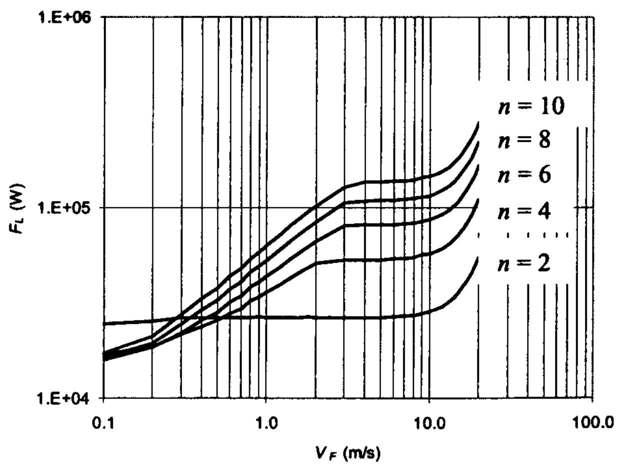

Fig. 9. Plots of min[$F_L(V_F)$] vs. n for F_C = 0.01 m, *WG*.

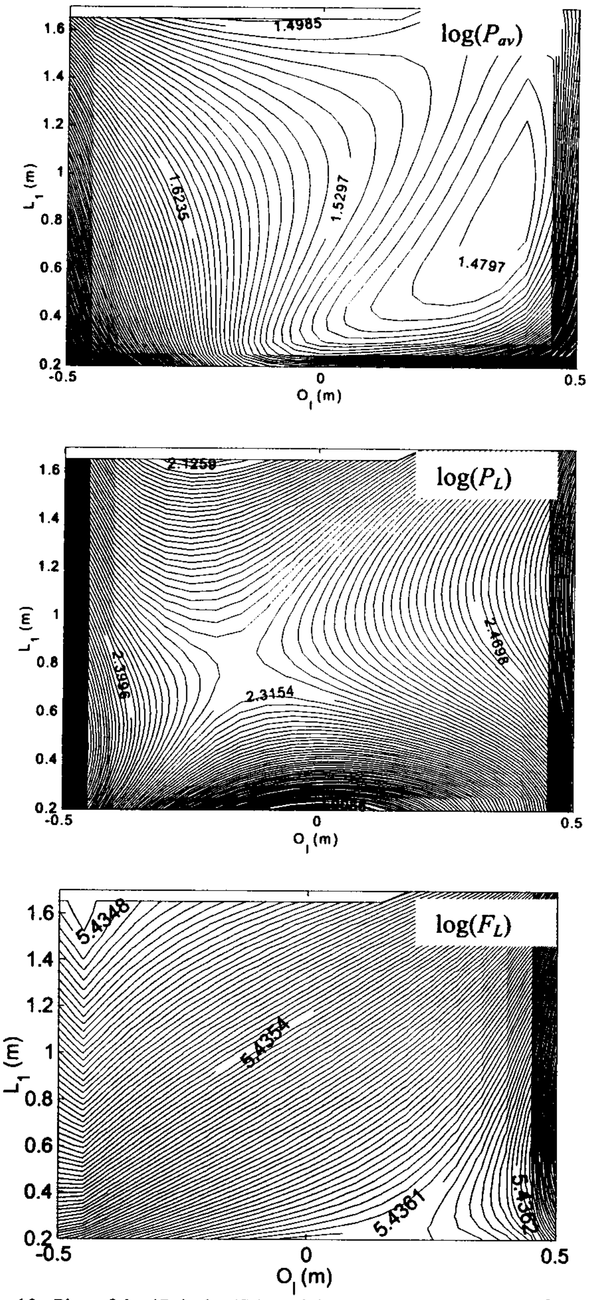

Fig. 10. Plot of $\log(P_{av})$, $\log(P_L)$ and $\log(F_L)$ vs. (L_{i1}, O_i) for $\beta = 50\%$, $L_S = 1.8$ m, $F_C = 0.01$ m, $H_B = 1.7$ m, $V_F = 1$ m/s, *WG*.

While our focus has been on a dynamic analysis in periodic gaits, certain aspects of locomotion are not necessarily captured by the proposed measures. Consequently, future work in this area will address the refinement of our models to incorporate more unstructured terrains, namely with distinct trajectory planning concepts. Moreover, we will also address the effects of the foot – ground interaction and a model describing the ground characteristics. The contact and reaction forces at the robot feet will enable further insight towards the development of efficient multi-legged locomotion robots.

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