

**Modelling, Identification,  
and Control**

Editor: K. Hangos

ISBN: 978-0-88966-515-9

52



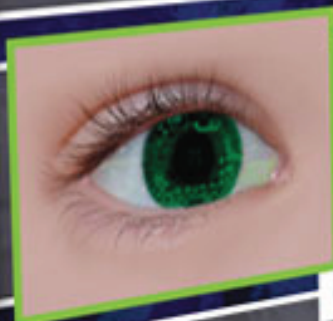
A Publication of the International Association  
of Science and Technology for Development

Proceedings of the 29th IASTED International Conference on

**Modelling,**



**Identification,**



**and**

**Control**

Editor: K. Hangos  
ISBN: 978-0-88966-515-9



A Publication of the International Association  
of Science and Technology for Development

Proceedings of the 29th IASTED International Conference on

**Modelling,**



**Identification,  
and**

**Control**



Editor: K. Hangos

February 15 - 17, 2010  
Heldbruck, Austria

ISBN: 978-0-88966-515-9

## OPTIMIZATION OF HEXAPOD LOCOMOTION USING GENETIC ALGORITHMS

Manuel F. Silva, Ramiro S. Barbosa, J. A. Tenreiro Machado  
Department of Electrical Engineering  
Institute of Engineering of Porto  
Rua Dr. António Bernardino de Almeida  
4200-072 Porto, Portugal  
email: {mss,rsb,jtm}@isep.ipp.pt

### 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, that allows the optimization of several locomotion, model and controller parameters, for different locomotion speeds and gaits. Here are studied the model and locomotion parameters that optimize the robot performance, in a large range of distinct velocities.

### KEY WORDS

Legged Robots, Locomotion, Gait, Optimization, Genetic Algorithms.

## 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, 4, 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 simultaneously generate the mechanical structure and the robot controller [8, 9, 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 introduces the simulation results and their analysis. Finally, section five outlines the main conclusions of this study.

## 2 Hexapod Robot Model and Control Architecture

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

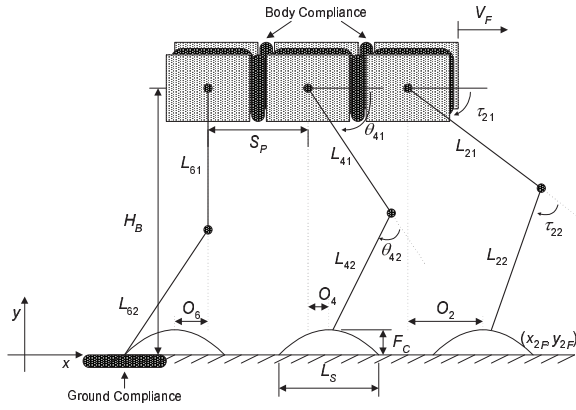


Figure 1. Kinematic and dynamic hexapod robot model

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  $L_{i2}$  (being the total length of each robot leg equal to 1 m) and the foot trajectory offset  $O_i$  ( $i = 1, \dots, n$ ). 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 the particular gait and the 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  $t_T$ ) [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, as inputs, the desired Cartesian trajectories of the leg hips  $\mathbf{p}_{Hd}(t) = [x_{iHd}(t), y_{iHd}(t)]^T$  (horizontal movement with a constant forward speed  $V_F = L_S / T$ ) and feet  $\mathbf{p}_{Fd}(t) = [x_{iFd}(t), y_{iFd}(t)]^T$  (periodic trajectory for each foot, being the trajectory of the swing leg foot computed through a cycloid function) and, by means of an inverse kinematics algorithm  $\psi^{-1}$ , generates as outputs the joint trajectories  $\Theta_d(t) = [\theta_{i1d}(t), \theta_{i2d}(t)]^T$  (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 (Figure 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  $B_{\eta F}$  ( $\eta = \{x, y\}$  in the {horizontal, vertical} directions, respectively) (Figure 1). The values for the parameters are based on the studies of soil mechanics (Table 1) [14].

The robot inverse dynamic model is formulated as:

Table 1  
Ground parameters

Ground parameters	
$K_{xF}$	$1.3 \times 10^6 \text{ Nm}^{-1}$
$K_{yF}$	$1.7 \times 10^6 \text{ Nm}^{-1}$
$B_{xF}$	$2.3 \times 10^6 \text{ Nsm}^{-1}$
$B_{yF}$	$2.7 \times 10^6 \text{ Nsm}^{-1}$

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

where  $\Gamma$  is the vector of forces/torques,  $\Theta$  is the vector of position coordinates,  $\mathbf{H}(\Theta)$  is the inertia matrix and  $\mathbf{c}(\Theta, \dot{\Theta})$  and  $\mathbf{g}(\Theta)$  are the vectors of centrifugal/Coriolis and gravitational forces/torques, respectively. The matrix  $\mathbf{J}^T(\Theta)$  is the transpose of the robot Jacobian matrix,  $\mathbf{F}_{RH}$  is the vector of the body inter-segment forces and  $\mathbf{F}_{RF}$  is the vector of the reaction forces that the ground exerts on the robot feet, being null during the foot transfer phase.

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

The general control architecture of the multi-legged locomotion system is presented in Figure 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.

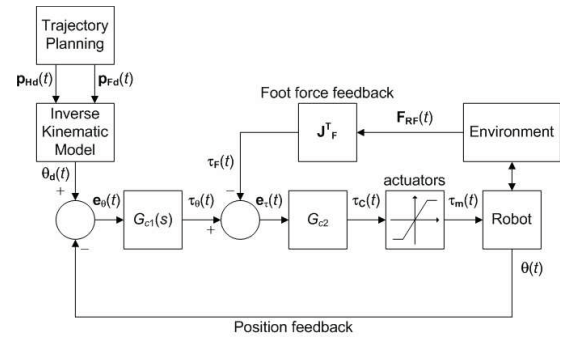


Figure 2. Quadraped robot control architecture

### 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, i.e., 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]. 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). 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) [17].

#### 3.3 Base Structure of the Developed GA

The outline of the specific GA is as follows:

1. **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 admissible values [17] for the corresponding parameters.
2. **Simulation:** Simulate the robot locomotion for all chromosomes in the population using the simulation model.
3. **Fitness:** Select and evaluate the fitness function for each chromosome. The robot locomotion performance is evaluated by computing the indices  $\{E_{av}\}$  and  $\{\varepsilon_{xyH}\}$  [15], according to the user's selection.

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

Minimum Value	Variable	Maximum Value
0 <	$L_s$	$\leq 10$ m
0 <	$H_B$	$\leq 1$ m
0 <	$\beta$	$\leq 100$ %
0 <	$F_C$	$\leq 1$ m
0 <	$L_{11}$	$\leq 1$ m
0 <	$L_{12}$	$\leq 1$ m
0 <	$L_{21}$	$\leq 1$ m
0 <	$L_{22}$	$\leq 1$ m
0 <	$L_{31}$	$\leq 1$ m
0 <	$L_{32}$	$\leq 1$ m
0 <	$O_1$	$\leq 10$ m
0 <	$O_2$	$\leq 10$ m
0 <	$O_3$	$\leq 10$ m
0 <	$M_b$	$\leq 100$ kg
0 <	$M_{11}$	$\leq 10$ kg
0 <	$M_{12}$	$\leq 10$ kg
0 <	$M_{21}$	$\leq 10$ kg
0 <	$M_{22}$	$\leq 10$ kg
0 <	$M_{31}$	$\leq 10$ kg
0 <	$M_{32}$	$\leq 10$ kg
0 <	$K_{xh}$	$\leq 10000$ Nm
0 <	$K_{yh}$	$\leq 10000$ Nm
0 <	$B_{xh}$	$\leq 10000$ Nms <sup>-1</sup>
0 <	$B_{yh}$	$\leq 10000$ Nms <sup>-1</sup>
-400 <	$\tau_{11min}$	$\leq 0$ Nm
0 <	$\tau_{11Max}$	$\leq 400$ Nm
-400 <	$\tau_{12min}$	$\leq 0$ Nm
0 <	$\tau_{12Max}$	$\leq 400$ Nm
-400 <	$\tau_{21min}$	$\leq 0$ Nm
0 <	$\tau_{21Max}$	$\leq 400$ Nm
-400 <	$\tau_{22min}$	$\leq 0$ Nm
0 <	$\tau_{22Max}$	$\leq 400$ Nm
-400 <	$\tau_{31min}$	$\leq 0$ Nm
0 <	$\tau_{31Max}$	$\leq 400$ Nm
-400 <	$\tau_{32min}$	$\leq 0$ Nm
0 <	$\tau_{32Max}$	$\leq 400$ Nm
0 <	$Kp_{11}$	$\leq 10000$
0 <	$Kd_{11}$	$\leq 1000$
0 <	$Kp_{12}$	$\leq 10000$
0 <	$Kd_{12}$	$\leq 1000$
0 <	$Kp_{21}$	$\leq 10000$
0 <	$Kd_{21}$	$\leq 1000$
0 <	$Kp_{22}$	$\leq 10000$
0 <	$Kd_{22}$	$\leq 1000$
0 <	$Kp_{31}$	$\leq 10000$
0 <	$Kd_{31}$	$\leq 1000$
0 <	$Kp_{32}$	$\leq 10000$
0 <	$Kd_{32}$	$\leq 1000$

4. **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).

5. **Loop:** If this iteration is the 200<sup>th</sup> 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 and Analysis

The main objective of this study is to find the optimal values for the locomotion, robot model and controller parameters, considering that the robot is moving with variable body velocities, while adopting the Wave Gait (WG).

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

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

We start by analyzing the evolution of the locomotion parameters with  $V_F$ . In a second phase, we repeat the analysis for the robot model parameters.

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).

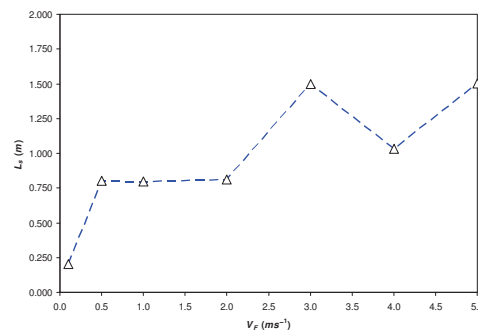


Figure 3. Evolution of the Step Length  $L_S$  with the forward locomotion speed  $V_F$

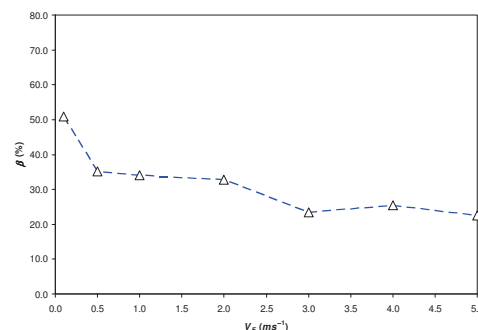


Figure 4. Evolution of the Duty Factor  $\beta$  with the forward locomotion speed  $V_F$

In Figure 4 it is presented the evolution of the Duty Factor ( $\beta$ ) with the forward locomotion speed ( $V_F$ ). It is seen that the optimal value of  $\beta$  decreases with  $V_F$ . For  $V_F = 0.1 \text{ ms}^{-1}$  the value of  $\beta$  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  $V_F \geq 0.5 \text{ ms}^{-1}$ , considered in this study.

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  $V_F \leq 3.0 \text{ ms}^{-1}$  ( $H_B \simeq 0.7 \text{ m}$ ) and increases slightly for higher values of  $V_F$  under study, until it reaches  $H_B \simeq 0.85 \text{ m}$ , for  $V_F = 5.0 \text{ ms}^{-1}$ .

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

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  $\beta$  should decrease and the value of  $L_S$  should increase. Regarding  $H_B$  and  $F_C$ , the first should increase for  $V_F > 3.0 \text{ ms}^{-1}$  while the second should be kept constant in the vicinity of  $F_C \simeq 0.1 \text{ m}$ .

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

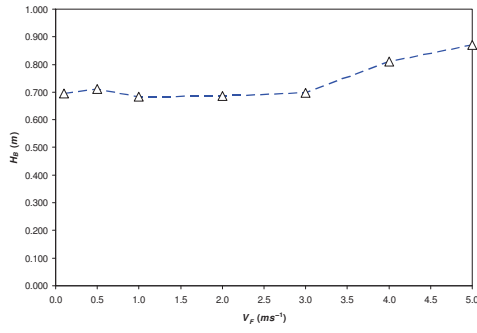


Figure 5. Evolution of the Body Height  $H_B$  with the forward locomotion speed  $V_F$

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 behavior 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 Figure 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  $L_{31}$  reduces for  $V_F \leq 1.0$   $\text{ms}^{-1}$ , but stabilizes around  $L_{31} \simeq 0.35$  m for higher values of  $V_F$ .

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 ( $V_F \leq 0.5$   $\text{ms}^{-1}$ ), decreasing slightly until reaching a value of  $L_{51} \simeq 0.2$  m for  $V_F \simeq 4.0$   $\text{ms}^{-1}$ . For values of  $V_F > 4.0$   $\text{ms}^{-1}$ ,  $L_{51}$  increases again until reaching  $L_{51} = 0.4$  m for  $V_F = 5.0$   $\text{ms}^{-1}$ .

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 Figures 9 – 11 it is presented the evolution of the front, middle and rear feet trajectory offset ( $O_i$ ,  $i = 1, \dots, n$ ) with  $V_F$ . The offset of the front ( $O_i$ ,  $i = 1, 2$ ) and middle ( $O_i$ ,  $i = 3, 4$ ) legs of the robot (Figures 9 and 10) shows a negative value for many values of  $V_F$  and, therefore, the robot should keep its feet backwards regarding its hips.

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  $V_F$ .

Similarly, Figure 13 shows the evolution of the hip trajectory tracking errors ( $\varepsilon_{xyH}$ ) with  $V_F$ . As in the previ-

ous case, the minimum values of  $\varepsilon_{xyH}$  also increase with  $V_F$ , in the entire range of  $V_F$  tested.

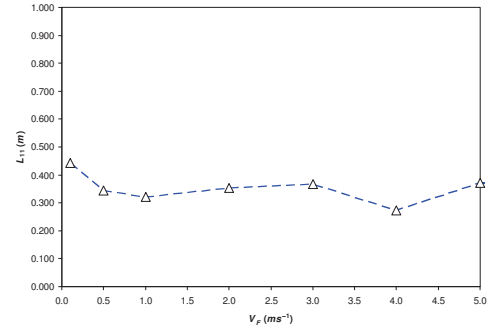


Figure 6. Evolution of the length of the first link of the front legs  $L_{11}$  with the forward locomotion speed  $V_F$ , keeping  $L_{11} + L_{12} = 1.0$  m

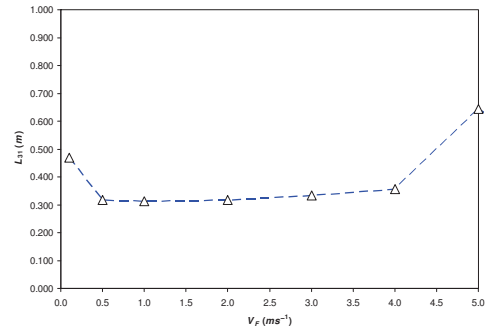


Figure 7. Evolution of the length of the first link of the middle legs  $L_{31}$  with the forward locomotion speed  $V_F$ , keeping  $L_{31} + L_{32} = 1.0$  m

## 5 Conclusion and Future Work

This paper describes the determination of the optimum locomotion and hexapod robot parameters, through a GA, while the robot is walking with the WG in the range  $0.1 \leq V_F \leq 5.0$   $\text{ms}^{-1}$ . 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  $\beta$  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 dimensions and trajectory offsets.

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  $\varepsilon_{xyH}$ , for distinct periodic gaits, and with distinct planned trajectories of the hips, on the range of  $V_F$  under consideration on this paper.

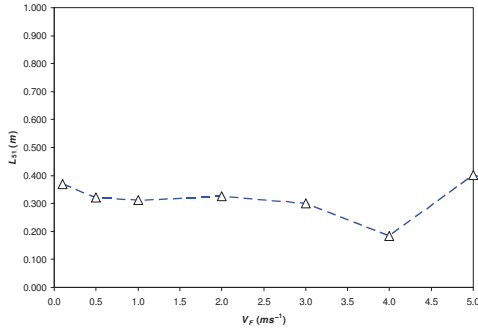


Figure 8. Evolution of the length of the first link of the rear legs  $L_{51}$  with the forward locomotion speed  $V_F$ , keeping  $L_{51} + L_{52} = 1.0 \text{ m}$

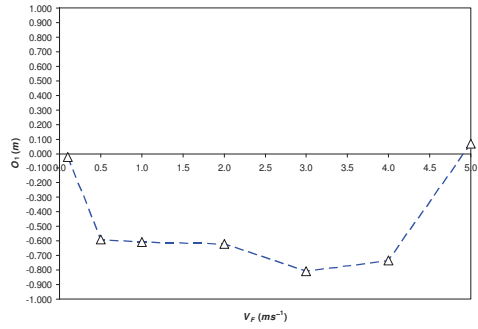


Figure 9. Evolution of the front feet trajectory offset  $O_1$  with the forward locomotion speed  $V_F$

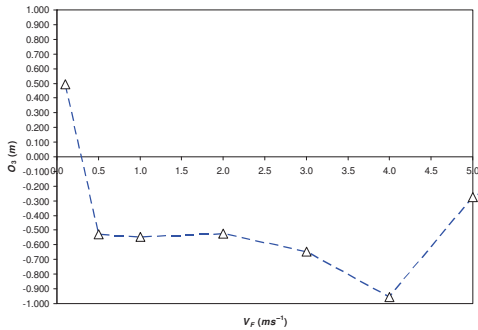


Figure 10. Evolution of the middle feet trajectory offset  $O_3$  with the forward locomotion speed  $V_F$

## Acknowledgements

The authors would like to thank their MSc. student Sérgio Carvalho and GECAD - Grupo de Investigação em Engenharia do Conhecimento e Apoio à Decisão, of ISEP-IPP.

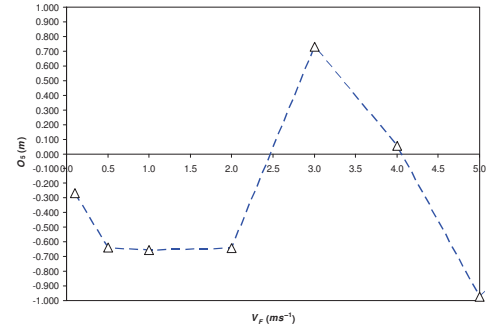


Figure 11. Evolution of the rear feet trajectory offset  $O_5$  with the forward locomotion speed  $V_F$

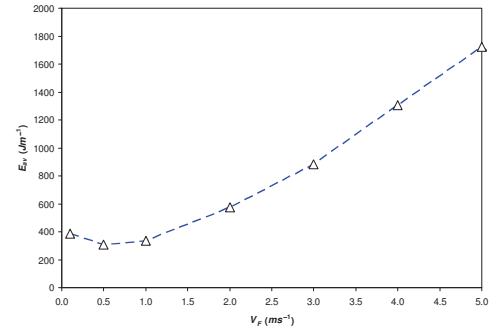


Figure 12. Evolution of the the mean absolute density of energy per travelled distance  $E_{av}$  with the forward locomotion speed  $V_F$

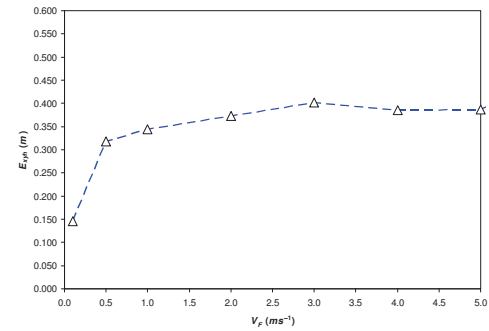


Figure 13. Evolution of the hip trajectory tracking errors  $\varepsilon_{xyH}$  with the forward locomotion speed  $V_F$

## References

- [1] D. C. Kar, Design of statically stable walking robot: A review, *Journal of Robotic Systems* 20 (11) (2003) 671–686.
- [2] M. F. Silva, J. A. T. Machado, A historical perspective of legged robots, *Journal of Vibration and Control* 13 (9–10) (2007) 1447–1486.

- [3] S. Farritor, S. Dubowsky, N. Rutman, J. Cole, A systems-level modular design approach to field robotics, in: Proc. of the IEEE Int. Conf. on Rob. and Aut., 1996, pp. 2890–2895.
- [4] C. Leger, DARWIN2K - An Evolutionary Approach to Automated Design for Robotics, Kluwer Academic Publishers, 2000.
- [5] S. Nolfi, D. Floreano, Evolutionary Robotics - The Biology, Intelligence, and Technology of Self-Organizing Machines, The MIT Press, 2000.
- [6] J. Jurez-Guerrero, Muoz-Gutierrez, W. W. M. Cuevas, Design of a walking machine structure using evolutionary strategies, in: Proc. of the IEEE Int. Conf. on Systems, Man and Cybernetics, 1998, pp. 1427–1432.
- [7] A. Ishiguro, K. Kawasumi, A. Fujii, Increasing evolvability of a locomotion controller using a passive-dynamic-walking embodiment, in: Proc. of the IEEE/RSJ Int. Conf. on Intel. Robots and Systems, 2002, pp. 2581–2586.
- [8] H. Lipson, J. B. Pollack, Towards continuously reconfigurable self-designing robots, in: Proc. of the IEEE Int. Conf. on Rob. and Aut., 2000, pp. 1761–1766.
- [9] K. Endo, F. Yamasaki, T. Maeno, H. Kitano, A method for co-evolving morphology and walking pattern of biped humanoid robot, in: Proc. of the IEEE Int. Conf. on Rob. and Aut., 2002, pp. 2775–2780.
- [10] K. Endo, T. Maeno, H. Kitano, Co-evolution of morphology and walking pattern of biped humanoid robot using evolutionary computation - consideration of characteristic of the servomotors, in: Proc. of the IEEE/RSJ Int. Conf. on Intel. Robots and Systems, 2002, pp. 2678–2683.
- [11] K. Endo, T. Maeno, Co-evolution of morphology and walking pattern of biped humanoid robot using evolutionary computation - designing the real robot, in: Proc. of the IEEE Int. Conf. on Rob. and Aut., 2003, pp. 1362–1367.
- [12] M. F. Silva, J. A. T. Machado, A. M. Lopes, Modelling and simulation of artificial locomotion systems, ROBOTICA 23 (5) (2005) 595–606.
- [13] S.-M. Song, K. Waldron, Machines that Walk: The Adaptive Suspension Vehicle, MIT Press, 1989.
- [14] M. F. Silva, J. A. T. Machado, A. M. Lopes, Position / force control of a walking robot, Machine Intelligence and Robotic Control 5 (2) (2003) 33–44.
- [15] M. F. Silva, J. A. T. Machado, Kinematic and dynamic performance analysis of artificial legged systems, ROBOTICA 26 (1) (2008) 19–39.
- [16] P. J. Fleming, R. C. Purshouse, Genetic algorithms in control systems engineering, in: IFAC (Ed.), IFAC Professional Brief, 2002.
- [17] M. F. Silva, R. S. Barbosa, J. A. T. Machado, Development of a genetic algorithm for the optimization of hexapod robot parameters, in: IASTED (Ed.), Proc. of the 18th IASTED International Conference on Applied Simulation and Modelling, Palma de Mallorca, Balears Islands, Spain, 2009.