An Evolutionary Algorithm for Trajectory Based Gait Generation of Biped Robot

Ruixiang Zhang, Prahlad Vadakkepat and Chee-Meng Chew
Department of Electrical and Computer Engineering, National University of Singapore
4 Engineering Drive 3, Singapore, 117576
Email: {g0202712, prahlad, mpeccm}@nus.edu.sg

Abstract–The evolution of a dynamic walking gait of biped robot is presented in this paper. The gait is generated for a biped robot to walk on flat ground and climb up stairs. For the trajectory based gait generation, various parameters satisfy ZMP criterion and can realize continuous walking. The evolutionary algorithm is used to choose the parameter combinations. Simulation studies show that the algorithm successfully achieves desired performance in dynamic walking. The RoboSapien, a 17 DOF biped robot is built to apply and verify the walking algorithm.

Keywords Biped robot; evolutionary algorithm; dynamic walking; Zero Moment Point.

1 INTRODUCTION

There are various algorithms to generate walking gait for humanoid robot. Trajectory based gait generation is simple to use and achieve desired performance. Static walking can be achieved by Center of Gravity (CG) control [1]. The Zero Moment Point (ZMP) trajectory control [2], [3] can realize stable dynamic walking. The ZMP is the point on the ground around which the sum of all the moments of the active forces equals zero. In order to achieve stable dynamic walking, the ZMP must be kept inside the support region. This criterion ensures that the support foot is stationary on the ground in single support phase. Under such circumstances, the biped robot can be considered as a traditional manipulator for analysis purposes.

In recent years, a lot of biped robots have been developed [4-7] and many researchers [8-20] have focused their research on biped walking control.

The walking cycle is divided into single supported phase and double support phase. In the single support phase, cubic polynomial is used to generate the hip and swing foot trajectories which satisfy the ZMP criterion. The swing foot should follow a desired trajectory to avoid obstacles and to satisfy the landing constraints. In the double support phase, the robot transfers the weight from the support foot to the landing foot. This is the weight acceptance phase [21].

From the biological point of view, human walking is also based on the memory of the gait. After learning, humans utilize the gait with the one that has the best performance. Various parameters are used in the gait generation for the robot. Normally the parameters are tuned manually. Although continuous dynamic walking can be realized, the best performance can not be achieved always.

Evolutionary algorithms (EA) [22] are stochastic search techniques based on natural selection and the survival of the fittest. Nature produces a population with individuals that fit the environment better. By mimicking this concept, EA are successfully used in various fields. In EA, each individual represents a search point in the space of potential solution of a given problem. Descendants of individuals are generated by randomized processes intended to model recombination and mutation. Recombination exchanges information between two or more parent individuals and mutation corresponds to an erroneous self-replication of individuals. To evaluate the performance of each individual, a fitness value is assigned to individuals. The probability of the individual to be selected as a parent depends on the fitness value. The individual with a better fitness value has more chance to be selected. This ensures that good quality is inherited by the following generation.

Evolutionary algorithms are also useful to generate optimal robot walking sequences. Some applications [23], [24] on robot motion control are very successful. This paper describes an evolutionary algorithm for planning motion patterns for the biped robot. Evolutionary algorithm is utilized to search for the combination of parameters that can result in the best performance.

The paper is organized as follows. The biped robot is introduced in Section 2. In Section 3, the trajectory based algorithm for gait generation is proposed. Evolutionary algorithm is described in Section 4. Simulation and experimental results are provided in Section 5. Section 6 concludes the work.

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2 BIPED ROBOT: ROBOSAPIEN

RoboSapien (Fig. 1) is a fully autonomous humanoid robot designed and built in the Mechatronics and Automation laboratory of National University of Singapore. The objective of the RoboSapien project is to design and build a research platform to investigate the humanoid robot walking motion and the use of artificial intelligence tools. The robot can achieve static and dynamic walking on flat ground avoiding obstacles. It can climb up and down stairs. RoboSapien also has the ability to locate and kick a ball into a goal. The robot is 47 cm tall and weights 2 kg.

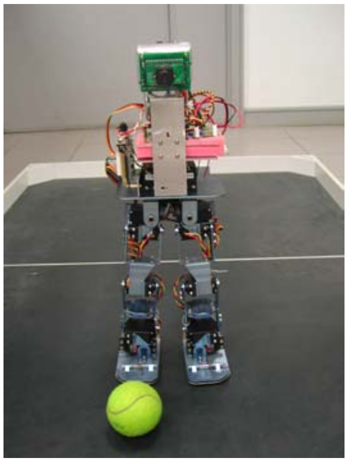

Fig. 1. RoboSapien

The joint configuration of RoboSapien is shown in Fig. 2. Table I lists the specifications of RoboSapien.

TABLE I
SPECIFICATIONS OF ROBOSAPIEN

	length	mass
Trunk	0.14 m	0.8 kg
Thigh	0.08 m	0.3 kg
Shank	0.08 m	0.2 kg
Foot	0.043 m	0.1 kg

The control system structure of RoboSapien is shown in Fig. 3. The system is divided into two parts: a high level control part and a walking control part. Digital Signal Processors (DSP) are used as the controller (Motorola 56F805 and 56F807) in the two parts. The two controllers communicate through Serial Peripheral Interface (SPI). The high level controller receives the video camera signals via serial port. The camera provides the position information of an object within a specified color range. The controller reads the IR sensor's signal to obtain the distance and position information of obstacles. The controller also receives the signal from a digital compass. The compass provides the directional information and navigates the robot. According to the information received from the sensors, the high level controller makes decisions and commands the low level controller. The high level controller also controls the DC sevo motors to drive the camera (up-down and left-right) and IR sensor (left-right).

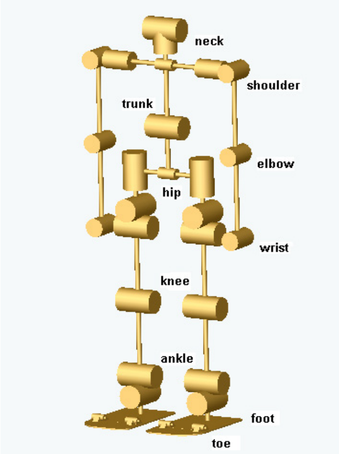

Fig. 2. Joint configuration of RoboSapien

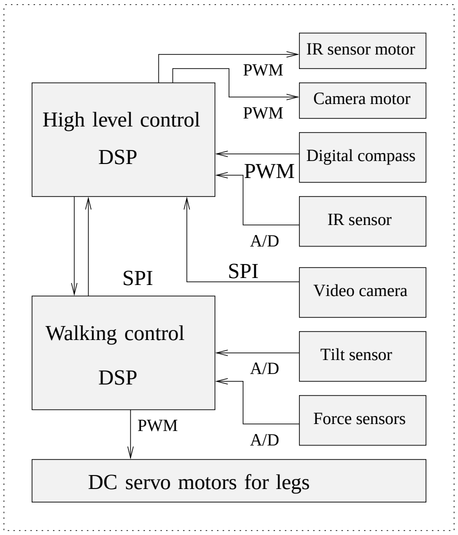

Fig. 3. Control system configuration

Based on the information from the tilt sensor and eight force sensors, the walking motion and other actions are generated according to the high level command. The high level controller commands the DC servo motors via PWM generator. After the desired positions are generated by the walking control algorithm, the position information are sent to the DC servo motors.

3 GAIT GENERATION

The walking motion of the biped can be determined by the hip and foot trajectory. Predetermined trajectories are used for the gait generation. The hip and swing foot trajectories are generated by cubic polynomial.

ZMP criterion is used to ensure the stability of dynamic walking. As shown in Fig. 4, if the initial and final states are known, the trajectory can be generated by a cubic polynomial. If the trajectory satisfies the ZMP criterion, the robot can achieve continuous walking. Only sagittal motion is discussed in this work.

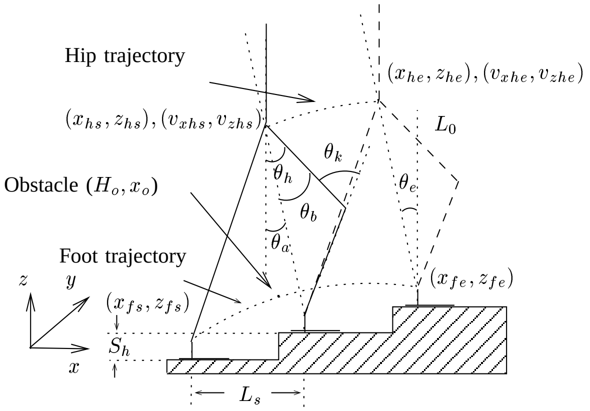

Fig. 4. Hip and foot trajectory

3.1 Derivation of the hip height

After careful observation of human walking, a general rule is derived to determine the optimal hip height for walking. The hip is lifted to a maximum height when walking up stairs. When walking down stairs, the hip is lowered down to enable the foot to reach the lower stair. This rule is represented by:

$$z_{he} = min(max(h_s), max(h_l)), \tag{1}$$

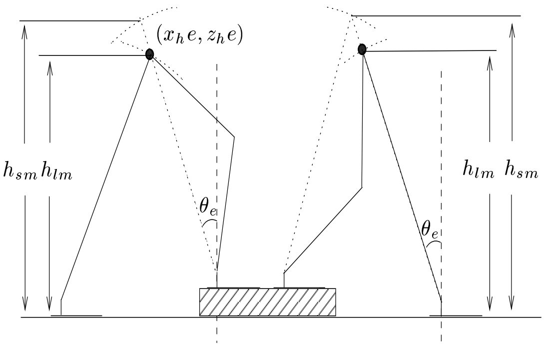

Fig. 5. Determine the height of hip

where h_s and $h_s m$ are respectively the possible and maximum hip heights for the support leg, h_l and $h_l m$ are respectively the possible and maximum hip height for the landing leg as shown in Fig. 5. Equation (1) is valid for various ground conditions, no matter what the terrain is: flat ground, rough or stairs.

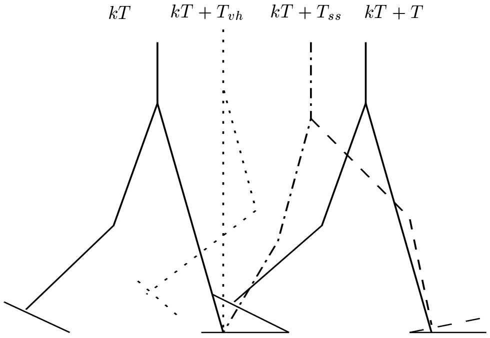

Fig. 6. Walking cycle

3.2 Hip trajectory generation

As shown in Fig. 4, hip trajectory can be generated by cubic polynomial if the initial and final states are known for single support phase. Generally, the initial state is known. The final state includes hip position $[x_{he}, z_{he}]^T$ and hip velocity $[v_{hxe}, v_{hze}]^T$. The desired hip velocity $[v_{hxe}, v_{hze}]^T$ is specified. For any given θ_e, z_{he} can be derived using (1). Consequently x_{he} is derived.

Since the initial and desired final states are known, the hip trajectory for single support phase can be generated. The initial and final constraints associated with a cubic trajectory for z direction $z_h(t)$ can be described as:

$$z_h(t) = \begin{cases} z_{hs} & \text{if } t = kT \\ z_{he} & \text{if } t = kT + T_{ss}, \end{cases} \tag{2}$$

$$\dot{z}_h(t) = \begin{cases} v_{zhs} & \text{if } t = kT \\ v_{zhe} & \text{if } t = kT + T_{ss}, \end{cases} \tag{3}$$

where T is the period for a single step and T_{ss} is the period of the single support phase.

The parameters of the cubic polynomial,

$$z_h(t) = a_0 + a_1(t-kT) + a_2(t-kT)^2 + a_3(t-kT)^3, \tag{4}$$

can be derived based on the initial and final constraints.

The cubic trajectory for x direction $x_h(t)$ is divided into two parts: between $x_h(kT)$ and $x_h(kT+T_{vh})$ and, between $x_h(kT+T_{vh})$ and $x_h(kT+T_{ss})$. T_{vh} is the time point, measured with respect to kT, at which the hip is vertically above the ankle joint. The constraints for $x_h(t)$ can be described as:

$$\begin{cases} x_h(t) = x_{hs} & \text{t=kT} \\ x_h(t) = x_{h1} & \text{t=kT+}T_{vh} \\ x_h(t) = x_{he} & \text{t=kT+}T_{ss} \\ \dot{x}_h(t) = v_{xhs} & \text{t=kT} \\ \dot{x}_h(t^-) = \dot{x}_h(t^+) & \text{t=kT+}T_{vh} \\ \dot{x}_h(t) = v_{xhe} & \text{t=kT+}T_{ss} \\ \ddot{x}_h(t) = a_s & \text{t=kT,} \end{cases} \tag{5}$$

where a_s is the specified initial acceleration. The parameters of a polynomial trajectory can be derived using the constraints in (5). T_{vh} and T_{ss} in a walking cycle are shown in Fig. 6. It is supposed that the initial acceleration and final speed are specified carefully such that a hip trajectory which satisfies the physical constraints can be generated.

3.3 *Swing foot trajectory*

Cubic polynomial is used to generate the swing foot trajectory of single support phase. At the starting and ending points, the following position and speed constraints must be satisfied:

$$\begin{cases} x_f(t) = x_{fs} & \text{t=kT} \\ x_f(t) = x_{fe} & \text{t=kT+}T_{ss} \\ z_f(t) = z_{fs} & \text{t=kT} \\ z_f(t) = z_{fe} & \text{t=kT+}T_{ss} \end{cases} \tag{6}$$

$$\begin{cases} \dot{x}_f(t) = 0 & t = kT \\ \dot{x}_f(t) = 0 & t = kT + T_{ss} \\ \dot{z}_f(t) = 0 & t = kT \\ \dot{z}_f(t) = 0 & t = kT + T_{ss}, \end{cases} \tag{7}$$

where $x_{fe} = x_{fs} + 2L_s$, $z_{fe} = z_{fs} + 2S_h$. As shown in Fig. 4, L_s is the step length and S_h is the stair height.

While climbing stairs, the steps are considered as obstacles. Such an obstacle is at a distance of x_o (the step width) and has a height of H_o (the step height). In order to avoid colliding with the obstacle the height of the swing foot should be larger than H_o at $x = x_o$. The associated constraints can be described as:

$$\begin{cases} z(t) = H_o & t = kT + T_o \\ \dot{z}(t) = 0 & t = kT + T_o. \end{cases} \tag{8}$$

Given the start and end positions on x and z directions, and the height of the obstacle H_o, a smooth foot trajectory $f(t) = [x_f(t), z_f(t)]^T$ can be generated with a cubic polynomial.

The joint position of hip and knee of the swing leg can be derived by inverse kinematics. Suppose the hip and swing foot positions in the sagittal plane at time t are $h(t) = [x_h(t), z_h(t)]^T$ and $f(t) = [x_f(t), z_f(t)]^T$, then the inverse kinematics of the swing leg can be derived as follows:

$$\begin{bmatrix} \theta_a \\ \theta_b \end{bmatrix} = \begin{bmatrix} sin^{-1}\frac{x_f(t)-x_h(t)}{\sqrt{(x_f(t)-x_h(t))^2+(z_h(t)-z_f(t))^2}} \\ cos^{-1}\frac{\sqrt{(x_f(t)-x_h(t))^2+(z_h(t)-z_f(t))^2}}{2L_o} \end{bmatrix}.$$

As shown in Fig. 4, $\theta_h = \theta_a + \theta_b$ and $\theta_k = 2\theta_b$. θ_h and θ_k are the hip and knee joint angles respectively. The thigh and shank are of the same length L_o.

For different parameters, the hip and foot trajectories are generated. ZMP can be derived from the ankle torque:

$$x_{zmp} = \frac{\tau_x}{\sum_i m_i(\ddot{z}_i + g)}, \tag{9}$$

where x_{zmp} is ZMP, τ_x is the ankle torque.

4 GAIT EVOLUTION

In the gait generation algorithm, introduced in the previous section, there are various parameters to tune to. This process is complicated and normally the best performance can not be achieved. This part introduces an evolutionary algorithm for turning the parameters.

In evolutionary algorithms, strings and characters are used to simulate chromosomes and genes. An evaluation function or fitness function $F(t)$ is defined to evaluate the performance of each gene combination. The ideas of population, generations, reproduction, crossover and mutation are also used to simulate a natural system. The reproduction genetic operation is based on the Darwinian principle of reproduction and survival of the fittest. In order to keep the best individuals, the fittest are copied to the next generation without any change. The genetic operation of crossover creates new individuals through the recombination of the genes from the previous generation. Two independent parents are selected based on the probability determined by the fitness. A mutation point in the string is chosen at random and the single character at that point is changed randomly. The changed individual is copied to the new generation.

A set of strings is used to represent the population and each string is evaluated by the fitness function. Another generation is created according to the performances of individuals of the current generation. During the formation of the following generation, the genetic operators of reproduction, crossover and mutation are utilized.

The process of the evolutionary algorithm is outlined below: [22]

```
Input:$\mu, \lambda, \Theta_l, \Theta_r, \Theta_m, \Theta_s$
Output: $a^*$, the best individual found during the run, or
$P^*$, the best population found during the run.
$t \leftarrow 0$;
$P(t) \leftarrow$ initialize($\mu$);
$F(t) \leftarrow$evaluate($P(t), \mu$);
while ($l(P(t), \Theta_l)$ true do
    $P'(t) \leftarrow$ recombine ($P(t), \Theta_r$);
    $P"(t) \leftarrow$ mutate ($P'(t), \Theta_m$);
    $F(t) \leftarrow$ evaluate ($P"(t), \lambda$);
    $P(t+1) \leftarrow$ select($P"(t), F(t), \mu, \Theta_s$);
    $t \leftarrow t + 1$;
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where μ and λ denote the parent and offspring population sizes. $P(t)$ characterizes a population at generation t. Parameter sets Θ_r, Θ_m and Θ_s are used to represent the characteristics of recombination, mutation and selection.

In the gait generation algorithm introduced in the previous section, there are various parameters to tune. Four of the parameters (θ_e, T_{vh}, T_{ss} and z_{fe}) which affect the performance greatly are optimized through EA. The walking performance is evaluated from the ZMP trajectory. The associated fitness function is:

$$F = \frac{1}{\sum_n^{i=1}((x_{zmp}(i) - x_{dzmp}(i))^2}$$

Table II lists the parameters used in the evolutionary algorithm.

TABLE II

PARAMETERS OF THE EVOLUTIONARY ALGORITHM

Parent size μ	20
Offspring size λ	40
Generation	100
Crossover Ratio	0.7
Mutation Ratio	0.15
Reproduction Ratio	0.05

5 SIMULATION AND EXPERIMENTATION

5.1 *Simulation*

A 12-DOF biped model in Yobotics [25] is used to verify the developed algorithm. Proportional-Differential (PD) controller is used on each joint. The biped model has the same parameters as that of the biped robot RoboSapien. The parameters utilized in the simulation study are listed in Table III.

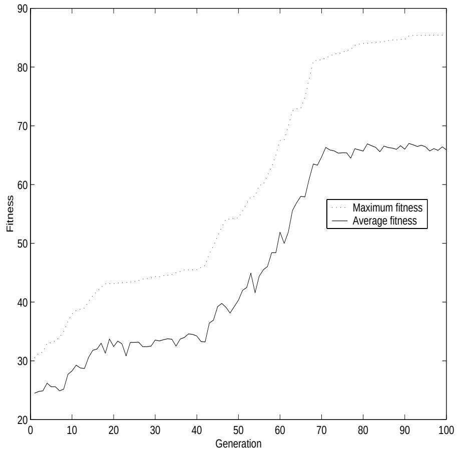

Fig. 7. Fitness changing with generation

As shown in Fig. 7, both the maximum fitness and average fitness converge after about 100 generation. In this evolutionary algorithm, the best individual in each generation is replicated to the next generation.

Fig. 8 and 9 show respectively the ZMP trajectory before and after the evolution. Fig. 10 shows the simulation of the biped robot climbing up stairs.

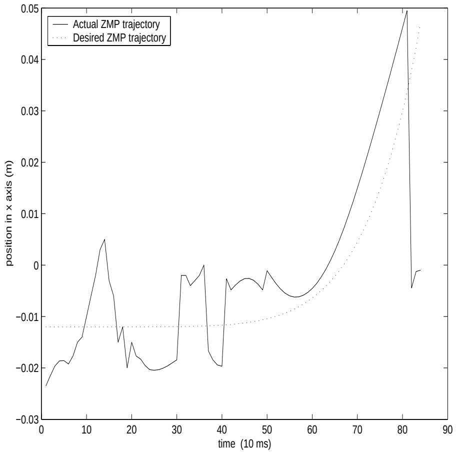

Fig. 8. ZMP before evolution

TABLE III

PARAMETERS OF WALKING SIMULATION

Parameter	value
step length	0.115 m
walking speed	0.1 m/sec

5.2 *Implementation*

The developed algorithm is implemented on the biped robot RoboSapien and stable walking is achieved.

6 CONCLUSION

In this work, an evolutionary algorithm based biped robot walking gait generation is presented. A 12-DOF biped robot is simulated in Yobotics to verify the performance. The performance is also validated by implementing the algorithm on a 17-DOF biped robot RobpSapien.

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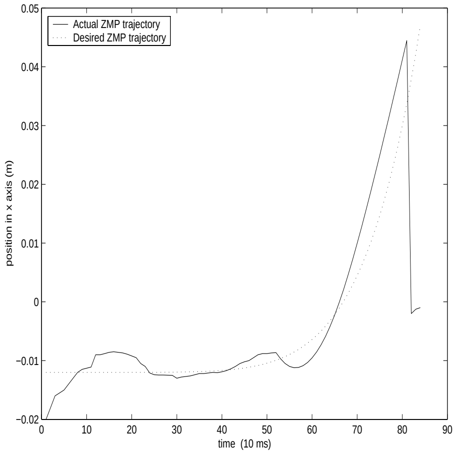

Fig. 9. ZMP after evolution

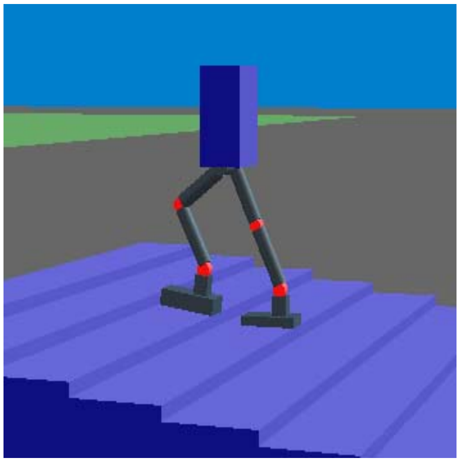

Fig. 10. Simulation of climbing stairs

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