GA Optimization of an Hexapod Robot Parameters for Periodic Gaits

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Abstract Different strategies have been adopted for the optimization of legged robots, either during their design and construction phases, or during their operation. Evolutionary strategies are a way to "imitate nature" replicating the process that nature designed for the generation and evolution of species. This paper presents a genetic algorithm, running over a simulation application of legged robots, allowing the optimization of several locomotion, model and controller parameters, for different locomotion speeds and hexapod periodic gaits. Here are studied the model and locomotion parameters that optimize the robot performance, in a large range of distinct velocities, when the robot walks with distinct periodic gaits.

1. Introduction

Legged robots present significant advantages over traditional vehicles having wheels and tracks. Their major advantage is to allow locomotion in terrain inaccessible to other type of vehicles, because they do not need a continuous support surface. Several different walking robots have been developed up to now [1, 2], but in the present state of development, several aspects need to be improved and optimized. With this idea in mind, different optimization strategies have been proposed and applied to these systems, either during their design and construction phases, or during their operation, namely in what respects to the selection of the gait to be adopted and on its adaptation to the terrain and to the locomotion conditions.

Legged locomotion robots are inspired in animals observed in nature. Therefore, a frequent approach to their design and construction is to make a mechatronic mimic of the animal that is intended to replicate, either in terms of its physical dimensions, or in terms of characteristics such as the gait and the actuation of the limbs. Several examples of robots that have been developed based on this approximation are discussed by Silva and Machado [2].

Evolutionary strategies are an alternative way of imitating nature. Animals characteristics are not directly copied but, instead, is replicated the process that nature conceives for its generation and evolution.

One possibility to implement this idea makes use of genetic algorithms (GAs) as the engine to generate robot structures [3 – 5]. In these applications it is performed a GA modular approach to the robot design. There is a library of elementary components, such as actuated joints, links, gears, power supplies, amongst others. Several of these elements are combined to originate different structures. The generated structures are evaluated, using pre-defined fitness functions, and recombined among them using genetic operators. Finally, the selection process originates a robotic system that represents the best design for a specific application. These computer applications present the capability of an easy reconfiguration and application in the generation of robotic systems for distinct situations [3, 4].

There are also works in which evolutionary strategies are used to optimize the structure of a specific robot [6, 7] and to simultaneous generate the mechanical structure and the robot controller [8 – 10].

One important criticism that can be made to the design approach based in evolutionary strategies concerns its convergence. There is some uncertainty about achieving a solution, due to the high complexity needed for the robot to be of practical use. As an example of a work that is being implemented one can mention the robot developed by Endo and Maeno [11].

Based on these ideas, the remainder of this paper is organized as follows. Section two presents the robot model and its control architecture. Section three presents the structure of the implemented GA. Section four presents the simulation results and, finally, section five outlines the main conclusions of this study.

2. Hexapod Robot Model and Control Architecture

We consider a hexapod walking system (Fig. 1) with $n = 6$ legs, equally distributed along both sides of the robot body, having each two rotational joints (i.e., j = {1, 2} ≡ {hip, knee}) [12].

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. Moreover, we consider a periodic trajectory for each foot, with body velocity $V_F = L_S / T$.

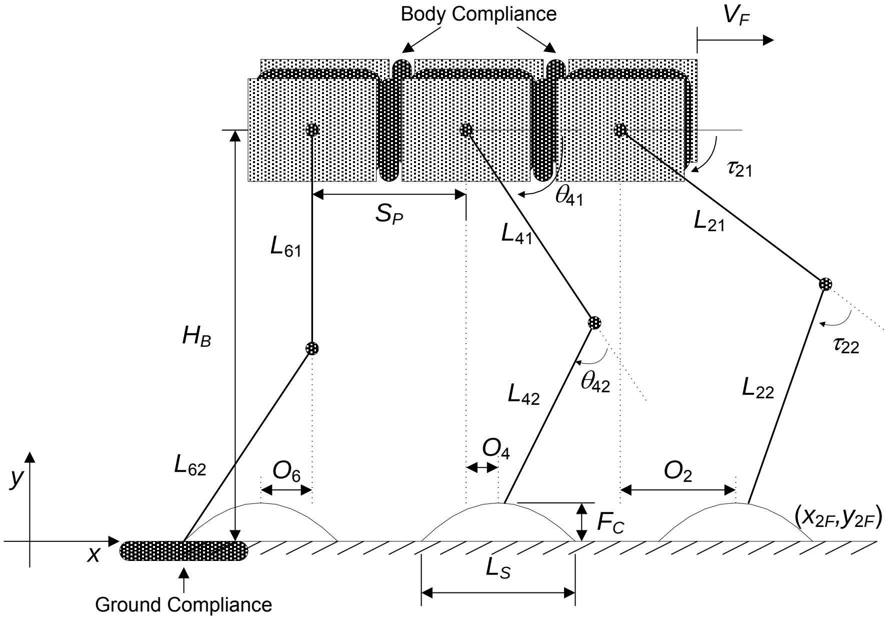

Fig. 1. Hexapod robot model

Gaits describe sequences of leg movements, alternating between transfer and support phases. Given a particular gait and duty factor β, it is possible to calculate, for leg i, the corresponding phase ϕ_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) [13]. Based on this data, the trajectory generator is responsible for producing a motion that synchronises and coordinates the legs.

The algorithm for the forward motion planning accepts the desired cartesian trajectories of the leg hips $\mathbf{p_{Hd}}(t) = [x_{iHd}(t), y_{iHd}(t)]^{\mathrm{T}}$ (horizontal movement with a constant forward speed $V_F = L_S / T$) and feet $\mathbf{p_{Fd}}(t) = [x_{iFd}(t), y_{iFd}(t)]^{\mathrm{T}}$ (periodic trajectory for each foot, being the trajectory of the swing leg foot computed through a cycloid function) as inputs and, by means of an inverse kinematics algorithm $\boldsymbol{\psi}^{-1}$, generates the related joint trajectories $\mathbf{\Theta_d}(t) = [\theta_{i1d}(t), \theta_{i2d}(t), \theta_{i3d}(t)]^{\mathrm{T}}$ (selecting the solution corresponding to a forward knee), that constitute the reference for the robot control system [12].

Concerning the dynamic model, it is considered a compliant robot body, being the robot body 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 (Fig. 1). The contact of the i^{th} robot foot with the ground is modelled through a non-linear system with linear stiffness $K_{\eta F}$ and non-linear damping $B_{\eta F}$ (η = {x, y}) in the {horizontal, vertical} directions, respectively) (Fig. 1}). The values for the parameters are based on the studies of soil mechanics (Table 1) [14].

Table 1. Ground parameters

Ground parameters	
K_{xF}	1.3×10^6 Nm^{-1}
K_{yF}	1.7×10^6 Nm^{-1}
B_{xF}	2.3×10^6 Nsm^{-1}
B_{yF}	2.7×10^6 Nsm^{-1}

The robot inverse dynamic model is formulated as:

$$\mathbf{\Gamma} = \mathbf{H}(\mathbf{\Theta})\ddot{\mathbf{\Theta}} + \mathbf{c}(\mathbf{\Theta}, \dot{\mathbf{\Theta}}) + \mathbf{g}(\mathbf{\Theta}) - \mathbf{F_{RH}} - \mathbf{J_F^T}(\mathbf{\Theta})\mathbf{F_{RF}} \quad (1)$$

where $\mathbf{\Gamma} = [f_{ix}, f_{iy}, \tau_{i1}, \tau_{i2}, \tau_{i3}]^T$ (i = 1, …, n) is the vector of forces/torques, $\mathbf{\Theta} = [x_{iH}, y_{iH}, \theta_{i1}, \theta_{i2}, \theta_{i3}]^T$ 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 $n \times m$ ($m = 3$) 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.

We consider that the joint actuators are not ideal, exhibiting saturation, being τ_{ijC} the controller demanded torque, τ_{ijMax} the maximum torque that the actuator can supply and τ_{ijm} the motor effective torque.

The general control architecture of the multi-legged locomotion system is presented in Fig. 2 [14]. The control algorithm considers an external position and velocity feedback and an internal feedback loop with information of foot-ground interaction force. For $G_{c1}(s)$ we adopt a PD controller and for G_{c2} a simple P controller. For the PD algorithm we have:

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

being Kp_j and Kd_j the proportional and derivative gains, respectively.

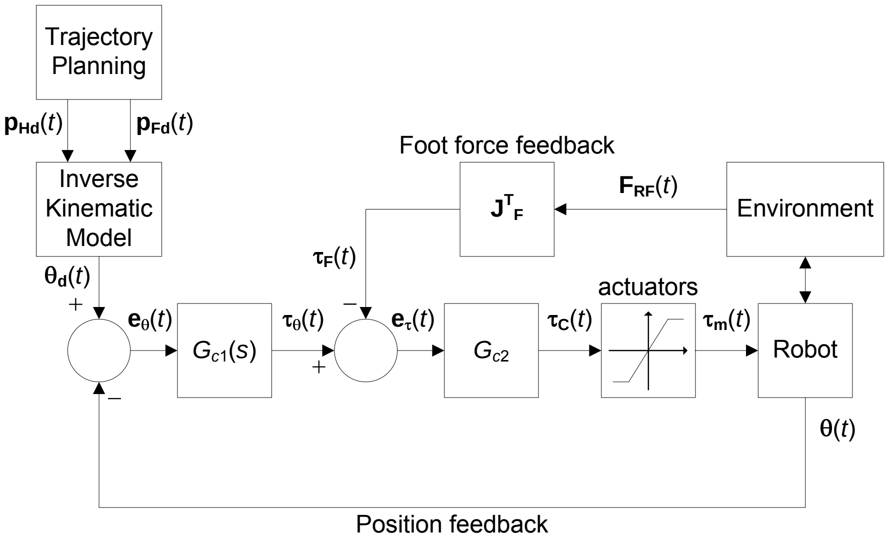

Fig. 2. Hexapod robot control architecture

3. Developed Genetic Algorithm

GAs are adaptive methods which may be used to solve search and optimization problems. By mimicking the principles of natural selection, GAs are able to evolve solutions towards an optimal one. Although the optimal is not guaranteed, the GA is a stochastic search procedure that, usually, generates good results. The GA maintains a population of candidate solutions (the individuals). Individuals are evaluated and fitness values are assigned based on their relative performance. They are then given a chance to reproduce replicating several of their characteristics. The offspring produced is modified by means of mutation and/or recombination operators before being evaluated and reinserted in the population. This is repeated until some condition is satisfied.

3.1. Measures for the Fitness Evaluation

Two global measures of the overall performance of the mechanism (in an average sense) were established. One index is inspired on the system dynamics $\{E_{av}\}$ and the other is based on the trajectory tracking errors $\{\varepsilon_{xyH}\}$ [15].

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 hexapod it yields $n = 6$ 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:

$$E_{av} = \frac{1}{d} \sum_{i=1}^{n} \sum_{j=1}^{m} \int_0^T \left| \boldsymbol{\tau}_{ij}(t) \dot{\boldsymbol{\theta}}_{ij}(t) \right| dt \quad \left[\text{Jm}^{-1} \right] \tag{3}$$

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

$$\begin{aligned} \varepsilon_{xyH} &= \sum_{i=1}^{n} \sqrt{\frac{1}{N_s} \sum_{k=1}^{N_s} \left(\Delta_{ixH}{}^2 + \Delta_{iyH}{}^2 \right)} \quad [\text{m}] \\ \Delta_{ixH} &= x_{iHd}(k) - x_{iH}(k),\ \Delta_{iyH} = y_{iHd}(k) - y_{iH}(k) \end{aligned} \tag{4}$$

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.

The performance optimization can be achieved through the separate minimization of each index or through the simultaneously minimization of both indices, applying a Pareto optimal front [16].

3.2. Structure of the Used Chromosome

The chromosome used in the developed GA presents 48 genes (i.e., 48 robot parameters) [17]. The genes are organized as presented in Table 2: the first gene (L_S) contains information regarding the step length and the last gene (Kd_{32}) contains the derivative gain of joint 2 of the robot rear legs. These values are coded directly into real numbers (value encoding).

Table 2. Interval of variation of the 48 genes used in the chromosome

Minimum Value	Variable	Maximum Value
$0 \leq$	L_S [m]	≤ 10
$0 \leq$	H_B [m]	≤ 1
$0 \leq$	β [%]	≤ 100
$0 \leq$	F_C [m]	≤ 1
$0 \leq$	L_{11} [m]	≤ 1
$0 \leq$	L_{12} [m]	≤ 1
$0 \leq$	L_{21} [m]	≤ 1
$0 \leq$	L_{22} [m]	≤ 1

$0 \leq$	L_{31} [m]	≤ 1
$0 \leq$	L_{32} [m]	≤ 1
$0 \leq$	O_1 [m]	≤ 10
$0 \leq$	O_2 [m]	≤ 10
$0 \leq$	O_3 [m]	≤ 10
$0 \leq$	M_b [kg]	≤ 100
$0 \leq$	M_{11} [kg]	≤ 10
$0 \leq$	M_{12} [kg]	≤ 10
$0 \leq$	M_{21} [kg]	≤ 10
$0 \leq$	M_{22} [kg]	≤ 10
$0 \leq$	M_{31} [kg]	≤ 10
$0 \leq$	M_{32} [kg]	≤ 10
$0 \leq$	K_{xh} [N/m]	≤ 10000
$0 \leq$	K_{yh} [N/m]	≤ 10000
$0 \leq$	B_{xh} [Ns/m]	≤ 10000
$0 \leq$	B_{yh} [Ns/m]	≤ 10000
$-400 \leq$	τ_{11min} [Nm]	≤ 0
$0 \leq$	τ_{11max} [Nm]	≤ 400
$-400 \leq$	τ_{12min} [Nm]	≤ 0
$0 \leq$	τ_{12max} [Nm]	≤ 400
$-400 \leq$	τ_{21min} [Nm]	≤ 0
$0 \leq$	τ_{21max} [Nm]	≤ 400
$-400 \leq$	τ_{22min} [Nm]	≤ 0
$0 \leq$	τ_{22max} [Nm]	≤ 400
$-400 \leq$	τ_{31min} [Nm]	≤ 0
$0 \leq$	τ_{31max} [Nm]	≤ 400
$-400 \leq$	τ_{32min} [Nm]	≤ 0
$0 \leq$	τ_{32max} [Nm]	≤ 400
$0 \leq$	Kp_{11}	≤ 10000
$0 \leq$	Kd_{11}	≤ 1000
$0 \leq$	Kp_{12}	≤ 10000
$0 \leq$	Kd_{12}	≤ 1000
$0 \leq$	Kp_{21}	≤ 10000
$0 \leq$	Kd_{21}	≤ 1000
$0 \leq$	Kp_{22}	≤ 10000
$0 \leq$	Kd_{22}	≤ 1000
$0 \leq$	Kp_{31}	≤ 10000
$0 \leq$	Kd_{31}	≤ 1000
$0 \leq$	Kp_{32}	≤ 10000
$0 \leq$	Kd_{32}	≤ 1000

3.3. Structure of the Developed GA

The outline of the implemented GA is as follows:

- Start: Generate a random population of $n = 20$ (n = maximum number of individuals defined by the user) suitable solutions (chromosomes). The values for the genes that constitute the chromosome are uniformly distributed in the ranges of the admissive values for the corresponding parameters (Table 2).
- Simulation: Simulate the robot locomotion for all chromosomes in the population using the simulation model.
- Fitness: Select and evaluate the fitness function for each chromosome. The robot locomotion performance is evaluated by computing the indices $\{E_{av}\}$ and $\{\varepsilon_{xyH}\}$, according to the user's selection.
- New population: Create a new population by repeating the following steps:
    - Selection - Select the $m = 1$ best parent chromosomes according to their fitness. These solutions are copied without changes to the new population (elitism);
    - Crossover - Select 80% of the individuals to be replaced by the crossover of the parents: two random parents are chosen and an arithmetic mean operation is performed to produce one new offspring;
    - Mutation - Select 2% of the individuals to be replaced by mutation of the parents: one random parent is chosen and, to selected genes of the chromosome, a small real number is added to make a new offspring;
    - Spontaneous generation - The remaining individuals are replaced by new randomly generated ones (such as in step 1).
- Loop: If this iteration is the 200^{th} or the GA has converged (the value of the fitness function for the chromosome with the best fitness function is equal to the one that is in the position corresponding to 90% of the population), stop the algorithm, else, go to step 2.

4. Simulation Results

The main objective of this study is to find the optimal values for the locomotion and robot model parameters, considering that the robot is moving with variable body velocities, while adopting the following periodic gaits: Wave gait, Equal Phase Half Cycle gait, Equal Phase Full Cycle gait, Backward Wave gait, Backward Equal Phase Half Cycle gait and Backward Equal Phase Full Cycle gait {WG, EPHC, EPFC, BW, BEPHC, BEPFC}.

We test the forward straight line quadruped robot locomotion, as a function of V_F, when adopting the above mentioned periodic gaits. The experiments are carried out, while considering the following values for the body velocity V_F = {0.1; 0.5; 1.0; 2.0; 3.0; 4.0; 5.0} ms^{-1}. For each body velocity, the set of robot model and locomotion parameters that simultaneously minimize both indices are determined.

This study was divided into two phases. We start by determining the optimum values of the locomotion, robot and controller parameters, for the forward and backward periodic gaits under study, considering that the robot is walking with $V_F = 1.0$ ms^{-1}. In a second phase, we repeat the analysis, studying the evolution of the locomotion and robot model parameters with V_F.

4.1. Optimum Hexapod Parameters for the locomotion with $V_F = 1.0$ ms^{-1}

In this subsection are presented the optimum values of the locomotion, robot and controller parameters, for the periodic gaits under study, considering that the robot is walking with $V_F = 1.0$ ms^{-1}.

The GA, with the parameters described above, and considering the simultaneously minimization of both indices (applying a Pareto optimal front [16]), lead to the results presented in the sequel.

In Table 3 are presented the optimum parameters considering that the robot is walking with the forward gaits. From the analysis of this table it is possible to conclude that the locomotion parameters (L_S, H_B, β, F_C) are the same for the EPHCG and for the EPFCG. All the remaining parameters under study are also very similar for both of these gaits.

Analysing the results in detail, it is possible to conclude that for this locomotion speed, the length of the first link of the legs should be smaller than the length of the second link (being the relation L_{i1} / L_{i2} approximately 1/2 for the WG and approximately 0.45/0.55 for the EPHCG and EPFCG). We can also conclude that the feet trajectory offset (O_i, i = 1, ..., n) shows a negative value for all studied gaits and, therefore, the robot should keep its feet backwards regarding its hips. Regarding the masses of the legs links, the results are contradictory. For the WG the simulations show that the mass of the first link of the legs should be higher than the mass of the second link (being the relation M_{i1} / M_{i2} approximately 3/1 for the front and middle legs and approximately higher than one for the rear legs). However, for the EPHCG and EPFCG, the results point to the opposite situation. In this case the optimum corresponds to the masses of the first link of the legs being lower than the mass of the second link.

Table 3. Optimum values of the locomotion, robot and controller parameters, for the forward periodic gaits, considering that the robot is walking with $V_F = 1.0\ \mathrm{ms}^{-1}$

	WG	EPHCG	EPFCG
L_S [m] =	0,798	0,996	0,996
H_B [m] =	0,685	0,733	0,733
β [%] =	34,112	42,972	42,972
F_C [m] =	0,125	0,173	0,173
L_{11} [m] =	0,321	0,521	0,502
L_{12} [m] =	0,679	0,479	0,498
L_{21} [m] =	0,314	0,449	0,449
L_{22} [m] =	0,686	0,551	0,551
L_{31} [m] =	0,311	0,426	0,411
L_{32} [m] =	0,689	0,574	0,589
O_1 [m] =	–0,606	–0,335	–0,328
O_2 [m] =	–0,546	–0,325	–0,301
O_3 [m] =	–0,657	–0,413	–0,413
M_b [kg] =	84,138	71,124	71,124
M_{11} [kg] =	3,634	4,498	4,498
M_{12} [kg] =	1,723	5,561	5,561
M_{21} [kg] =	3,574	3,937	3,937
M_{22} [kg] =	1,449	6,261	6,261
M_{31} [kg] =	2,959	3,921	3,921
M_{32} [kg] =	2,523	4,698	4,698
K_{xh} [N/m] =	89106,766	95452,297	95452,289
K_{yh} [N/m] =	9990,477	11012,926	11012,926
B_{xh} [Ns/m] =	776,511	883,493	883,491
B_{yh} [Ns/m] =	90,151	97,097	97,097
τ_{11min} [Nm] =	–358,508	–212,238	–212,238
τ_{11max} [Nm] =	176,209	241,178	240,257
τ_{12min} [Nm] =	–288,704	–200,241	–193,803
τ_{12max} [Nm] =	53,051	240,882	240,883
τ_{21min} [Nm] =	–264,891	–216,674	–216,674
τ_{21max} [Nm] =	75,424	202,856	202,678
τ_{22min} [Nm] =	–229,980	–219,617	–219,617
τ_{22max} [Nm] =	156,389	230,988	230,988
τ_{31min} [Nm] =	–386,089	–232,821	–232,821
τ_{31max} [Nm] =	123,213	233,590	233,590
τ_{32min} [Nm] =	–378,953	–226,783	–226,783
τ_{32max} [Nm] =	80,422	247,631	247,631
Kp_{11} =	943,627	3213,644	3213,645
Kd_{11} =	336,111	331,793	331,881
Kp_{12} =	3582,081	3928,315	3928,315
Kd_{12} =	14,327	393,434	393,434

Kp_{21} =	831,258	3384,143	3384,143
Kd_{21} =	100,013	348,813	373,052
Kp_{22} =	3948,079	3954,050	3954,048
Kd_{22} =	30,294	382,481	382,481
Kp_{31} =	3934,615	4167,394	4167,401
Kd_{31} =	183,397	356,461	356,461
Kp_{32} =	1275,400	4456,879	4456,879
Kd_{32} =	109,285	371,735	398,928
V_F [ms^{-1}] =	1,000	1,000	1,000
E_{av} [J/m] =	334,135	566,696	572,301
ε_{xyH} [m] =	0,344	0,419	0,429
d [m] =	0,789	0,990	0,990

When the simulation results are considered, we conclude that the locomotion with the WG shows lower values for the performance indices E_{av} and ε_{xyH}, but with the EPHCG and EPFCG the robot moves along a higher distance (d = 0.99 m).

The same analysis is now repeated for the backward gaits, namely the BWG, BEPHCG and BEPFCG.

In Table 4 are presented the optimum parameters for this case. From the analysis of this table it is possible to conclude that most of the optimum parameters found are the same for the BEPHCG and for the BEPFCG. One of the few exceptions is the parameter L_S, that must be higher in the case of the BEPFCG.

Analysing the results in detail, it is possible to conclude that for this locomotion speed, the length of the first link of the legs should be smaller than the length of the second link, being the relation L_{i1} / L_{i2} different for the distinct pairs of legs under consideration and for the gaits analysed. The feet trajectory offset (O_i, i = 1, ..., n) shows positive and negative values for the different pairs of legs, and for the distinct gaits; therefore, no definite conclusion can be extrapolated regarding the robot feet offset in relation to its hips. Concerning the masses of the legs links, the simulations show that the mass of the first link of the legs should be lower than the mass of the second link, for all studied gaits. However, the relations between M_{i1} / M_{i2} are distinct for the different pairs of legs and for different gaits. It should also be noticed that, for the backward gaits, the relation between the sum of the legs masses and the body mass is higher than for the forward gaits. In this case the relation $\sum M_{ij}$ / M_B is approximately 4 / 6, while in the forward gaits it is approximately 3 / 7.

When the simulation results are considered, we conclude that the locomotion with the BWG shows the lower values for the performance indices E_{av} and ε_{xyH}, and for the travelled distance d, while the BEPFCG shows the higher values for all these metrics.

Table 4. Optimum values of the locomotion, robot and controller parameters, for the backward periodic gaits, considering that the robot is walking with $V_F = 1.0$ ms^{-1}

	BWG	**BEPHCG**	**BEPFCG**
L_S [m] =	1,234	1,347	1,406
H_B [m] =	0,874	0,747	0,747
β [%] =	35,471	45,160	45,160
F_C [m] =	0,286	0,261	0,261
L_{11} [m] =	0,443	0,417	0,417
L_{12} [m] =	0,557	0,583	0,583
L_{21} [m] =	0,335	0,306	0,306
L_{22} [m] =	0,665	0,694	0,694
L_{31} [m] =	0,412	0,312	0,312
L_{32} [m] =	0,588	0,688	0,688
O_1 [m] =	0,131	–0,890	–0,890
O_2 [m] =	0,212	0,315	0,315
O_3 [m] =	–0,837	–0,803	–0,803
M_b [kg] =	60,840	64,121	64,121
M_{11} [kg] =	2,261	3,456	3,456
M_{12} [kg] =	6,025	5,561	5,561
M_{21} [kg] =	5,152	7,502	7,502
M_{22} [kg] =	6,088	6,809	6,809
M_{31} [kg] =	4,233	1,333	1,333
M_{32} [kg] =	15,400	11,218	11,218
K_{xh} [N/m] =	84325,609	84620,438	84620,438
K_{yh} [N/m] =	10652,140	11263,390	11263,390
B_{xh} [Ns/m] =	1023,130	1154,109	1154,109
B_{yh} [Ns/m] =	111,217	98,594	98,594
τ_{11min} [Nm] =	–417,609	–239,559	–239,559
τ_{11max} [Nm] =	242,097	164,180	164,180
τ_{12min} [Nm] =	–121,740	–404,738	–404,738
τ_{12max} [Nm] =	299,230	346,426	346,426
τ_{21min} [Nm] =	–227,569	–210,971	–210,971
τ_{21max} [Nm] =	172,693	207,571	207,571
τ_{22min} [Nm] =	–251,289	–242,419	–242,419
τ_{22max} [Nm] =	116,233	69,649	69,649
τ_{31min} [Nm] =	–332,831	–361,092	–361,092
τ_{31max} [Nm] =	277,395	412,507	412,507
τ_{32min} [Nm] =	–112,641	–118,282	–118,282
τ_{32max} [Nm] =	104,715	379,033	379,033
Kp_{11} =	1642,866	4344,789	4344,789
Kd_{11} =	732,050	446,979	446,979
Kp_{12} =	1463,171	2175,358	2175,358
Kd_{12} =	53,706	303,462	303,462

Kp_{21} =	8459,506	5601,465	5601,465
Kd_{21} =	399,984	529,078	529,078
Kp_{22} =	41,854	3254,481	3254,481
Kd_{22} =	155,758	242,931	242,931
Kp_{31} =	4303,043	6898,499	6898,499
Kd_{31} =	447,706	437,147	437,147
Kp_{32} =	2771,249	7846,035	7846,035
Kd_{32} =	395,324	527,509	527,509
V_F [ms^{-1}] =	1,000	1,000	1,000
E_{av} [J/m] =	476,209	750,408	752,677
ε_{xyH} [m] =	0.236	0,249	0,250
d [m] =	1.241	1,346	1,406

4.2. Evolution of the optimum hexapod parameters with V_F

Figure 3 presents the evolution of the Step Length (L_S) with the forward locomotion speed (V_F). This figure shows that the optimal value of L_S must increase with V_F when considering the simultaneous minimization of these performance indices (in the perspective of the Pareto optimal front).

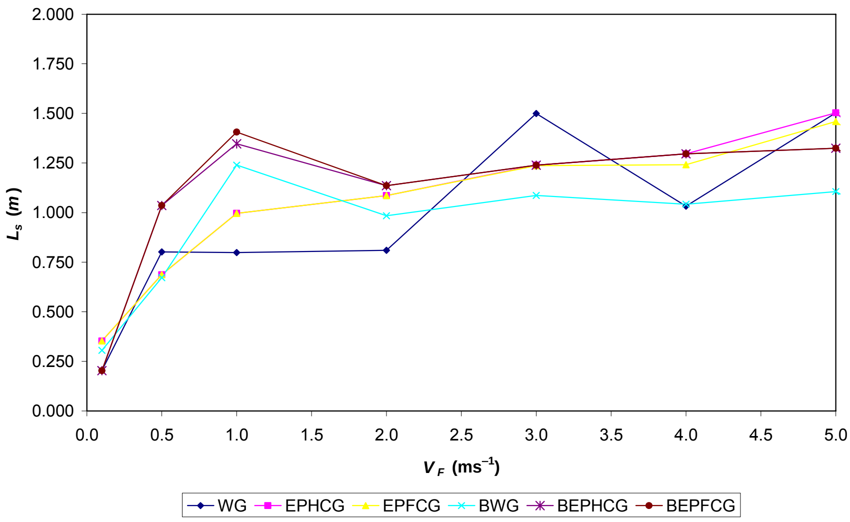

Fig. 3. Evolution of the Step Length L_S with the forward locomotion speed V_F

In Fig. 4 it is presented the evolution of the Duty Factor (β) with the forward locomotion speed (V_F). It is seen that the optimal value of β decreases with V_F. For $V_F = 0.1$ ms^{-1} the value of β is higher than 50%, but for all other values of V_F is it lower than 50%. This means that the robot is actually "running" for the values of $V_F \geq 0.5$ ms^{-1}, considered in this study.

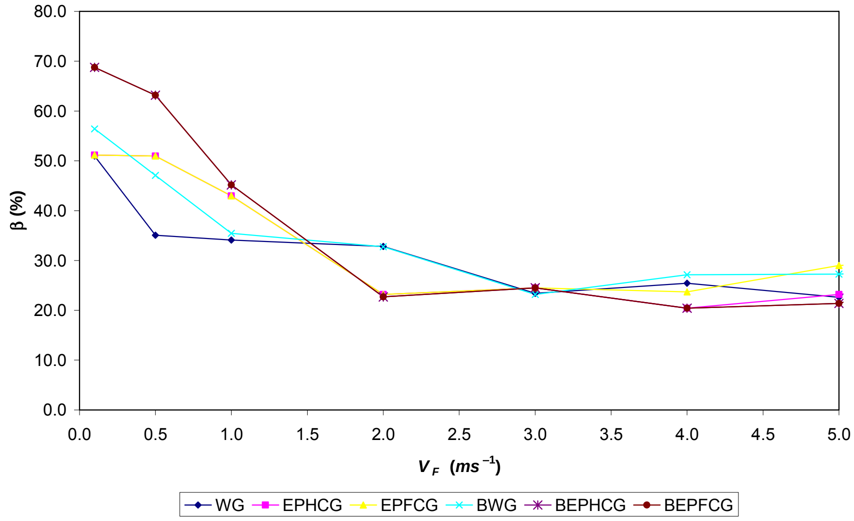

Fig. 4. Evolution of the Duty Factor β with the forward locomotion speed V_F

Figure 5 shows the evolution of the parameter Body Height (H_B) with V_F. From the analysis of the chart one can conclude that H_B remains almost constant for $V_F \leq 3.0$ ms^{-1} ($H_B \approx 0.7$ m) and increases slightly for higher values of V_F under study, until it reaches $H_B \approx 0.75 - 0.85$ m, for $V_F = 5.0$ ms^{-1}.

Although not presented here, the chart that depicts the behaviour of F_C with V_F, shows that F_C remains almost constant in the entire range of V_F studied, around the value $F_C \approx 0.1$ m.

In conclusion, regarding the locomotion parameters, we verify that they should be adapted to the walking velocity in order to optimize the robot performance. As V_F increases, the value of β should decrease and the value of L_S should increase. Regarding H_B and F_C, the first should increase for $V_F > 3.0$ ms^{-1} while the second should be kept constant in the vicinity of $F_C \approx 0.1$ m.

In the sequel we present the variation of the robot model parameters with V_F.

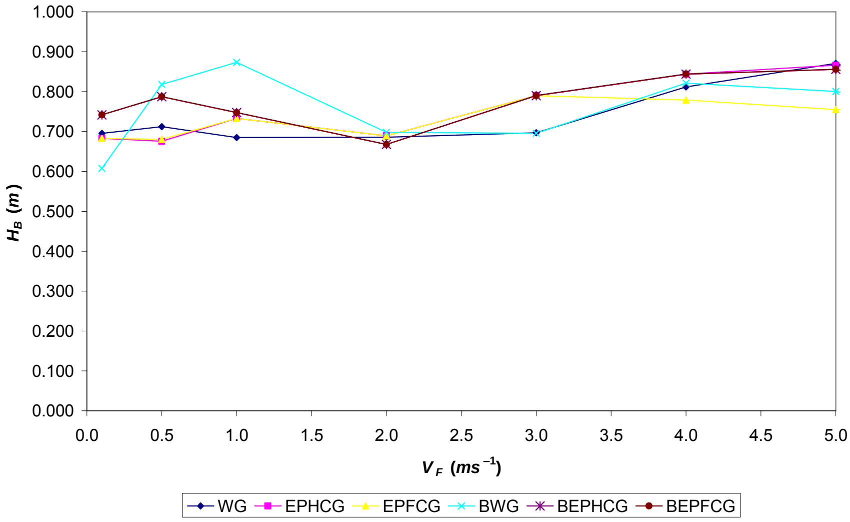

Fig. 5. Evolution of the Body Height H_B with the forward locomotion speed V_F

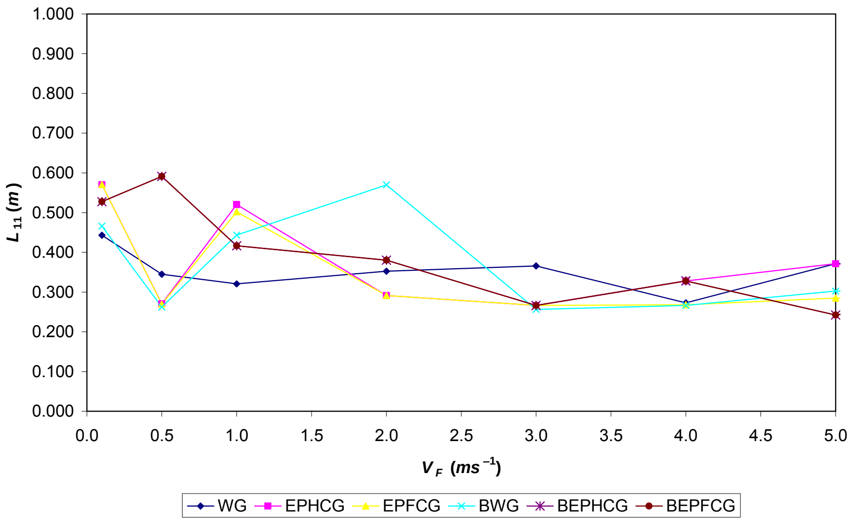

Fig. 6. Evolution of the length of the first link of the front legs L_{11} with the forward locomotion speed V_F, keeping $L_{11} + L_{12} = 1.0$ m

Figure 6 shows the evolution of the optimal length of the first link of the front legs of the robot (L_{i1}, $i = 1, 2$) with V_F. For low values of V_F the length of the first link is around 0.45 m and, as the velocity increases, this value decreases slightly and stays around 0.25 m. The length of the second link has the opposite behaviour of the front legs of the robot, since the total length of the legs of the robot is fixed ($L_{11} + L_{12} = 1.0$ m).

In Fig. 7 it is presented the evolution of the length of the first link of the middle legs (L_{i1}, $i = 3, 4$) with the forward locomotion speed (V_F). The length of L_{31} presents an "erratic" behaviour for $V_F \leq 1.0$ ms^{-1}, diminishing for the WG and BWG gaits and increasing for the others, but stabilizes around $L_{31} \approx 0.35$ m for higher values of V_F.

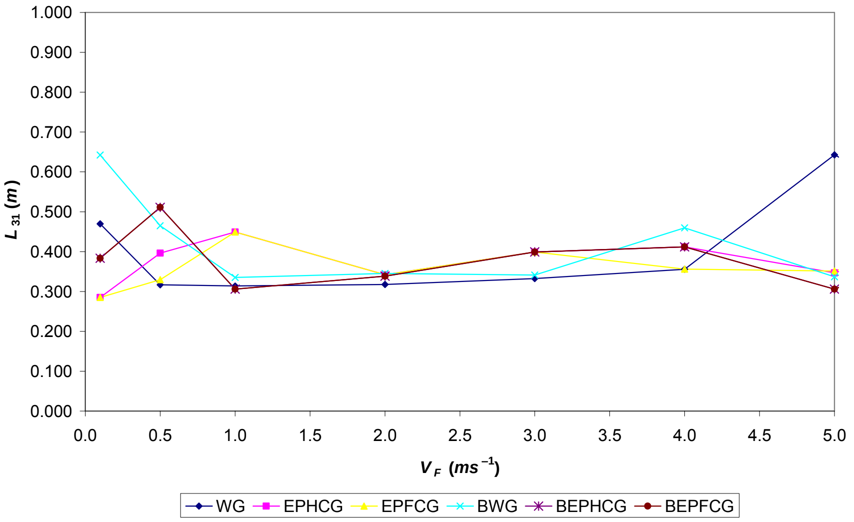

Fig. 7. Evolution of the length of the first link of the middle legs L_{31} with the forward locomotion speed V_F, keeping $L_{31} + L_{32} = 1.0$ m

Figure 8 depicts the evolution of the length of the first link of the rear legs (L_{i1}, $i = 5, 6$) with the forward locomotion speed (V_F). The value of L_{51} is close to 0.4 m for reduced speeds ($V_F \leq 0.5$ ms^{-1}), decreasing slightly until reaching a value of $L_{51} \approx 0.2$ m for $V_F \approx 4.0$ ms^{-1}. For values of $V_F > 4.0$ ms^{-1}, L_{51} increases again until reaching $L_{51} = 0.4$ m for $V_F = 5.0$ ms^{-1}.

Analyzing the lengths of the links of the robot legs, it is possible to conclude that the upper segment of the legs should be longer than the lower one, and that the relation L_{i1} / L_{i2} is approximately 1/3.

In Figs. 9 – 11 it is presented the evolution of the front, middle and rear feet trajectory offset (O_i, $i = 1, ..., n$) with V_F. We conclude that these charts are very "noisy", being difficult to identify clear trends. However, the offset of the front (O_i, $i = 1, 2$), middle (O_i, $i = 3, 4$) and rear (O_i, $i = 5, 6$) legs of the robot (Figs. 9 – 11) shows a negative value for most of the values of V_F analysed and, therefore, the robot should keep its feet backwards regarding its hips.

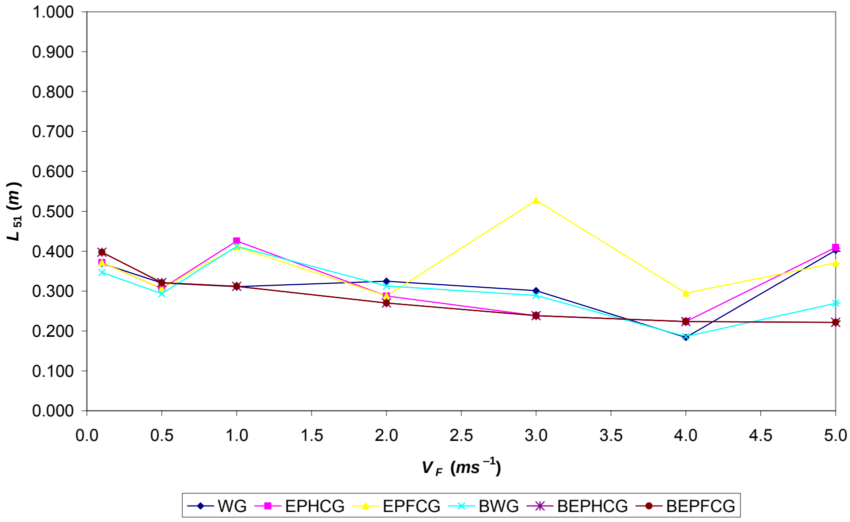

Fig. 8. Evolution of the length of the first link of the rear legs L_{51} with the forward locomotion speed V_F, keeping $L_{51} + L_{52} = 1.0$ m

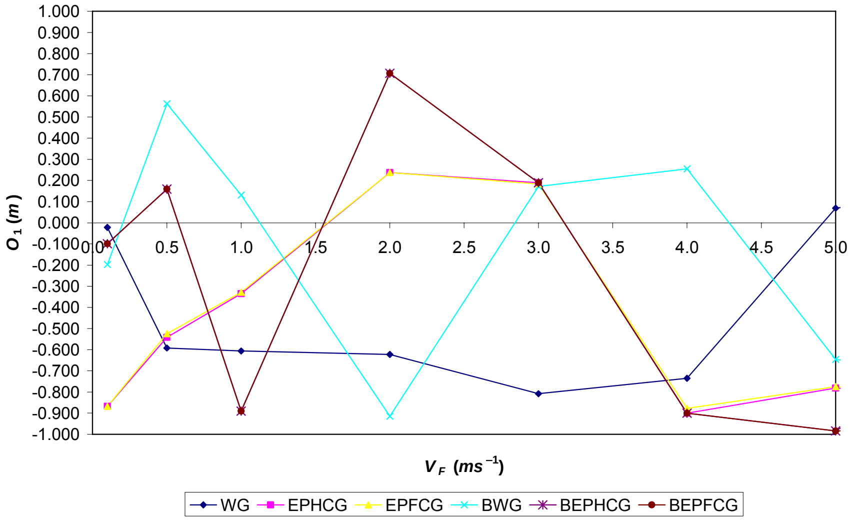

Fig. 9. Evolution of the front feet trajectory offset O_1 with the forward locomotion speed V_F

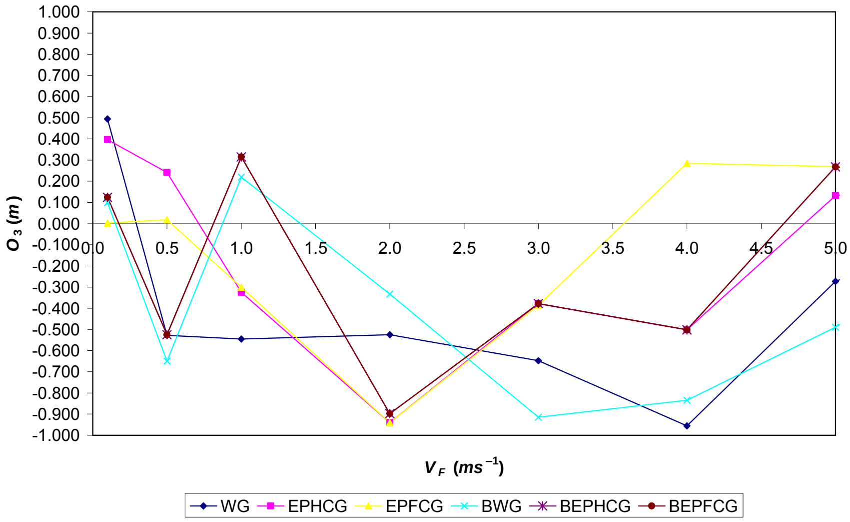

Fig. 10. Evolution of the middle feet trajectory offset O_3 with the forward locomotion speed V_F

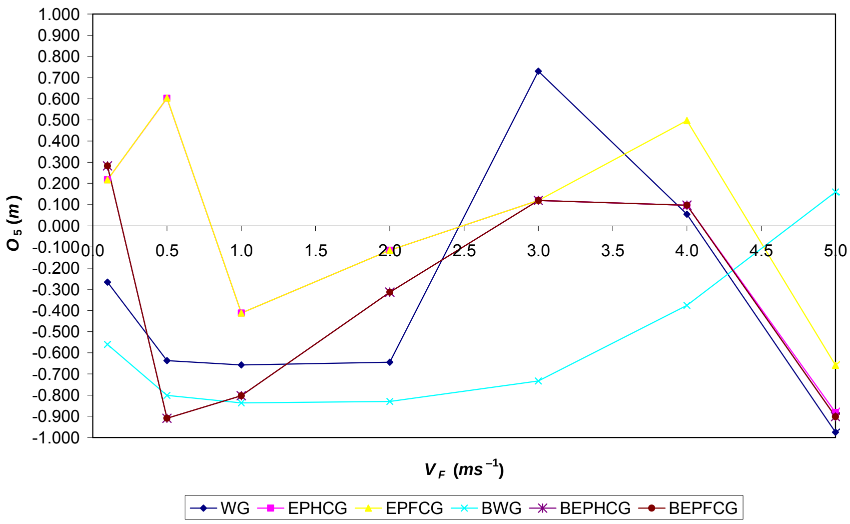

Fig. 11. Evolution of the rear feet trajectory offset O_5 with the forward locomotion speed V_F

Finally, it is presented the evolution of the performance indices with V_F.

Figure 12 presents the evolution of the mean absolute density of energy per travelled distance (E_{av}) with V_F, on the range of V_F under consideration. It is possible to conclude that the minimum values of the index E_{av} increase with V_F.

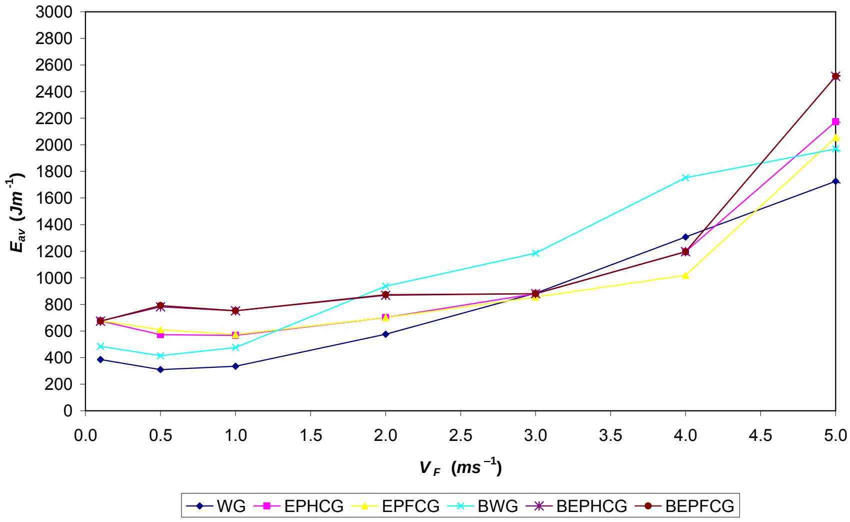

Fig. 12. Evolution of the mean absolute density of energy per travelled distance E_{av} with the forward locomotion speed V_F

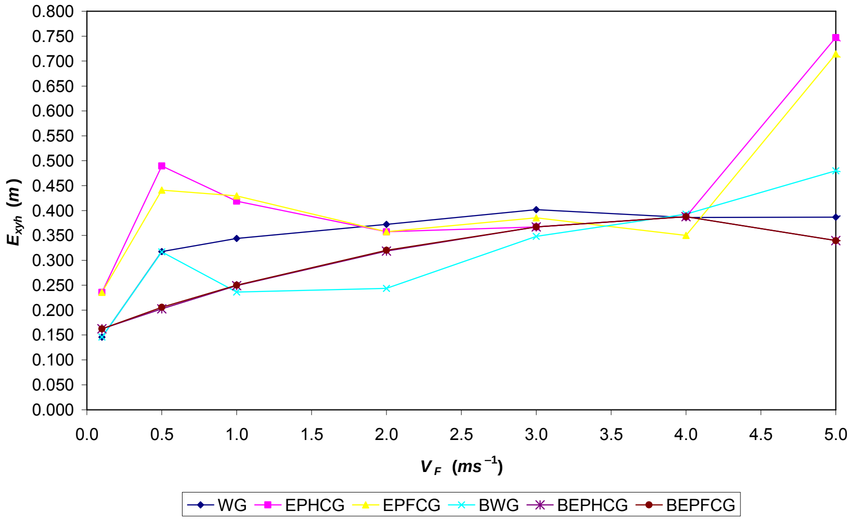

Fig. 13. Evolution of the hip trajectory tracking errors ε_{xyH} with the forward locomotion speed V_F

Similarly, Fig. 13 shows the evolution of the hip trajectory tracking errors (ε_{xyH}) with V_F. As in the previous case, the minimum values of ε_{xyH} also increase with V_F, in the entire rage of V_F tested. It should be mentioned, however, that the EPHCG and the EPFCG present a peak of this metric for $V_F = 0.5$ ms^{-1}.

5. Conclusions

This paper describes the determination of the optimum locomotion and hexapod robot parameters, through a GA, while the robot is walking with different periodic gaits in the range $0.1 \leq V_F \leq 5.0$ ms^{-1}. The GA runs over a simulation application of legged robots (developed in the C programming language), which allows the optimization of the parameters of the robot model and gaits, for different locomotion speeds.

The results reveal that the robot model and locomotion parameters should be adapted to the walking velocity in order to optimize the robot performance. In particular, as the forward velocity increases, the values of β and H_B, should be decreased and the value of L_S increased. It was also concluded that the front, middle and rear legs should present distinct trajectory offsets and their segments should present different dimensions and masses.

Based on the described GA, the authors plan to develop several simulation experiments to find the parameters that optimize the robot locomotion, from the viewpoint of the indices E_{av} and ε_{xyH}, for distinct hip trajectories, on the range of V_F under consideration on this paper.

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