Humanoid Robot Gait Planning Resorting to an Adaptive Simulated Annealing Algorithm

José L. Lima, José A. Gonçalves, Paulo G. Costa and A. Paulo Moreira

***Abstract*— This paper addresses a new approach to optimize gait parameter sets using an Adaptive Simulated Annealing optimization algorithm. It presents the issue of reducing energy consumption with planning optimization. The developed realistic simulator, based on a real and commercial robot, emulates the mechanical and electrical aspects of the humanoid robot and reduces the software and prototyping production time. It also allows to develop and test different algorithms and optimization procedures. The developed simulator is used to optimize the energy consumption and the distance travelled by the robot in each step based on a Adaptive Simulated annealing optimization approach. Final results prove the benefits of the presented approach.**

I. INTRODUCTION

Researches in humanoid robots have made notable progress in design, control and systemization of biped machines. However, gait generation and optimization still remain a challenge for such a high-order highly-coupled nonlinear dynamical system [1]. The humanoid robot gait planning presents a large number of unknown parameters that should be found to make the humanoid robot to move (walk). It can be approached in two ways: the online (done in real-time that requires high computational effort) and the offline gait generation methods. This offline approach, brings some advantages such as the ability to use complex algorithms to find an optimal solution.

The optimization of the humanoid robot gait is a good area to apply optimization methods over the simulated robot. It is prudent to avoid time-consuming optimization runs that wear out the robot hardware.

In order to generate walking patterns for different locomotion kinematics, the common way of most existing approaches is to precompute reference trajectories [2]. Similarly, using precomputed reference trajectory, this paper presents an overview of our efforts to develop a new simulated gait planning methods for humanoid robots. For that purpose, the approach was used for the optimization technique. It is a generic probabilistic method for the global optimization problem. It tries to find the global minimum of a given function in a large search space (as it happens in humanoid gait planning) and can escape from local minima. Besides, there must be used an optimizing method because it is unthinkable to perform a complete search once the search space is huge.

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Before the optimization on the real robot, several iterations were evaluated using a simulated model of the humanoid robot. The simulations were conducted in [3], a physical robot simulator that is capable to simulate user-defined robots in three-dimensional space since it includes a physical model based on rigid body dynamics (the - [4]).

The paper is organized as follows: Section II, shortly point out the developed Simulator ( ) and the humanoid robot modeling with its parameters. This is followed by the gait planning optimization section that presents a brief description of an Adaptive Simulated Annealing approach and the optimizations criteria. Section IV presents a discussion of results and finally, section V concludes this work and gives a short outlook on ongoing and future work on this topic.

II. DEVELOPED SIMULATOR

There are several simulators with humanoid simulation capability. , as a developed simulator, is a generic simulator that allows the access to the low level behaviour, such as dynamical model, friction model, servomotor model and sensors model in a way that can be mapped to the real robot, with a minimal overhead. The developed simulator, based on , allows to build several robots. was developed having in mind the full access to all control levels and the possibility of adding several sensors and its modeling. This simulator was presented in previous works [5] [6]. Its is actually serving as the base of humanoid, wheeled and manipulator robots simulator in other projects. The realism of the dynamics implemented in is achieved by decomposing the robot in several rigid bodies and electric motors accurate modeling. The mechanics involved in the body are simulated numerically considering its physical shape, mass and moments of inertia, friction surfaces and elasticity. Joints that connect different bodies are explicitly defined and may be associated with a drive system and sensors. The drive system consists of a DC motor with or without a gearbox and a controller. The controller can be of various types: a PID signal applied to the position or velocity or state feedback controller. The model of the DC motor contains several elements such as nonlinear saturation of the applied voltage, current limit and Coulomb friction that are already published [7] and [5]. Beyond the low level control, offers the possibility to provide reference signals for joints from a highest level implemented by the user. Fig. 1 presents a screenshot of the main window that shows the built humanoid robot on its stand up posture in the environment.

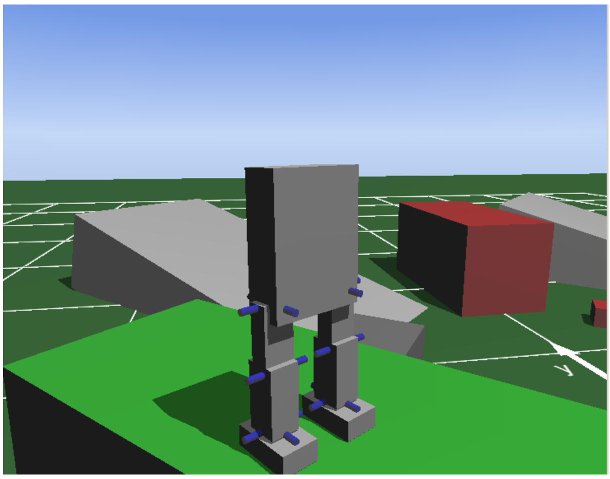

Fig. 1. Simulator main window screenshot.

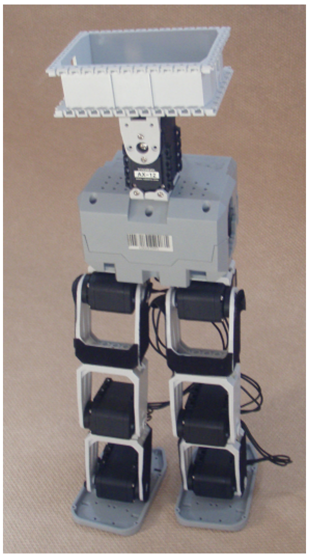

Fig. 2. Real simplified model.

There are several secondary windows that allow to control the simulator environment such as robots position, joints states, frictions constants, graphics issues and debug matter. The environment, composed by robots, static and dynamic objects are described by files that are loaded when starts. The graphical environment allows to test different gaits in order to get smooth walking in any direction, satisfies the stability, movement ranges, speed and torque requirements. Please refer to [3] for more information.

A. Humanoid robot model

Whereas the joint constraints are implemented by the ODE, the total number of connected joints should be reduced in order to get lower numerical errors during simulations. For the simulation, it can be used a simplified robot, presented in Fig. 2, with the same dimensions and weights of the real humanoid robot.

So, head, arms, forearms and hands are despised (included in the trunk) remaining the legs (ankles and hips) two-dimensional joints and knees one-dimensional joints (amount of 10 joints). Future simulations should include these members that assists the equilibrium once is in development stage and thus becoming more accurate. Once hips and ankles have frontal and lateral joints, trunk does not need to oscillate as it happened in older simplified robots developed by the authors [8]. Based on the Bioloid from Robotis [9] real robot, dimensions, masses, positions, articulations, frictions and torques are presented in the simulator model and summarized in Tables I and II according to axis presented in Fig. 3. The ground contact forces are not part of the model (it is computed by ODE) and, just like happens with the real robot, energy recovery is not available. The servomotor and the friction models were already presented in [5]. The [10] well known humanoid robot from Aldebaran Robotics, that has been used in some Robocup [11] competitions, will be used in future simulations.

So, it is desired to find the gait parameters or the states

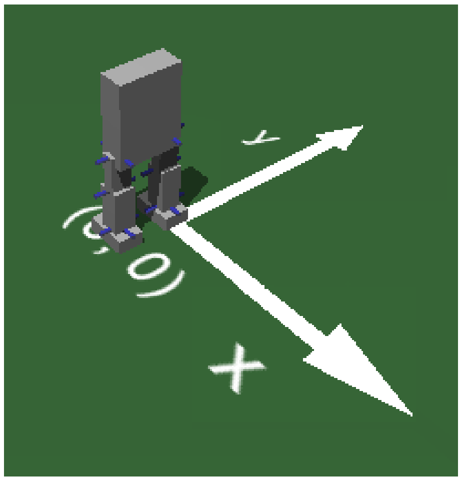

Fig. 3. SimTwo Axis.

TABLE I

SIZES, POSITIONS AND MASSES OF ROBOT BODIES

Body	Position x y z ( )	Size x y z ( )	Mass ( )
Trunk	-0.03 -0.06 0	0.06 0.15 0.2	0.335
Left foot	-0.035 0 -0.28	0.1 0.06 0.033	0.139
Right foot	-0.035 -0.12 -0.280	0.1 0.06 0.033	0.139
Left leg	-0.03 0 -0.21	0.049 0.047 0.101	0.077
Right leg	-0.03 -0.12 -0.21	0.049 0.047 0.101	0.077
Left thigh	-0.03 0 -0.12	0.03 0.048 0.09	0.173
Right thigh	-0.03 -0.12 -0.12	0.03 0.048 0.09	0.173

TABLE II

JOINT POSITIONS AND CONNECTIONS

Joint	Position x y z ( )	Axis	Bodies junction
Left knee	-0.039 0 -0.17	y	Left leg - thigh
Left ankle	-0.027 0 -0.26	xy	Left foot - leg
Right knee	-0.039 -0.12 -0.17	y	Right leg - thigh
Right ankle	-0.027 -0.12 -0.26	xy	Right foot - leg
Left hip	-0.03 0 -0.08	xy	Trunk - left thigh
Right hip	-0.03 -0.12 -0.08	xy	Trunk - right thigh

for each joint that allows the robot to walk. For each state it is needed to find ten optimal values (one for each joint) and a step is composed by several states. Unstable solutions are avoided by their high cost value.

III. Gait Planning and Optimization

The gait-planning is one of the fundamental problems in humanoid mobile robots. The problem of gait planning for humanoid robots is fundamentally different from the path planning for wheeled robots due to the inherent characteristics of legged locomotion. The humanoid locomotion gait planning method can be classified as two main categories: one is online simplified model based gait generation method [12] [13]; and the other one is offline position based gait generation method [14]. The first one, should be done in real time and requires a high computational effort. There are currently some ways for generating dynamically stable gaits, e.g., heuristic research approach, such as genetic algorithms based gait synthesis, model simplification with iteration, and problem optimization methods [15] [16] [17]. The main challenge of gait planning is to find constraint functions and their associated gait parameters. However, finding repeatable gait when the constraint equations involve higher order differential equations still remained unsolved [14]. So, a popular way to solve this problem is to resort to offline optimization techniques such as particle swarm optimization [15]. Using efficient optimal control techniques and stability optimization, it is possible to determine model parameters and actuator inputs that lead to fully open-loop stable running motions [18]. Having in mind the most basic locomotion of a humanoid robot (a simple step) it is desired to obtain the gait planning that allow joints to move the robot. It should be optimized according to some criteria: minimizing energy consumption or maximizing the step distance, for example. For the optimization technique, it was used the approach. The search space in the present problem depends on the step complexity. A complete and symmetrical step can be composed by 4 states, once further states can be achieved through the first 4 states (repeatability of the gait). Each state is composed by 10 degrees of freedom (each joint axis). At the end, the optimization should be applied to a dimension ( ) of 40. The algorithm can be implemented in the simulator adding some random noise (perturb of dimension) to each iteration for present state and analyze the objective (cost) function. If the solution is better than the last solution then it is accepted as the new solution to start a new search. The random vector size ( ) depends on the missed iterations. The process ends when objective function is no longer better. Algorithm 1 presents the described adaptive simulated annealing optimization algorithm where and are support variables, is the iterations number, is the new solution, and are the energy consumption. The Fig. 4 presents a graphical description for two iterations (each iteration is represented by a group of arrows) and for two dimensions (and) of search space.

Input: Initial state
Output: Optimized state

while **do**
  if **then**
  end
  if **then**
  end
  return
end

Algorithm 1: Adaptative Simulated Annealing.

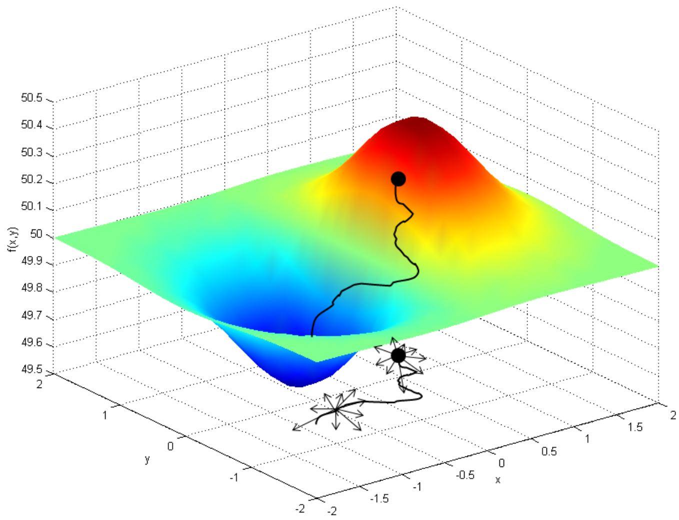

Fig. 4. Optimization based on Adaptive Simulated Annealing.

Starting with a first gait approach, based on ZMP biped walking pattern generator [19] and partially presented in the sequence snapshot of Fig. 5 (repetitive sequence), several simulations should be done in order to achieve the best cost function. Next subsection presents two examples of optimizations (energy per distance minimization and distance maximization) that were run separately. Research in energy optimal walking is also going towards energy recovery through elastic elements in the joints. This is a topic of research by the authors as presented in previous work [8].

A. Energy Consumption Minimization

As humanoid robots are powered by on-board batteries, its autonomy depends on the energy consumption. The trajectory controller can be optimized having in mind the energy consumption minimization [20] with the walking gait optimization [17]. It is desired to minimize the function

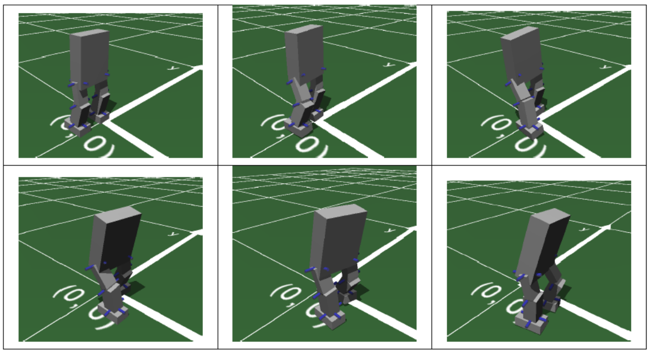

Fig. 5. Simplified model complete walking snapshots.

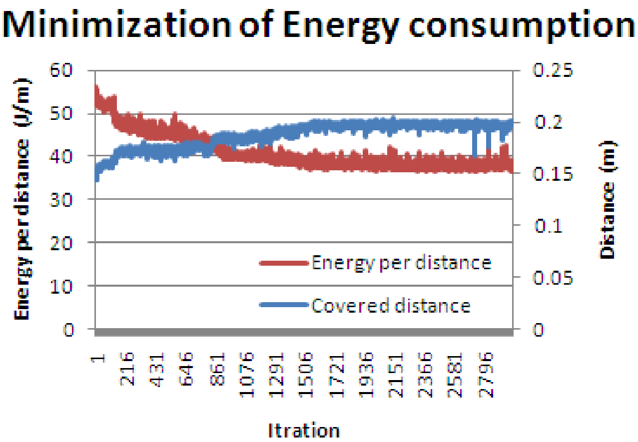

Fig. 6. Minimization of step energy consumption - all iterations.

energy consumption per distance ( ). Starting with the presented in Fig. 5, it is possible to achieve the result presented in Fig. 6 after 2500 iterations. Fig. 6 presents the energy consumption and the distance travelled by the robot in each step each iterations whereas Fig. 7 presents the successful iterations only. As presented, energy per distance consumption has decreased becoming a step more efficient. However, results are further discussed in section IV.

B. Distance travelled by the robot in each step maximization

It is also possible to optimize the to get the maximum of the distance travelled by the robot in each step. Starting with the same presented in Fig. 5, it is possible to achieve the result presented in Fig. 8 after 2000 iterations. Fig. 8 presents the energy consumption and the distance travelled by the robot in each step for each iterations whereas Fig. 9 presents the successful iterations only. As presented, the distance travelled by the robot in each step has increased becoming a step more spaced. However, results are further discussed in section IV.

IV. RESULTS

There are several ways to obtain the optimized gait planning. The presented work optimizes the gait in order to get both approaches: energy consumption and the distance travelled by the robot in each step. Through some iterations in the

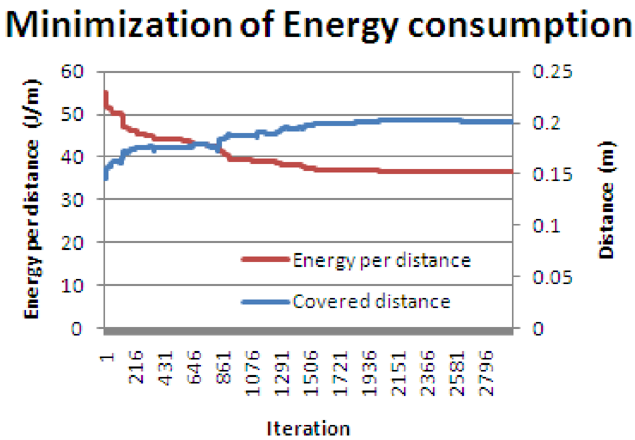

Fig. 7. Minimization of step energy consumption - hit iterations.

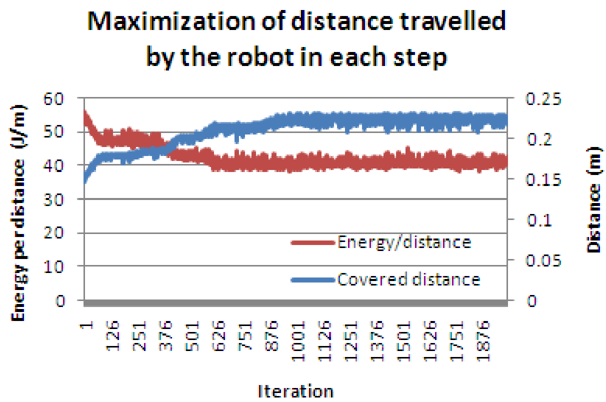

Fig. 8. Maximizations of the distance travelled by the robot in each step - all iterations.

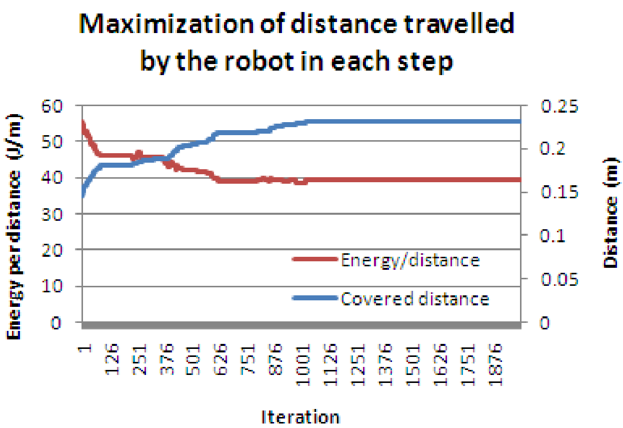

Fig. 9. Maximizations of the distance travelled by the robot in each step - hit iterations.

TABLE III

ENERGY CONSUMPTION AND STEP DISTANCE SUMMARY

Optimization	Energy	Energy %	Distance	Distance %
	55.05		0.14	
Energy minim.		33.75 %		39.65 %
	36.47		0.20	
	55.6		0.14	
Distance maxim.		31.00 %		58.67 %
	38.38		0.23	

TABLE IV

OPTIMIZATION HIT RATE SUMMARY

Optimization	Iterations done	Iteration success	Last iteration success	Hit rate %
Energy minim.	3000	74	2629	2.81 %
Distance maxim.	2000	79	1022	7.70 %

simulator, the final results allow to validate the optimizing method. For the first case (energy per distance optimization), the initial gait consumption was 56.05 and decreased to 36.46 , that means 33.7% of decreasing (note that the distance travelled by the robot in each step also increased from 0.14 to 0.20). For the second case (maximization of the distance travelled by the robot in each step) the distance increased from 0.14 to 0.23 that means 58.67%. Besides, the energy per distance has decreased from 55.62 to 38.38 that means 31.0 %. Table III presents the summary for the results. The presented results validate the simulation approach to optimize the gait planning.

It can also be measured the hit rate for each optimization. The hit rate can be found through the number of successful iterations and the last iteration number ratio. Table IV presents the summary data for both optimizations.

It can be observed that is easier to achieve the distance travelled by the robot in each step best solution than the best energy consumption, once hit rates are 2.81 % and 7.7 %.

V. CONCLUSION AND FUTURE WORK

In this paper we presented a fast and hardware-saving optimization based on Adaptive Simulated Annealing approach to optimize the gait of a biped humanoid robot. The parameters of a gait were optimized for a different conditions: minimizing energy consumption and maximizing step distance. Final results, that validate the approach, show the optimized gait to walk with minimum energy consumption and to walk with the longest step distance. As future work, it is expected the substitution of Bioloid for the NAO from Aldebaran Robotics model and the use of the complete model (all joints instead of the simplified robot).

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