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Full paper

Application of Genetic Algorithms for biped robot gait synthesis optimization during walking and going up-stairs

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Abstract—Selecting an appropriate gait can reduce consumed energy by a biped robot. In this paper, a Genetic Algorithm gait synthesis method is proposed, which generates the angle trajectories based on the minimum consumed energy and minimum torque change. The gait synthesis is considered for two cases: walking and going up-stairs. The proposed method can be applied for a wide range of step lengths and step times during walking; or step lengths, stair heights and step times for going up-stairs. The angle trajectories are generated without neglecting the stability of the biped robot. The angle trajectories can be generated for other tasks to be performed by the biped robot, like going down-stairs, overcoming obstacles, etc. In order to verify the effectiveness of the proposed method, the results for minimum consumed energy and minimum torque change are compared. A Radial Basis Function Neural Network is considered for the real-time application. Simulations are realized based upon the parameters of the 'Bonten-Maru I' humanoid robot, which is under development in our laboratory. The evaluation by simulations shows that the proposed method has a good performance.

Keywords: Biped robots; Genetic Algorithms; consumed energy; torque change; gait synthesis; neural networks.

1. INTRODUCTION

An advantage of legged robots, compared with mobile ones is their possibility to walk on uneven terrain, overcome obstacles, go up- and down-stairs, etc. — which are made difficult when an external power supply is used. To have a long operation time when the power is supplied by a battery, the consumed energy must

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be minimized. Among other factors, such as the robot's weight and the motor type, it also depends on angle trajectory synthesis.

Gait synthesis for the dynamic stable walking of biped robots is a complex problem on which much research has been concentrated. In most of the previous papers related to biped robots [1, 2], the angle trajectories of the leg part are prescribed based on data taken from humans. The motion of the upper body is calculated in order to have the Zero Moment Point (ZMP) inside the sole region. Minimum consumed energy gait synthesis during walking is treated in [3]. The body mass is considered concentrated on the hip of the biped robot. The Coriolis terms of the torque are neglected. In [4], the body link is restricted to the vertical position and the body forward velocity is considered to be constant. The consumed energy, related to the walking velocity and step length, is analyzed in [5]. The gait synthesis of the biped robot is generated based on the calculus of variation method. As the number of d.o.f. is high, the calculation of the partial differential is complex. Also, when the model or the constraints are changed, the formulation of the optimum control is needed again. Biped walking on floor and stairs is treated in [6]. The angular momentum of the locomotion system is put close to the reference function given in advance by using the torque distribution method. The distribution functions of input torque are obtained by minimizing the joint torques. However, their minimization goal is different from ours.

In this paper, a Genetic Algorithm (GA) approach is used as an optimization tool. GA is known to be robust for search and optimization problems [7]. It has been used to solve difficult problems with objective functions that do not possess properties such as continuity, differentiability, etc. These algorithms manipulate a family of possible solutions that allow for the concurrent exploration of several promising areas of the solution space. We deal with two important tasks for biped robot gait synthesis: Case 1 (walking) and Case 2 (going up-stairs). In our work, the angle trajectories are generated based on Consumed Energy (CE) and Torque Change (TC). By using the GA as an optimization tool it is easy to include new constraints and add new variables to be optimized. Except for gait synthesis optimization, we also consider the stability and real-time implementation. The stability is verified through the ZMP concept. For the real-time application of the proposed method, a Radial Basis Function Neural Network (RBFNN) is taught based upon GA results.

The paper is organized as follows. Section 2 gives a brief introduction of GA. Section 3 deals with the gait and body motion. In Section 4, the problem formulation and proposed method are discussed. Boundary conditions and GA variables are treated in Section 5. Simulation results are given in Section 6. A Neural Network implementation for the real-time application is presented in Section 7. Finally, conclusions and future works are given in Section 8.

2. GA

GA is a search algorithm based on the mechanics of natural selection and population genetics. The search mechanism is based on the interaction between individuals and the natural environment. GA comprises a set of individuals (the population) and a set of biologically inspired operators (the genetic operators). The individuals have genes, which are the potential solutions for the problem. The genetic operators are crossover and mutation. GA generates a sequence of populations by using genetic operators among individuals. Only the most suited individuals in a population can survive and generate offspring, thus transmitting their biological heredity to the new generation. The symbolic representation of GA is shown in Fig. 1 and the main steps are shown below:

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(1) Supply a population $P_0$ of $N$ individuals and respective function values
(2) $i \leftarrow 1$
(3) $P_i' \leftarrow$ selection_function $(P_{i-1})$
(4) $P_i \leftarrow$ reproduction_function $(P_i')$
(5) Evaluate $(P_i)$
(6) $i \leftarrow i + 1$
(7) Repeat step (3) until termination
(8) Print out the best solution
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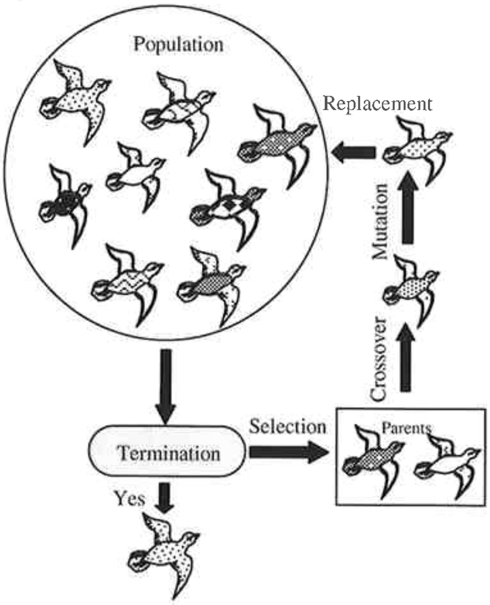
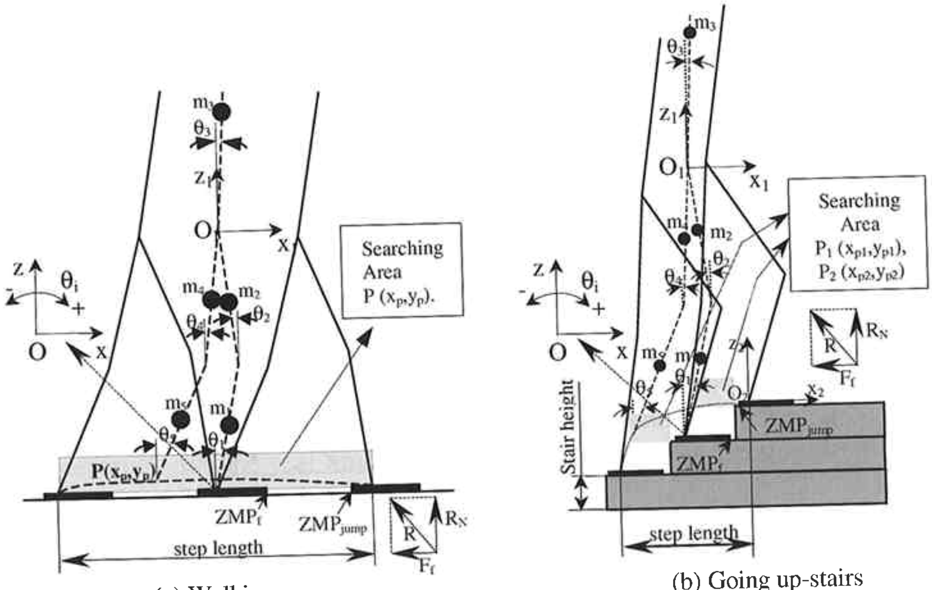


Figure 1. Symbolic presentation of GA.

3. GAIT AND BODY MOTION

During motion, the arms of the humanoid robot will be fixed on the chest. Therefore, it can be considered as a five-link biped robot in the saggital plane, for walking and going up-stairs, as shown in Fig. 2a and b. This model assembles most of the characteristics of the human equivalents of the two aforementioned motions.

The motion of the biped robot is considered to be composed from a single support phase and an instantaneous double support phase. The friction force between the robot's feet and the ground is considered to be great enough to prevent sliding. During the single support phase, the ZMP must be within the sole length, so the contact between the foot and the ground will remain. In this paper, we calculate the ZMP by considering the link mass concentrated at one point. In most of the previous works, the moments generated by the motion of the lower limbs are not considered for ZMP calculation [2]. However, the authors plan to include the moments generated by the lower limbs in the future work. To have a stable periodic walking motion, when the swing foot touches the ground, the ZMP must jump in its sole. This is realized by accelerating the body link. To have an easier relative motion of the body, the coordinate system from the ankle joint of the supporting leg is moved transitionally to the waist of the robot ($O_1X_1Z_1$). Referring to the new



(a) Walking

(b) Going up-stairs

Figure 2. Five-link biped robot.

coordinate system, the ZMP position is written as follows:

$$\overline{X}_{\mathrm{ZMP}} = \frac{\sum_{i=1}^{5} m_i(\ddot{\overline{z}}_i + \ddot{z}_{\mathrm{w}} + g_z)\overline{x}_i - \sum_{i=1}^{5} m_i(\ddot{\overline{x}}_i + \ddot{x}_{\mathrm{w}})(\overline{z}_i + z_{\mathrm{w}})}{\sum_{i=1}^{5} m_i(\ddot{\overline{z}}_i + \ddot{z}_{\mathrm{w}} + g_z)}, \tag{1}$$

where m_i is mass of the particle i, x_{w} and z_{w} are the coordinates of the waist with respect to the coordinate system at the ankle joint of supporting leg, $\overline{x}_i$ and $\overline{z}_i$ are the coordinates of the mass particle i with respect to the $O_1X_1Z_1$ coordinate system and $\ddot{\overline{x}}_i$ and $\ddot{\overline{z}}_i$ are the acceleration of the mass particle i with respect to the $O_1X_1Z_1$ coordinate system.

Based on (1), if the position, $\overline{x}_i$, $\overline{z}_i$, and acceleration, $\ddot{\overline{x}}_i$, $\ddot{\overline{z}}_i$, of the leg part ($i = 1, 2, 4, 5$), the body angle, θ_3, and the body angular velocity, $\dot{\theta}_3$, are known, then because $\ddot{\overline{x}}_3$, $\ddot{\overline{z}}_3$ are functions of l_3, θ_3, $\dot{\theta}_3$, $\ddot{\theta}_3$, it is easy to calculate the body angular acceleration based on the ZMP position. When going up-stairs, the vertical position of the ankle joint of swing leg changes. For this reason, the ZMP position, which is needed to calculate the body acceleration at the beginning of the step, is determined related with the $O_2X_2Y_2Z_2$ coordinate system. Let (0) and (f) be the indexes at the beginning and at the end of the step, respectively. At the beginning of the step, $\ddot{\theta}_{30}$ causes the ZMP to be in the position $\mathrm{ZMP}_{\mathrm{jump}}$. At the end of the step, the angular acceleration $\ddot{\theta}_{3\mathrm{f}}$ is calculated in order to have the ZMP at the position $\mathrm{ZMP}_{\mathrm{f}}$, so that the difference between $\ddot{\theta}_{3\mathrm{f}}$ and $\ddot{\theta}_{30}$ is minimal. Therefore, the torque necessary to change the acceleration of the body link will also be minimal.

4. PROBLEM FORMULATION AND PROPOSED METHOD

4.1. Problem formulation

The problem, with respect to walking or going up-stairs, consists of finding the joint angle trajectories to connect the first and last posture of the biped robot for which the CE or TC is minimal. It can be assumed that the energy to control the position of the robot is proportional to the integration of the square of the torque with respect to time, because the joint torque is proportional to current. Therefore, minimizing the joint torque can solve the minimum CE problem. The cost function *En*, which is a quantity proportional to the energy required for the motion, is defined as follows:

$$En = \frac{1}{2}\left(\int_0^{t_{\mathrm{f}}} \tau^{\mathrm{T}}\tau \,\mathrm{d}t + \Delta\tau_{\mathrm{jump}}^2 \Delta t + \int_0^{t_{\mathrm{f}}} C \,\mathrm{d}t\right), \tag{2}$$

where t_{f} is the step time, τ is the torque vector, $\Delta\tau_{\mathrm{jump}}$ and Δt are the addition torque applied to the body link to cause the ZMP to jump and its duration time, and

C is the constraint function, given as follows:

$$C = \begin{cases} 0 & \text{if the constraints are satisfied} \\ c_i & \text{if the constraints are not satisfied} \end{cases}$$

c denotes the penalty function vector. We consider the following constraints for our system:

- The ZMP to be within the sole length.
- The distance between the hip and ankle joint of the swing leg must not be longer then the length of the extended leg.
- The swing foot, during walking, must not touch the ground prematurely. When going up-stairs the swing foot must not hit the step.

The results generated for minimum CE cost function are compared with the angle trajectories that minimize the rate of change of the torque [8]. The cost function is as follows:

$$J_{\text{torque change}} = \frac{1}{2}\left(\int_0^{t_f} \left(\frac{d\tau}{dt}\right)^{T}\left(\frac{d\tau}{dt}\right) dt + \left(\frac{\Delta\tau}{\Delta t}\right)^{2} + \int_0^{t_f} C\, dt\right). \qquad (3)$$

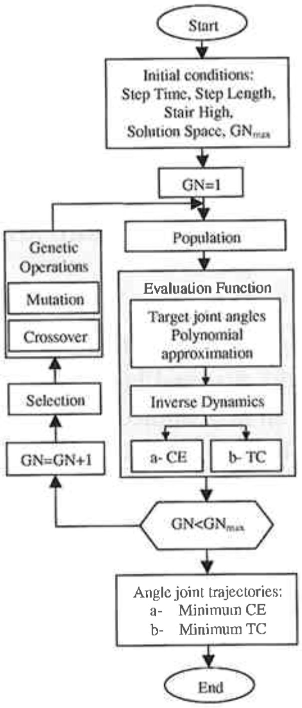


Figure 3. Block diagram of the proposed method.

4.2. Proposed method

The block diagram of the proposed method is presented in Fig. 3. Based on the initial conditions and the range of searching variables, an initial population is generated. Every angle trajectory is presented as a polynomial of time. Its range is determined based on the number of angle trajectory constraints and the coefficients are calculated to satisfy these constraints. The torque vector is calculated from the inverse dynamics of the five-link biped robot [9] as follows:

$$J(\theta)\ddot{\theta} + X(\theta)\dot{\theta}^2 + Y\dot{\theta} + Z(\theta) = \tau. \tag{4}$$

According to (2) and (3), the cost function is calculated for minimum CE and minimum TC, respectively. The value of the cost function is attached to every individual in the population. The GA moves from generation to generation, selecting parents and producing offspring until the termination criterion (maximum number of generations $\mathrm{GN}_{\max}$) is met. Based on the GA results, the gait synthesis is generated for minimum CE and minimum TC, respectively.

5. BOUNDARY CONDITIONS AND GA VARIABLES

To have a continuous periodic motion, the posture of the biped robot is considered to be the same at the beginning and at the end of the step. Therefore, the following relations must be satisfied:

$$\theta_{10} = \theta_{5\mathrm{f}}, \quad \theta_{20} = \theta_{4\mathrm{f}}, \quad \theta_{1\mathrm{f}} = \theta_{50}, \quad \theta_{2\mathrm{f}} = \theta_{40}, \quad \theta_{30} = \theta_{3\mathrm{f}}. \tag{5}$$

In order to find the best posture for walking, the optimum value of θ_{10}, θ_{20} and θ_{30} must be determined by GA. For a given step length during walking or a given step length and stair height when going up-stairs, it is easy to calculate θ_{40} and θ_{50}. When referring to Fig. 2, it is clear that links 1, 2, 4 at the beginning of the step and links 2, 4, 5 at the end of the step change the direction of rotation. Therefore, we can write:

$$\dot{\theta}_{10} = \dot{\theta}_{20} = \dot{\theta}_{40} = \dot{\theta}_{2\mathrm{f}} = \dot{\theta}_{4\mathrm{f}} = \dot{\theta}_{5\mathrm{f}} = 0. \tag{6}$$

The angular velocity of link 1 at the end of the step and link 5 at the beginning of the step is considered to be the same. This can be written in the form $\dot{\theta}_{1\mathrm{f}} = \dot{\theta}_{50}$. In order to find the best value of angular velocity, we consider it as one variable of GA, because the rotation direction of these links does not change. GA will determine the optimal value of the angular velocity of the body link, which is considered to be the same at the beginning and at the end of the step. The following relations are considered for the angular acceleration:

$$\ddot{\theta}_{10} = \ddot{\theta}_{5\mathrm{f}}, \ \ddot{\theta}_{20} = \ddot{\theta}_{4\mathrm{f}}, \ \ddot{\theta}_{1\mathrm{f}} = \ddot{\theta}_{50}, \ \ddot{\theta}_{2\mathrm{f}} = \ddot{\theta}_{40}. \tag{7}$$

In this way, during the instantaneous double support phase, we do not need to apply an extra torque to change the angular acceleration of the links. To find the