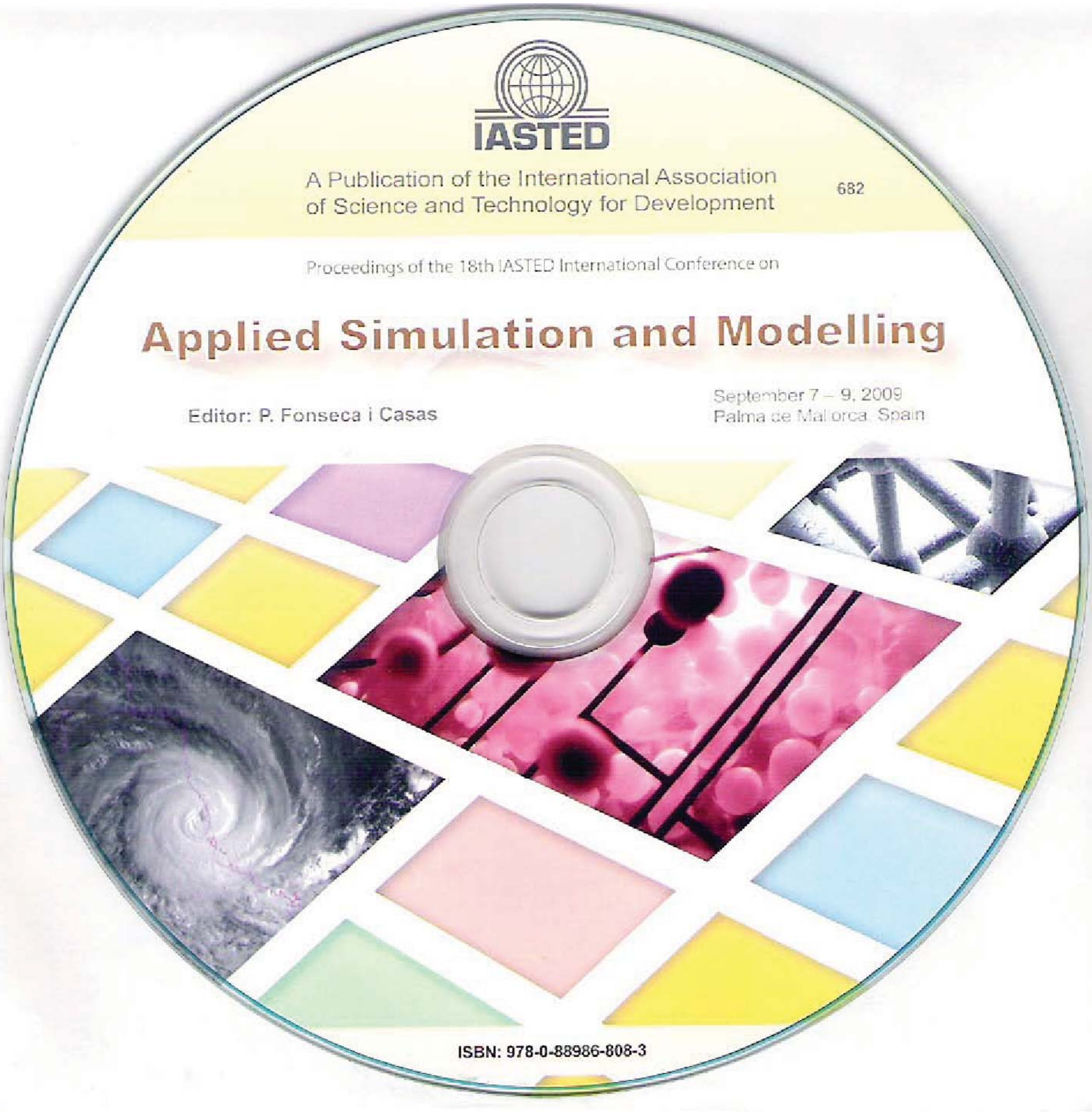

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DEVELOPMENT OF A GENETIC ALGORITHM FOR THE OPTIMIZATION OF HEXAPOD ROBOT PARAMETERS

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ABSTRACT

Legged robots allow the locomotion on terrains inaccessible to other type of vehicles because they do not need a continuous support surface. Different strategies have been adopted for the optimization of these systems, during their design and construction phases, and during their operation. Among the different optimization criteria followed by different authors, it is possible to find issues related to energy efficiency, stability, speed, comfort, mobility and environmental impact. Evolutionary strategies are a way to ”imitate nature” replicating the process that nature designed for the generation and evolution of species. The objective of this paper is to present a genetic algorithm, running over a simulation application of legged robots, which allows the optimization of several parameters of the robot model and of its gaits, for different locomotion speeds.

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

1. Introduction

Legged robots present significant advantages when compared with traditional vehicles having wheels and tracks. Their major advantage is the fact of allowing locomotion in terrain inaccessible to other type of vehicles, since they do not need a continuous support surface. Several different walking robots have been developed up to date [1, 2], but in the present state of development, there are several aspects that need to be improved and optimized. With this idea in mind, different optimization strategies have been proposed and applied to these systems, either during its design and construction phases, or during its operation, namely in what respects to the selection of the gait to be adopted and on its adaptation to the terrain and locomotion conditions. Among the distinct optimization criteria, one may include aspects related to energy efficiency, stability, velocity, comfort, mobility and environmental impact.

This paper reviews two approaches frequently adopted for the optimization of the structure and locomotion modes of artificial legged systems. Such approaches are the mechatronic mimic of the characteristics of biological animals and the use of genetic algorithms (GAs) for the optimization of the legged structure parameters.

The remainder of this paper is organized as follows. Section two presents some biological approximations to walking machines development and introduces the adoption of evolutionary algorithms to the design of legged robots. Sections three and four present the robot model and its control architecture, and the implemented GA, respectively. Finally, section five outlines the main conclusions of this study.

2. Optimization of Legged Robots

2.1 Biological Approximations

Legged locomotion robots are inspired in animals observed in nature and 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. With this objective in mind, detailed studies of the locomotion and anatomy of the animals to be replicated have been made. Works joining researchers from the robotics and the biology areas are often presented [3, 4, 5, 6]. Several examples of robots that have been developed based on this approximation are discussed by Silva and Machado [2]. This approach is also followed in the design and development of biped and humanoid robots. The designers of these systems get much of their inspiration from humans beings, as proved by several machines with characteristics similar to the humans, namely in the number of degrees of freedom (dof) and in their physical dimensions.

2.2 Evolutionary Strategies

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 as the engine to generate robot structures [7, 8, 9, 10]. 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 [7, 8].

There are also works on which evolutionary strategies are used to optimize the structure of a specific robot. Jurez-Guerrero, et al. [11] developed a biped robot using evolutionary strategies. The final goal was to evolve the biped robot structure, equipped with a passive tail to help keeping balance. The attained robot was built and its adequacy to the proposed task was verified. The use of GAs for optimising the structure of a biped robot was also adopted by Ishiguro, et al. [12]. In their study, the robot should be able to move passively on sloped surfaces and through actuated joints in flat surfaces. On a first phase, the robot body parameters were optimised using a GA and supposing that the robot was passive. After optimizing the robot structure, these authors made use of a second genetic algorithm to optimize the parameters of a controller based on a Central Pattern Generator (CPG) scheme.

Contrary to the examples described previously, where the structure and the control system are optimised separately, Lipson and Pollack proposed the use of GAs for the simultaneous generation of the mechanical structure and the robot controller [13]. Also Endo, et al. adopted a GA to simultaneously optimize the structure and the control system of the biped humanoid robot PINO [14, 15].

The main criticism that can be made to the design approach based in evolutionary strategies lays in its convergence. By other words, 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 [16].

3. Robot Model and Control Architecture

3.1 Kinematics and Trajectory Planning

We consider a hexapod walking system (Figure 1) with $n = 6$ legs, equally distributed along both sides of the robot body, having each one two rotational joints ($i.e., j = \{1, 2\}$ $\equiv$ {hip, knee}) [17].

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} (being the total length of each robot leg equal to 1 m) and the foot trajectory offset O_i ($i = 1, \ldots, n$). Moreover, we consider a periodic trajectory for each foot, with body velocity $V_F = L_S \,/\, T$.

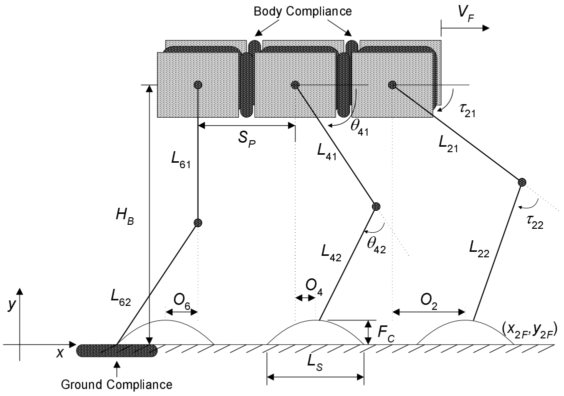

Figure 1. Kinematic and dynamic quadruped robot model

Gaits describe sequences of leg movements, alternating between transfer and support phases. Given the particular gait and the 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) [18]. Based on this data, the trajectory generator is responsible for producing a motion that synchronises and coordinates the legs.

The robot body, and by consequence the legs hips, is assumed to have a desired horizontal movement with a constant forward speed V_F, being the Cartesian coordinates of the hip of the legs, for leg i, given by $\mathbf{p_{Hd}}(t) = [x_{iHd}(t), y_{iHd}(t)]^{\mathbf{T}}$ [17].

Regarding the feet trajectories, for each cycle, the desired trajectory of the foot of the swing leg is computed through a cycloid function and described by (for leg i) $\mathbf{p_{Fd}}(t) = [x_{iFd}(t), y_{iFd}(t)]^{\mathbf{T}}$ [17].

The algorithm for the forward motion planning accepts, as inputs, the desired Cartesian trajectories of the leg hips $\mathbf{p_{Hd}}(t)$ and feet $\mathbf{p_{Fd}}(t)$ and, by means of an inverse kinematics algorithm ψ^{-1}, generates as outputs the joint trajectories $\mathbf{\Theta_d}(t) = [\theta_{i1d}(t), \theta_{i2d}(t)]^{\mathbf{T}}$ [17], that constitute the reference for the robot control system.

In this study it is adopted the mammal leg configuration, namely selecting in ψ^{-1} the solution corresponding to a forward knee.

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

3.2 Robot Dynamic Model

The model for the robot inverse dynamics is formulated as:

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

where $\mathbf{\Gamma}$ is the vector of forces/torques, $\mathbf{\Theta}$ is the vector of position coordinates, $\mathbf{H}(\mathbf{\Theta})$ is the inertia matrix and $\mathbf{c}\left(\mathbf{\Theta}, \dot{\mathbf{\Theta}}\right)$ and $\mathbf{g}(\mathbf{\Theta})$ are the vectors of centrifugal/Coriolis and gravitational forces/torques, respectively. The matrix $\mathbf{J^T}(\mathbf{\Theta})$ 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.

The joint actuators are not considered ideal, exhibiting a saturation given by:

$$\tau_{ijm} = \begin{cases} \tau_{ijC} & , \ |\tau_{ijm}| \le \tau_{ijMax} \\ sgn\left(\tau_{ijC}\right)\tau_{ijMax} & , \ |\tau_{ijm}| > \tau_{ijMax} \end{cases} \tag{2}$$

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

The dynamic model for the hexapod body and foot-ground interaction (Figure 1) considers a compliant robot body, divided in n identical segments (each with mass $M_b n^{-1}$, while making the total mass of the robot equal to 100 kg) and a linear spring-damper system is adopted to implement the intra-body compliance according with [17]:

$$f_{i\eta H} = \sum_{i'=1}^{u} \left[-K_{\eta H}\left(\eta_{iH} - \eta_{i'H}\right) - B_{\eta H}\left(\dot{\eta}_{iH} - \dot{\eta}_{i'H}\right)\right] \tag{3}$$

where $(x_{i'H}, y_{i'H})$ are the hip coordinates and u is the total number of segments adjacent to leg i, respectively. $K_{\eta H}$ and $B_{\eta H}$ ($\eta = \{x, y\}$ in the {horizontal, vertical} directions, respectively) are defined so that the body behavior is similar to the one expected to occur on an animal.

The contact of the i^{th} robot foot with the ground is modelled through a non-linear system (Figure 1) with linear stiffness $K_{\eta F}$ and non-linear damping $B_{\eta F}$ ($\eta = \{x, y\}$ in the {horizontal, vertical} directions, respectively) yielding [19]:

$$\begin{array}{l} f_{i\eta F} = -K_{\eta F}\left(\eta_{iF} - \eta_{iF0}\right) - \\ -B_{\eta F}\left[-\left(y_{iF} - y_{iF0}\right)\right]^{v_\eta}\left(\dot{\eta}_{iF} - \dot{\eta}_{iF0}\right) \\ v_x = 1.0, \ v_y = 0.9 \end{array} \tag{4}$$

where x_{iF0} and y_{iF0} are the coordinates of foot i touchdown and the exponent v_η of the non-linear dashpot is a parameter dependent on the ground characteristics. The values for the parameters $K_{\eta F}$ and $B_{\eta F}$ (Table 1) are based on the studies of soil mechanics [19].

The general control architecture of the multi-legged locomotion system is presented in Figure 2 [19]. The trajectory planning is held 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.

Table 1. Ground parameters

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

The control algorithm considers an external position and velocity feedback and an internal feedback loop with information of foot-ground interaction force.

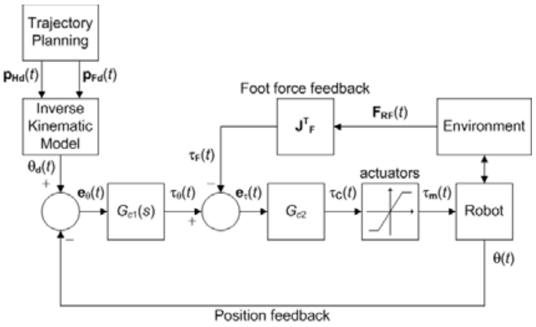

Figure 2. Quadruped robot control architecture

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

$$G_{C1j}(s) = Kp_j + Kd_j s, \quad j = 1, 2 \tag{5}$$

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

4. 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 are modified by means of mutation and/or recombination operators before they are evaluated and reinserted in the population. This is repeated until some condition is satisfied.

4.1 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 $\{\varepsilon_{xyH}\}$ [20]. 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.

4.2 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).

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
$0 <$	β	$\leq$ 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^{-1}
$0 <$	B_{yh}	$\leq$ 10000 Nms^{-1}
$-400 <$	τ_{11min}	$\leq$ 0 Nm
$0 <$	τ_{11Max}	$\leq$ 400 Nm
$-400 <$	τ_{12min}	$\leq$ 0 Nm
$0 <$	τ_{12Max}	$\leq$ 400 Nm
$-400 <$	τ_{21min}	$\leq$ 0 Nm
$0 <$	τ_{21Max}	$\leq$ 400 Nm
$-400 <$	τ_{22min}	$\leq$ 0 Nm
$0 <$	τ_{22Max}	$\leq$ 400 Nm
$-400 <$	τ_{31min}	$\leq$ 0 Nm
$0 <$	τ_{31Max}	$\leq$ 400 Nm
$-400 <$	τ_{32min}	$\leq$ 0 Nm
$0 <$	τ_{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

4.3 Base Structure of the Developed GA

The outline of the specific GA is as follows:

1. **Start:** Generate a random population of $10 < n \leq 50$ (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 mentioned above as the minimum and maximum admissive values 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 $\{\varepsilon_{xyH}\}$ [20], according to the user's selection.

4. **New population:** Create a new population by repeating the following steps:

    - Selection - Select the $1 \leq m \leq 4$ best parent chromosomes according to their fitness. These solutions are copied without changes to the new population (elitism).
    - Crossover - Select 60 % to 90 % 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 0.1 % to 5 % of the individuals to be replaced by mutation of the parents:

one random parent is chosen and, to selected values, is added a small number 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 ith 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.

4.4 Simulation Results

The main objective of this study was to find the optimal values for the robot model and controller parameters, considering that the robot was moving with $V_F = 1\ ms^{-1}$, while adopting the Wave Gait (WG).

Running the GA, with the parameters described above, and considering the simultaneously minimization of both indices (applying a Pareto optimal front) the algorithm converged to the results given in Table 3.

Analyzing the results presented in Table 3 it should be referred that the length of the upper segment of the leg should be smaller than the corresponding length of the lower segment. In the same way, the upper segment of the leg should be heavier than the lower segment. Finally, the trajectory of the legs must be displaced to the rear of the moving direction, as indicated by the values of the parameters O_i.

In Figure 3 it is presented a picture of the hexapod robot while walking with the kinematic and dynamic models parameters found by the GA.

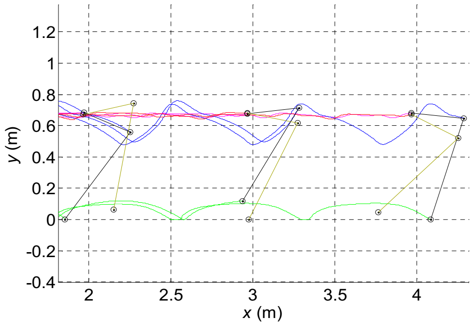

Figure 3. Simulation of the hexapod robot locomotion, while adopting the WG, and with the optimum parameters

5. Conclusion

This paper describes the development of a GA for the optimization of hexapod robot parameters, while walking with

Table 3. Optimum values for the hexapod parameters while walking with the WG, being $V_F = 1\ ms^{-1}$, E_{av} = 334.135 J/m, ε_{xyh} = 0.344 m and the travelled distance d =0 .789 m.

Parameter	Optimum Value
L_s	= 0.798 m
H_B	= 0.685 m
β	= 34.112 %
F_C	= 0.125 m
L_{11}	= 0.321 m
L_{12}	= 0.679 m
L_{21}	= 0.314 m
L_{22}	= 0.686 m
L_{31}	= 0.311 m
L_{32}	= 0.689 m
O_1	= − 0.606 m
O_2	= − 0.546 m
O_3	= − 0.657 m
M_b	= 84.138 kg
M_{11}	= 3.634 kg
M_{12}	= 1.723 kg
M_{21}	= 3.574 kg
M_{22}	= 1.449 kg
M_{31}	= 2.959 kg
M_{32}	= 2.523 kg
K_{xh}	= 89106.766 Nm
K_{yh}	= 9990.477 Nm
B_{xh}	= 776.511 Nms^{-1}
B_{yh}	= 90.151 Nms^{-1}
τ_{11min}	= − 358.508 Nm
τ_{11Max}	= 176.209 Nm
τ_{12min}	= − 288.704 Nm
τ_{12Max}	= 53.051 Nm
τ_{21min}	= − 264.891 Nm
τ_{21Max}	= 75.424 Nm
τ_{22min}	= − 229.980 Nm
τ_{22Max}	= 156.389 Nm
τ_{31min}	= − 386.089 Nm
τ_{31Max}	= 123, 213 Nm
τ_{32min}	= − 378.953 Nm
τ_{32Max}	= 80.422 Nm
Kp_{11}	= 943.627
Kd_{11}	= 336.111
Kp_{12}	= 3582.081
Kd_{12}	= 14.327
Kp_{21}	= 831.258
Kd_{21}	= 100.013
Kp_{22}	= 3948.079
Kd_{22}	= 30.294
Kp_{31}	= 3934.615
Kd_{31}	= 183.397
Kp_{32}	= 1275.400
Kd_{32}	= 109.285

the WG at $V_F = 1\ ms^{-1}$. This GA runs over a simulation application of legged robots (developed in the C programming language), which allows the optimization of several parameters of the robot model and of its gaits for different locomotion speeds.

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 different values of V_F.

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