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# Optimum Gait Selection for Quadruped Robots

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*Abstract:* **This paper studies periodic gaits of quadruped animals and its application to multilegged artificial locomotion systems. The purpose is to determine the best set of gait and locomotion variables during walking, for different robot velocities and intra-body compliance characteristics, based on two formulated performance measures. A set of experiments reveals the influence of the gait and locomotion variables upon the proposed indices, namely that the gait and the locomotion parameters should be adapted to the robot forward velocity and to the robot intra-body compliance characteristics.**

*Keywords:* **Robotics, locomotion, modelling, simulation**

## I. INTRODUCTION

Walking machines allow locomotion in terrain inaccessible to other type of vehicles. In order for this to become possible, gait analysis and selection is a research area requiring an appreciable modelling effort for the improvement of mobility with legs in unstructured environments. Several robots have been developed which adopt different quadruped gaits such as the bound [1 – 3], trot [4] and gallop [5]. Nevertheless, detailed studies on the best set of gait and locomotion variables for different robot velocities are missing [6].

In this line of thought, a simulation model for multi-legged locomotion systems was developed, for several periodic gaits [7]. Based on this model, we test the quadruped robot locomotion, as a function of $V_F$, when adopting different periodic gaits often observed in several quadruped animals while they walk / run at variable speeds [8].

This study intends to generalize previous work [9, 10] through the formulation of two indices measuring the average energy consumption and the hip trajectory errors during forward straight line walking at different velocities. First, a set of simulation experiments are develop to estimate the optimum values for the parameters step length $L_S$ and body height $H_B$, during the robot locomotion, while the robot is moving along the planned trajectories. Following the best locomotion gait in the velocity range $0.1 \le V_F \le 10.0$ ms$^{-1}$ is determined, from the viewpoint of energy efficiency, being the controller tuned for each particular locomotion velocity, while minimizing the index $E_{av}$, and adopting the optimum locomotion parameters $L_S$ and $H_B$ determined previously. These experiments are repeated for distinct characteristics of the robot intra-body compliance.

Bearing these facts in mind, the paper is organized as follows. Section two introduces the robot kinematic model and the motion planning scheme. Sections three and four present the robot dynamic model and control architecture and the optimizing indices, respectively. Section five develops a set of experiments that reveal the influence of the locomotion parameters and robot gaits on the performance measures, as a function of robot body velocity. Finally, section six outlines the main conclusions.

## II. KINEMATICS AND TRAJECTORY PLANNING

We consider a quadruped walking system (Figure 1) with $n = 4$ legs, equally distributed along both sides of the robot body, having each two rotational joints (*i.e.*, $j = \{1, 2\} \equiv$ {hip, knee}).

Motion is described by means of a world coordinate system. The kinematic model comprises: the cycle time $T$, the duty factor $\beta$, 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 $V_F = L_S / T$.

Gaits describe sequences of leg movements, alternating between transfer and support phases. Given a particular gait and duty factor $\beta$, it is possible to calculate, for leg $i$, the corresponding phase $\phi_i$, the time instant where each leg leaves and returns to contact with the ground and the cartesian trajectories of the tip of the feet (that must be completed during $t_T$) [7]. Based on this data, the trajectory generator is responsible for producing a motion that synchronizes and coordinates the legs.

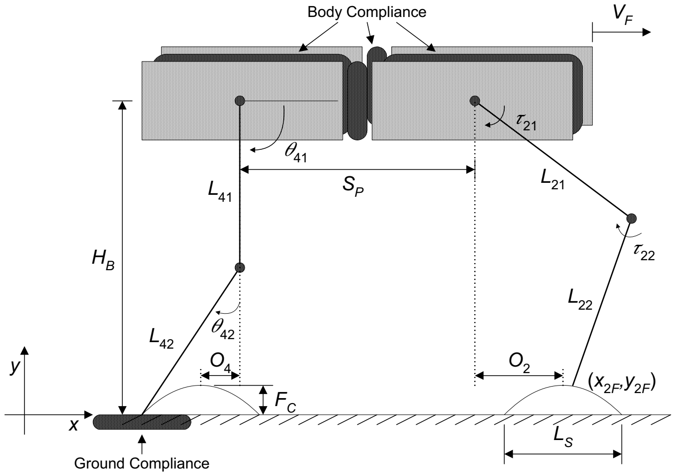


Fig. 1. Kinematic and dynamic quadruped robot model.

The robot body, and by consequence the legs hips, is assumed to have a desired 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 $\mathbf{p_{Hd}}(t) = [x_{iHd}(t), y_{iHd}(t)]^T$:

$$\mathbf{p_{Hd}}(t) = \left[V_F t + Sp\left(1 - \text{ceil}(i/2)\right) \quad H_B\right]^T \tag{1}$$

Regarding the feet trajectories, on a previous work we evaluated two alternative space-time foot trajectories, namely a cycloidal and a sinusoidal function [11]. It was demonstrated that the cycloid is superior to the sinusoidal function, since it improves the hip and foot trajectory tracking, while minimising the corresponding joint torques. However, a step acceleration profile is assumed for the feet trajectories. These results do not present significant changes for different acceleration profiles of the foot trajectory.

In order to avoid the impact and friction effects, at the planning phase we impose null velocities of the feet in the instants of landing and taking off, assuring also the velocity continuity.

Considering the above conclusions, for each cycle the desired geometric trajectory of the foot of the swing leg is computed through a cycloid function (Eq. 2). For example, considering that the transfer phase starts at $t = 0$ s for leg $i = 1$ we have for $\mathbf{p_{Fd}}(t) = [x_{iFd}(t), y_{iFd}(t)]^T$:

- during the transfer phase:

$$\mathbf{p_{Fd}}(t) = \left[V_F\left[t - \frac{t_T}{2\pi}\sin\left(\frac{2\pi t}{t_T}\right)\right], \quad \frac{F_C}{2}\left[1 - \cos\left(\frac{2\pi t}{t_T}\right)\right]\right]^T \tag{2}$$

- during the stance phase:

$$\mathbf{p_{Fd}}(t) = \left[V_F T \quad 0\right]^T \tag{3}$$

The algorithm for the forward motion planning accepts the desired cartesian trajectories of the leg hips $\mathbf{p_{Hd}}(t)$ and feet $\mathbf{p_{Fd}}(t)$ as inputs and, by means of an inverse kinematics algorithm $\boldsymbol{\psi}^{-1}$, generates the related joint trajectories $\mathbf{\Theta_d}(t) = [\theta_{i1d}(t), \theta_{i2d}(t)]^T$, selecting the solution corresponding to a forward knee:

$$\mathbf{p_d}(t) = \left[x_{id}(t) \quad y_{id}(t)\right]^T = \mathbf{p_{Fd}}(t) - \mathbf{p_{Hd}}(t) \tag{4a}$$

$$\mathbf{p_d}(t) = \boldsymbol{\psi}\left[\mathbf{\Theta_d}(t)\right] \Rightarrow \mathbf{\Theta_d}(t) = \boldsymbol{\psi}^{-1}\left[\mathbf{p_d}(t)\right] \tag{4b}$$

$$\dot{\mathbf{\Theta}}_\mathbf{d}(t) = \mathbf{J}^{-1}\left[\dot{\mathbf{p}}_\mathbf{d}(t)\right], \ \mathbf{J} = \frac{\partial \boldsymbol{\psi}}{\partial \mathbf{\Theta_d}} \tag{4c}$$

## III. Robot Dynamics and Control Architecture

### A. Inverse Dynamics Computation

The planned joint trajectories constitute the reference for the robot control system. The model for the robot inverse dynamics is formulated as:

$$\mathbf{\Gamma} = \mathbf{H}(\mathbf{\Theta})\ddot{\mathbf{\Theta}} + \mathbf{c}\left(\mathbf{\Theta}, \dot{\mathbf{\Theta}}\right) + \mathbf{g}(\mathbf{\Theta}) - \mathbf{F_{RH}} - \mathbf{J_F^T}(\mathbf{\Theta})\mathbf{F_{RF}} \tag{5}$$

TABLE I

System Parameters

| Robot model parameters | | Locomotion parameters | |
|---|---|---|---|
| $S_P$ | 1 m | $L_S$ | 1 m |
| $L_{ij}$ | 0.5 m | $H_B$ | 0.9 m |
| $O_i$ | 0 m | $F_C$ | 0.1 m |
| $M_b$ | 88.0 kg | | |
| $M_{ij}$ | 1 kg | **Ground parameters** | |
| $K_{xH}$ | $10^5$ Nm$^{-1}$ | $K_{xF}$ | $1.3 \times 10^6$ Nm$^{-1}$ |
| $K_{yH}$ | $10^4$ Nm$^{-1}$ | $K_{yF}$ | $1.7 \times 10^6$ Nm$^{-1}$ |
| $B_{xH}$ | $10^3$ Nsm$^{-1}$ | $B_{xF}$ | $2.3 \times 10^6$ Nsm$^{-1}$ |
| $B_{yH}$ | $10^2$ Nsm$^{-1}$ | $B_{yF}$ | $2.7 \times 10^6$ Nsm$^{-1}$ |

where $\mathbf{\Gamma} = [f_{ix}, f_{iy}, \tau_{i1}, \tau_{i2}]^T$ ($i = 1, \ldots, n$) is the vector of forces / torques, $\mathbf{\Theta} = [x_{iH}, y_{iH}, \theta_{i1}, \theta_{i2}]^T$ is the vector of position coordinates, $\mathbf{H}(\mathbf{\Theta})$ is the inertia matrix and $\mathbf{c}(\mathbf{\Theta}, \dot{\mathbf{\Theta}})$ and $\mathbf{g}(\mathbf{\Theta})$ are the vectors of centrifugal / Coriolis and gravitational forces / torques, respectively. The $n \times m$ ($m = 2$) matrix $\mathbf{J_F^T}(\mathbf{\Theta})$ is the transpose of the robot Jacobian matrix, $\mathbf{F_{RH}}$ is the $m \times 1$ vector of the body inter-segment forces and $\mathbf{F_{RF}}$ is the $m \times 1$ vector of the reaction forces that the ground exerts on the robot feet. These forces are null during the foot transfer phase. During the system simulation, Eq. (5) is integrated through the Runge-Kutta method.

We consider that the joint actuators are not ideal, exhibiting a saturation given by:

$$\tau_{ijm} = \begin{cases} \tau_{ijC} & , \ |\tau_{ijm}| \le \tau_{ijMax} \\ \text{sgn}\left(\tau_{ijC}\right) \cdot \tau_{ijMax} & , \ |\tau_{ijm}| > \tau_{ijMax} \end{cases} \tag{6}$$

where, for leg $i$ and joint $j$, $\tau_{ijC}$ is the controller demanded torque, $\tau_{ijMax}$ is the maximum torque that the actuator can supply and $\tau_{ijm}$ is the motor effective torque.

### B. Robot Body Model

Figure 1 presents the dynamic model for the hexapod body and foot-ground interaction. It is considered robot body compliance because most walking animals have a spine that allows supporting the locomotion with improved stability. In the present study, the robot body is divided in $n$ identical segments (each with mass $M_b n^{-1}$) and a linear spring-damper system is adopted to implement the intra-body compliance according to:

$$f_{i\eta H} = \sum_{i'=1}^{u}\left[-K_{\eta H}\left(\eta_{iH} - \eta_{i'H}\right) - B_{\eta H}\left(\dot{\eta}_{iH} - \dot{\eta}_{i'H}\right)\right] \tag{7}$$

where $(x_{i'H}, y_{i'H})$ are the hip coordinates and $u$ is the total number of segments adjacent to leg $i$.

In this study, the parameters $K_{\eta H}$ and $B_{\eta H}$ ($\eta = \{x, y\}$) in the {horizontal, vertical} directions, respectively, are defined so that the body behaviour is similar to the one expected to occur on an animal (Table I).

### C. Foot-Ground Interaction Model

The contact of the $i^{th}$ robot feet with the ground is modelled through a non-linear system [11] with linear stiffness $K_{\eta F}$ and non-linear damping $B_{\eta F}$ ($\eta$ = {$x$, $y$}) in the {horizontal, vertical} directions, respectively (see Figure 1), yielding:

$$f_{i\eta F} = -K_{\eta F}\left(\eta_{iF} - \eta_{iF0}\right) - B_{\eta F}\left[-\left(y_{iF} - y_{iF0}\right)\right]^{v_\eta}\left(\dot{\eta}_{iF} - \dot{\eta}_{iF0}\right)$$
$$v_x = 1.0,\ v_y = 0.9 \qquad (8)$$

where $x_{iF0}$ and $y_{iF0}$ are the coordinates of foot $i$ touchdown and $v_\eta$ ($\eta$ = {$x$, $y$}) is a parameter dependent on the ground characteristics. The values for the parameters $K_{\eta F}$ and $B_{\eta F}$ (Table I) are based on the studies of soil mechanics [11].

### D. Control Architecture

The general control architecture of the hexapod robot is presented in Figure 2. In the control architecture implemented for this simulation model, the trajectory planning is carried out in the cartesian space but the control is performed in the joint space, which requires the integration of the inverse kinematic model in the forward path. The control algorithm includes an external position feedback loop and an internal loop with information of the foot-ground interaction force.

On a previous work were demonstrated the advantages of this cascade controller, with PD position control and foot force feedback, over a classical PD with, merely, position feedback, particularly in real situations where we have non-ideal actuators with saturation and being also more robust for variable ground characteristics [4].

For $G_{c1}(s)$ we adopt a PD controller and for $G_{c2}$ a simple P controller. For the PD algorithm we have:

$$G_{C1j}\left(s\right) = Kp_j + Kd_j s, \quad j = 1,2 \qquad (9)$$

being $Kp_j$ and $Kd_j$ the proportional and derivative gains.

## IV. Measures for Performance Evaluation

In mathematical terms we establish two global measures of the overall performance of the mechanism in an average sense. In this perspective, we define one index {$E_{av}$} inspired on the system dynamics and another one {$\varepsilon_{xyH}$} based on the trajectory tracking errors.

Regarding the mean absolute density of energy per travelled distance $E_{av}$, it is computed assuming that energy regeneration is not available by actuators doing negative work (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 a quadruped it yields $n$ = 4 legs), the mechanical power is the product of the motor torque and angular velocity. The global index $E_{av}$ is obtained by averaging the mechanical absolute energy delivered over the travelled distance $d$:

$$E_{av} = \frac{1}{d}\sum_{i=1}^{n}\sum_{j=1}^{m}\int_0^T \left|\boldsymbol{\tau}_{ij}\left(t\right)\dot{\boldsymbol{\theta}}_{ij}\left(t\right)\right| dt \quad \left[\mathrm{Jm}^{-1}\right] \qquad (10)$$

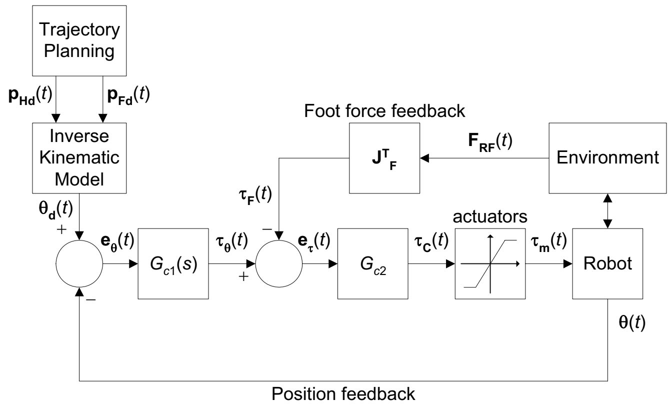


Fig. 2. Quadruped robot control architecture.

TABLE II
Quadruped Controller Parameters

| Gait | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\phi_4$ | $\beta$ |
|---|---|---|---|---|---|
| Walk | 0 | 0.5 | 0.75 | 0.25 | 0.65 |
| Chelonian Walk | 0 | 0.5 | 0.5 | 0 | 0.8 |
| Amble | 0 | 0.5 | 0.75 | 0.25 | 0.45 |
| Trot | 0 | 0.5 | 0.5 | 0 | 0.4 |
| Pace | 0 | 0.5 | 0 | 0.5 | 0.4 |
| Canter | 0 | 0.3 | 0.7 | 0 | 0.4 |
| Transverse Gallop | 0 | 0.2 | 0.6 | 0.8 | 0.3 |
| Rotary Gallop | 0 | 0.1 | 0.6 | 0.5 | 0.3 |
| Half-Bound | 0.7 | 0.6 | 0 | 0 | 0.2 |
| Bound | 0 | 0 | 0.5 | 0.5 | 0.2 |

In what concerns the hip trajectory following errors we define the index:

$$\varepsilon_{xyH} = \sum_{i=1}^{n}\sqrt{\frac{1}{N_s}\sum_{k=1}^{N_s}\left(\Delta_{ixH}{}^2 + \Delta_{iyH}{}^2\right)} \quad \left[\mathrm{m}\right] \qquad (11)$$
$$\Delta_{ixH} = x_{iHd}(k) - x_{iH}(k),\ \Delta_{iyH} = y_{iHd}(k) - y_{iH}(k)$$

where $N_s$ is the total number of samples for averaging purposes and {$d$, $r$} indicate the $i^{th}$ samples of the desired and real position, respectively.

In all cases the performance optimization requires the minimization of each index.

## V. 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 parameters $L_S$ and $H_B$, when adopting periodic gaits [8]. We consider three walking gaits (Walk, Chelonian Walk and Amble), two symmetrical running gaits (Trot and Pace) and five asymmetrical running gaits (Canter, Transverse Gallop, Rotary Gallop, Half-Bound and Bound). These gaits are usually adopted by animals moving at low, moderate and high speed, respectively, being their main characteristics presented in Table II.

In a first phase, we develop a set of simulation experiments to estimate the optimum values for the parameters step length $L_S$ and body height $H_B$ with $V_F$, during the robot locomotion, when adopting the periodic gaits and while the robot is moving along the planned trajectories.

In a second phase we determine the best locomotion gait, from the viewpoint of energy efficiency, in the velocity range $0.1 \le V_F \le 10.0$ ms$^{-1}$. The controller is tuned for each particular locomotion velocity, while minimizing the index $E_{av}$, first keeping the locomotion parameters $L_S$ = 1.0 m and $H_B$ = 0.9 m fixed and, on a second phase, adopting the optimum locomotion parameters $L_S$ and $H_B$ determined previously. These experiments are repeated for distinct values of the robot intra-body compliance parameters, since animals use their body compliance to store energy at high velocities

For the system simulation we consider the robot body parameters, the locomotion parameters and the ground parameters presented in Table I. Moreover, we assume high performance joint actuators with a maximum torque of $\tau_{ijMax}$ = 400 Nm. To tune the controller we adopt a systematic method, testing and evaluating a grid of several possible combinations of controller parameters, while minimising $E_{av}$ (Eq. (10)).

### *A. Locomotion Parameters versus Body Forward Velocity*

In order to analyse the evolution of the locomotion parameters $L_S$ and $H_B$ with $V_F$, we test the forward straight line quadruped planned robot locomotion, as a function of $V_F$, when adopting different gaits often observed in several quadruped animals while they walk / run at variable speeds [8].

With this purpose, the robot forward straight line planned locomotion is simulated for different gaits, while varying the body velocity on the range $0.2 \le V_F \le 10.0$ ms$^{-1}$. For each gait and body velocity, the set of locomotion parameters ($L_S$, $H_B$) that minimises the performance index $E_{av}$ is determined.

The chart presented in Figure 3 depicts the minimum value of the index $E_{av}$, on the range of $V_F$ under consideration, for three different robot gaits. It is possible to conclude that the minimum values of the index $E_{av}$ increase with $V_F$, independently of the adopted locomotion gait. It is also possible to conclude that gaits with higher values of the duty factor $\beta$ show a higher increase for the values of the performance index $E_{av}$. Although not presented here, due to space limitations, the behaviour of the charts min[$E_{av}(V_F)$], for all other gaits present similar shapes.

Next we analyse how the locomotion parameters vary with $V_F$. Figure 4 shows, for three locomotion gaits, that the optimal value of $L_S$ must increase with $V_F$ when considering the performance index $E_{av}$. The next figure (Figure 5) shows that $H_B$ must decrease with $V_F$ from the viewpoint of the same performance index.

For the other periodic walking gaits considered on this study, the evolution of the optimization index $E_{av}$ and the locomotion parameters ($L_S$, $H_B$) with $V_F$ follows the same pattern. Therefore, we conclude that the locomotion parameters should be adapted to the walking velocity in order to optimize the robot performance. As $V_F$ increases, the value of $H_B$ should be decreased and the value of $L_S$ increased. These results seem to agree with the observations of the living quadruped creatures [12].

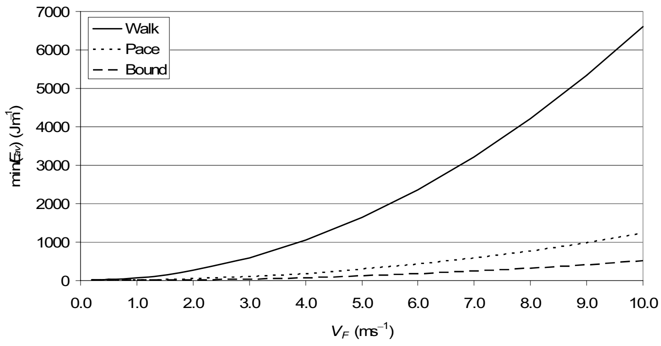


Fig. 3. min[$E_{av}(V_F)$] for $F_C$ = 0.1 m.

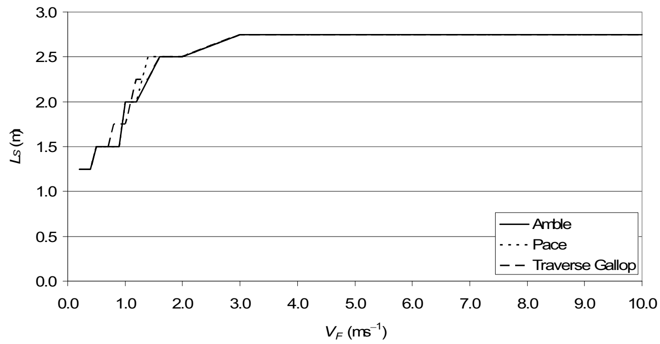


Fig. 4. $L_S(V_F)$ for min($E_{av}$), with $F_C$ = 0.1 m.

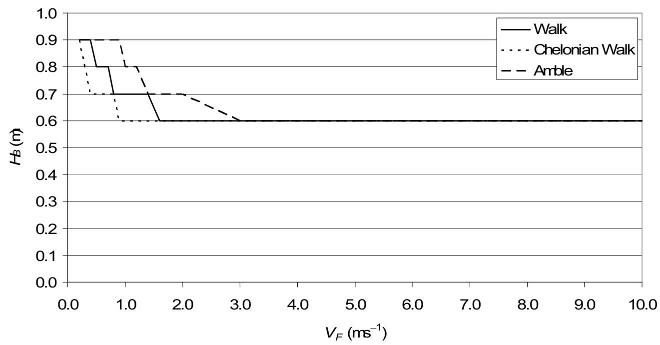


Fig. 5. $H_B(V_F)$ for min($E_{av}$), with $F_C$ = 0.1 m.

### *B. Gait Selection versus Body Forward Velocity Keeping $L_S$ and $H_B$ Fixed*

In a second phase we determine the best locomotion gait, from the viewpoint of energy efficiency, at each forward robot velocity on the range $0.1 \le V_F \le 10.0$ ms$^{-1}$. For this phase of the study, the controller is tuned for each particular locomotion velocity, while minimizing the index $E_{av}$, and adopting the locomotion parameters $L_S$ = 1.0 m and $H_B$ = 0.9 m.

Figure 6 presents the charts of min[$E_{av}(V_F)$] and Figure 7 the minimum values of $\varepsilon_{xyH}$ for the different gaits. The index $E_{av}$ suggests that the locomotion should be Amble, Bound and Half-Bound as the speed increases. The other gaits under consideration present values of min[$E_{av}(V_F)$] higher than these ones, on all range of $V_F$ under consideration. In particular, the gaits Walk and Chelonian Walk present the higher values of this performance measure.

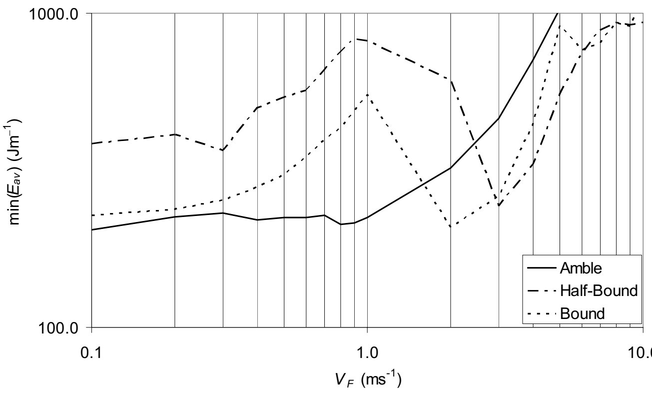


Fig. 6. $\min[E_{av}(V_F)]$ for $F_C = 0.1$ m, with $L_S = 1.0$ m and $H_B = 0.9$ m.

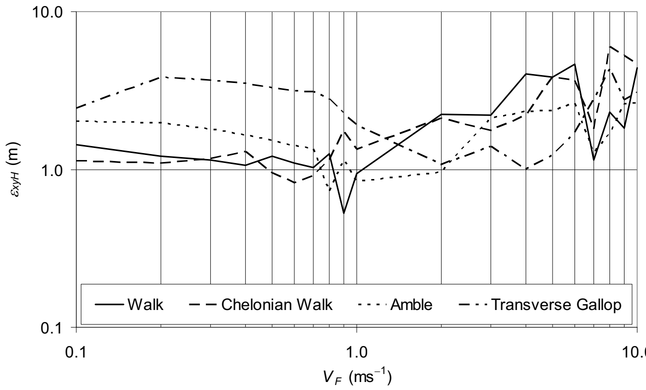


Fig. 7. $\min[\varepsilon_{xyH}(V_F)]$, for $F_C = 0.1$ m, with $L_S = 1.0$ m and $H_B = 0.9$ m.

Analysing the locomotion though the index $\varepsilon_{xyH}$, we verify that for low values of $V_F$ ($V_F < 1$ ms$^{-1}$), the gaits Walk and Chelonian Walk allow the lower oscillations of the hips. For increasing values of the locomotion velocity the Amble and Transverse Gallop gaits present the lower values of $\varepsilon_{xyH}$.

### *C. Gait Selection versus Body Forward Velocity Varying $L_S$ and $H_B$*

In order to analyse the influence of the optimization of the locomotion parameters $L_S$ and $H_B$ on the locomotion performance, in the sequel we determine the best locomotion gait, from the viewpoint of the minimization of the index $E_{av}$, at each forward robot velocity on the range $0.1 \le V_F \le 10.0$ ms$^{-1}$. To conduct this study, the controller is tuned for each particular locomotion velocity, while minimizing the index $E_{av}$, and adopting for each gait at each tested value of $V_F$ the locomotion parameters $L_S$ and $H_B$ determined at section V.*A*.

Figure 8 presents the chart of $\min[E_{av}(V_F)]$. This index points out that the locomotion should be Amble, Trot and Bound as the speed increases. The other gaits under consideration present values of $\min[E_{av}(V_F)]$ higher than these ones, on all range of $V_F$ under consideration. In particular, and once again, the gaits Walk and Chelonian Walk present the higher values of this performance measure.

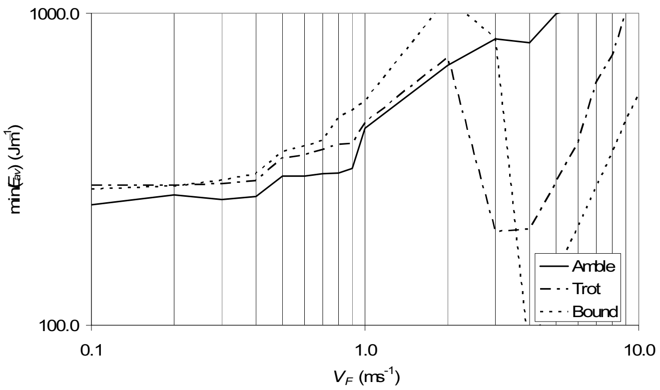


Fig. 8. $\min[E_{av}(V_F)]$ for $F_C = 0.1$ m, considering the optimum values of $L_S$ and $H_B$.

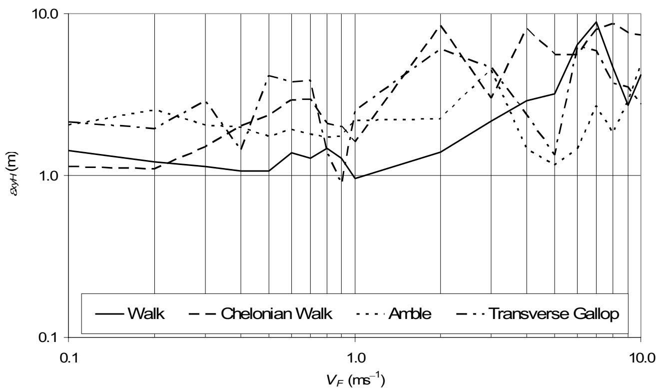


Fig. 9. $\min[\varepsilon_{xyH}(V_F)]$, for $F_C = 0.1$ m, considering the optimum values of $L_S$ and $H_B$.

Comparing the results for this case with those for the previous one, we may conclude that for the Trot and Bound gaits there is a decrease in the values of $E_{av}$ for $V_F > 2$ ms$^{-1}$. Therefore, by correctly choosing the gait to adopt and optimising correspondingly the locomotion parameters $L_S$ and $H_B$ the quadruped robot can move with increased performance.

From the viewpoint of the performance index $\varepsilon_{xyH}$ (Figure 9), we verify that for low values of $V_F$ ($V_F < 0.2$ ms$^{-1}$), the gait Chelonian Walk allows the lower oscillations of the hips. For medium values of $V_F$ ($0.2$ ms$^{-1} < V_F < 2$ ms$^{-1}$), it is the Walk gait that presents the lower values of $\varepsilon_{xyH}$. For high values of the locomotion velocity ($V_F > 3.0$ ms$^{-1}$), the Amble and Transverse Gallop gaits allow the lower oscillations of the hips.

### *D. Gait Selection versus Body Forward Velocity for Stiff Body*

The experiments performed in the previous section are now repeated for the case of assuming a stiff robot body. For this case, and considering the base parameters presented in Table I, the values of the intra-compliance defining parameters $\{K_{xH}, B_{xH}, K_{yH}$ and $B_{yH}\}$ are varied simultaneously through a multiplying factor $K_{mult} = 10$. For this case, the charts of $\min[E_{av}(V_F)]$ and of $\min[\varepsilon_{xyH}(V_F)]$, for the different gaits, are presented in Figures 10 and 11, respectively.

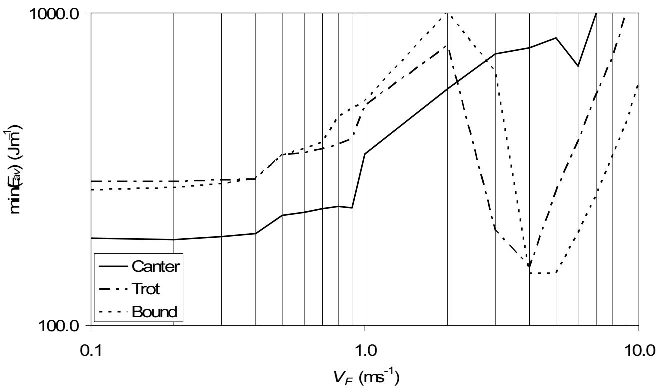


Fig. 10. min[$E_{av}(V_F)$] for $F_C = 0.1$ m, considering the optimum values of $L_S$ and $H_B$.

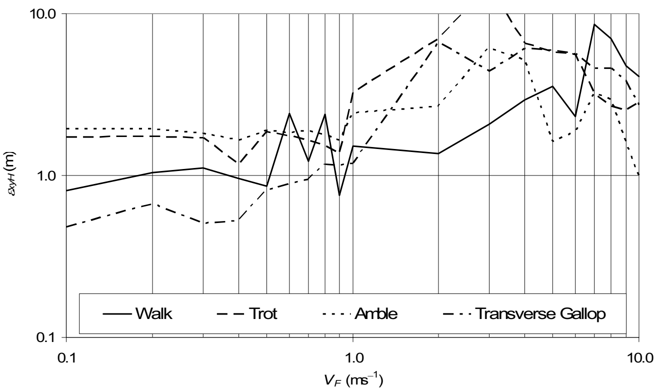


Fig. 11. min[$\varepsilon_{xyH}(V_F)$], for $F_C = 0.1$ m, considering the optimum values of $L_S$ and $H_B$.

From the analysis of Figure 10, it is concluded that the most efficient way to perform the locomotion, measured through the index $E_{av}$, is to adopt the canter gait for $V_F < 2.0$ ms$^{-1}$), the Trot gait for 2.0 ms$^{-1}$ $< V_F <$ 4.0 ms$^{-1}$ and the Bound gait for $V_F >$ 4.0 ms$^{-1}$. All the remaining gaits under study present values of min[$E_{av}(V_F)$] higher than these ones, on all range of $V_F$ under consideration.

Such as in the previous case, we observe that for values of $V_F > 2$ ms$^{-1}$ there is a pronounced decrease in the values of min[$E_{av}(V_F)$] for the Trot and Bound gaits.

Concerning the locomotion performance, analysed from the viewpoint of the performance index $\varepsilon_{xyH}$ (Figure 11), we conclude that for increasing values of the locomotion velocity the gaits Transverse Gallop (for $V_F <$ 0.8 ms$^{-1}$), Walk (for 0.9 ms$^{-1}$ $< V_F <$ 4.0 ms$^{-1}$) and Amble (for $V_F >$ 5.0 ms$^{-1}$) are the ones that allow the lower oscillations of the hips.

*E. Gait Selection versus Body Forward Velocity for Soft Body*

Finally, the study that is being developed is repeated for the case of assuming a soft robot body. For this case, and considering the base parameters presented in Table I, the values of the intra-compliance defining parameters {$K_{xH}$, $B_{xH}$, $K_{yH}$ and $B_{yH}$} are varied simultaneously through a multiplying factor $K_{mult} = 0.1$.

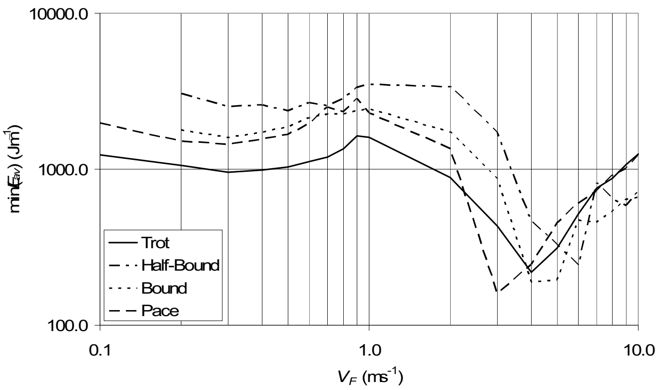


Fig. 12. min[$E_{av}(V_F)$] for $F_C = 0.1$ m, considering the optimum values of $L_S$ and $H_B$.

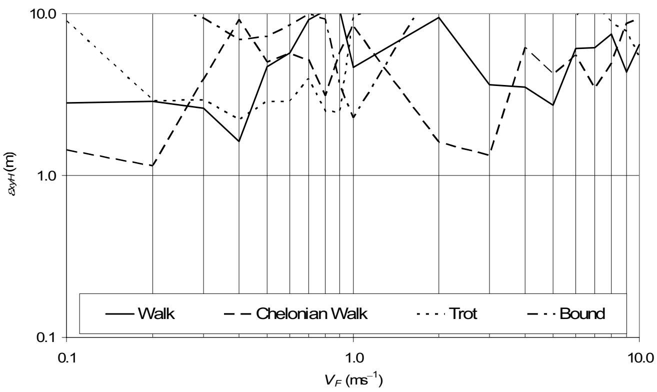


Fig. 13. min[$\varepsilon_{xyH}(V_F)$], for $F_C = 0.1$ m, considering the optimum values of $L_S$ and $H_B$.

Figure 12 presents the charts of min[$E_{av}(V_F)$] and Figure 13 the charts of min[$\varepsilon_{xyH}(V_F)$] for the different gaits. The index $E_{av}$ suggests that the locomotion should be Trot, Pace, Bound and Half-Bound as the speed increases. The other gaits under consideration present values of min[$E_{av}(V_F)$] higher than these ones, on all range of $V_F$ under consideration.

Analysing the locomotion though the index $\varepsilon_{xyH}$ we verify that, on most of the range of $V_F$ under consideration, the gaits Walk and Chelonian Walk allow the lower oscillations of the hips. For medium values of the locomotion velocity (for 0.5 ms$^{-1}$ $< V_F <$ 2.0 ms$^{-1}$) the Trot and Bound gaits present the lower values of $\varepsilon_{xyH}$.

Comparing the results for this situation, with the ones for the previous cases, it is observed that for values of $V_F <$ 2.0 ms$^{-1}$ a soft body demands higher values of min[$E_{av}(V_F)$] for implementing the locomotion and the hip trajectory following errors, measured through $\varepsilon_{xyH}$, are also higher on all $V_F$ range under study.

*F. Discussion of the Results*

From these above presented results, we can conclude that, from the viewpoint of each proposed optimising index, the robot gait should change with the desired forward body velocity. These results seem to agree with the observations of the living quadruped creatures [12].

In general terms, the values of min[$E_{av}(V_F)$] for the robot locomotion increase with $V_F$. This increase is more pronounced for the walking gaits (Walk, Chelonian Walk and Amble). For the case of the running gaits (Trot, Pace, Canter, Transverse Gallop, Rotary Gallop, Half-Bound and Bound) there is a minimum of this index for values of $V_F > 0.9$ ms$^{-1}$, being this minimum more pronounced in case the locomotion parameters $L_S$ and $H_B$ are adapted to the locomotion velocity.

Concerning the minimum values of the performance index $\varepsilon_{xyH}$, we conclude that the walking gaits (Walk, Chelonian Walk and Amble) allow the locomotion with lower hip trajectories oscillations, and the asymmetrical running gaits (in particular the Half-Bound and Bound) impose the higher oscillations in the hips trajectories.

In conclusion, the locomotion gait and the parameters $L_S$ and $H_B$ should be chosen according to the intended robot forward velocity (generally, the value of $L_S$ should be increased and the value of $H_B$ decreased) in order to optimize the energy efficiency or the oscillation of the hips trajectories.

## VI. Conclusions

In this paper we have compared several aspects of periodic quadruped locomotion gaits. By implementing different motion patterns, we estimated how the robot responds to the locomotion parameters step length and body height and to the forward speed.

For analyzing the system performance two quantitative measures were defined based on the system energy consumption and on the hip trajectory errors.

A set of experiments determined the best set of gait and locomotion variables, as a function of the forward velocity $V_F$, and for different characteristics of the robot body intra-compliance.

The results show that the locomotion parameters should be adapted to the walking velocity in order to optimize the robot performance. As the forward velocity increases, the value of $L_S$ should be increased and the value of $H_B$ decreased. Furthermore, for the case of a quadruped robot, we concluded that the gait should be adapted to $V_F$.

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 characteristics of the ground. Moreover, we plan to develop this analysis process in just one phase, simultaneously finding the optimum values of the locomotion parameters $L_S$ and $H_B$ and of the gait, versus $V_F$, through the use of a genetic algorithm.

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