Walking Pattern Generator Using an Evolutionary Central Pattern Generator

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Abstract. For the generation of locomotion, such as walking, running or swimming, vertebrate and invertebrate animals use the Central Pattern Generator (CPG). In this paper, a walking pattern generator is proposed using an evolutionary optimized CPG. Sensory feedback pathways in CPG are proposed, which uses Force Sensing Resistor (FSR) signals. For the optimization of CPG parameters, quantum-inspired evolutionary algorithm is employed. Walking pattern generator is developed to generate trajectories of ankles and hip using CPG. The effectiveness of the proposed scheme is demonstrated by simulations and real experiments using a Webot dynamic simulator and a small sized humanoid robot, HSR-IX.

1 Introduction

Despite the complexity of high-DOF systems, these days many humanoid robots have been developed and their performance has been improved a lot[1]-[5]. However, their control algorithm still needs to be improved further to perform a practical task. In this regard, research on developing robust walking patterns of humanoid robots plays one of important roles in this field.

For generation of robust walking patterns of humanoid robots, there are two typical approaches, such as dynamic model based approach and biologically inspired approach. In the former, equations of motion are derived and utilized from mathematical model of the robot in the same way of conventional control researches of manipulator [6]-[8]. In the latter, Central Pattern Generator (CPG) is widely used. Animals are using CPG for generating locomotion, which consists of biological neural networks. It can produce coordinated rhythmic signals using simple input signals [9]. CPG was used to control an 8-link simulated planar biped model by generating the torque of each joint of its lower body [10].

The walking pattern algorithm based on the CPG has two problems. Firstly, the walking pattern algorithm based on the CPG requires much effort to make appropriate oscillation signals for biped locomotion. In order to overcome this, a position control method was presented [11]. However, it is not enough considering stable biped locomotion in 3D space. Secondly, the walking pattern generator based on the CPG is difficult to design by appropriate parameters for feedback pathways in neural oscillators. Therefore, genetic algorithm or reinforcement learning was applied to optimize the involved parameters in neural oscillators [12], [13]. However, these methods need a great number of iterations to optimize them.

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This paper proposes a walking pattern generator using an evolutionary optimized CPG. Walking pattern generator is developed to generate trajectories of the ankles and hip in the Cartesian coordinate system using CPG. It is easy to set up parameters of CPG for generation of appropriate output signals for biped locomotion. The proposed scheme generates trajectory of the position of the center of hip along the lateral direction in addition to trajectories of the position of both ankles along the sagittal and vertical directions for stable biped locomotion in 3D space. The body posture for sensory feedback is obtained using signals of Force Sensing Resistor (FSR) sensors attached on the sole of foot. Also, the Quantum-inspired Evolutionary Algorithm (QEA) is employed to optimize parameters of CPG [14]. The effectiveness of the proposed scheme is demonstrated by computer simulations with the Webot model of a small sized humanoid robot in a dynamic environment and by real experiments with HSR-IX developed in the RIT Lab., KAIST.

This paper is organized as follows. In Section II, evolutionary CPG-based walking pattern generator is proposed. In Section III, simulation and experiment results are presented and finally concluding remarks follow in Section IV.

2 CPG-Based Walking Pattern Generator

This section presents the proposed CPG-based walking pattern generator architecture for stable biped locomotion. For biped locomotion, walking pattern generator generates position trajectories of both ankles and the hip using CPG. The body posture for sensory feedback is obtained using signals of FSR sensors attached on the sole of foot. Parameters of the CPG are optimized using the quantum-inspired evolutionary algorithm.

2.1 Neural Oscillator

In this paper, the neural oscillators as CPG are developed to generate rhythmic signals for humanoid robots. The neural oscillator is biologically inspired to generate a rhythmic signal, defined as follows [15]:

$$\tau \dot{u}_i = -u_i - \sum_{j=1}^{N} w_{ij} o_j - \beta v_i + u_0 + Feed_i, \tag{1}$$

$$\tau' \dot{v}_i = -v_i + o_i, \tag{2}$$

$$o_i = max(0, u_i) \tag{3}$$

where u_i is the inner state of the ith neuron, v_i is the self-inhibition state of the ith neuron, u_0 is the constant input signal, o_i is the output signal, w_{ij} is the connecting weight between ith and jth neuron, τ and τ' are time constants, β is the weight of the self-inhibition, and $Feed_i$ is the sensory feedback signal which is necessary for stable biped locomotion, of the ith neuron. u_0, τ, τ' and w_{ij} are constant parameters. τ and τ' decide the output wave shape and frequency, u_0 determines the output amplitude and w_{ij} determines the phase difference between ith and jth neurons.

2.2 Application to Walking Pattern Generator of CPG

In this paper, walking pattern generator generates trajectories of ankles and the center of hip, respectively, in the Cartesian coordinate system. This approach is easy to set up parameters of CPG, the initial states of neurons and connecting weight in neural oscillators, and feedback pathways, and to change step length or height. Walking pattern generator is provided to generate the trajectory of left and right ankles, respectively, along the sagittal and vertical directions as follows:

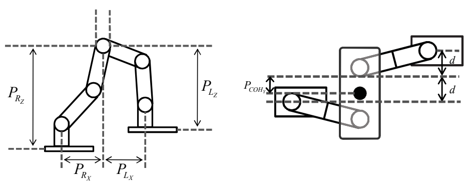
$$P_{L_X} = -A_X(o_1 - o_2), \tag{4}$$

$$P_{R_X} = A_X(o_1 - o_2), \tag{5}$$

$$P_{L_Z} = Z_c - A_Z(o_3 - o_4), \tag{6}$$

$$P_{R_Z} = Z_c + A_Z(o_3 - o_4) \tag{7}$$

where P_{L_X} and P_{R_X} are the distance between the center of hip and left and right ankles, respectively, along the sagittal direction, P_{L_Z} and P_{R_Z} are the distance between the center of hip and left and right ankles, respectively, along the vertical direction,A_X, A_Z are amplitude scaling factor and Z_c is offset factor.



(a) (b)

Fig. 1. Trajectories of ankles and the center of hip. (a) Trajectories of ankles along sagittal and vertical directions. (b) Trajectories of the center of hip along lateral direction.

In 3D space, positions along the lateral direction in addition to sagittal and vertical directions have to be considered for stable biped locomotion. Therefore, generation of position trajectory of the center of hip along the lateral direction is added. Walking pattern generator is provided to generate the trajectory of the center of hip along the lateral direction as follows:

$$P_{COH_Y} = A_Y(o_5 - o_6) \tag{8}$$

where P_{COH_Y} is the distance between the center of hip and the center position of both ankles along the lateral direction.

The projection of trajectories of swing leg's ankle on X-Z plane can be approximated as semi-ellipsoidal trajectories on the X-Z plane, such as $P_X = lcos\theta$ and $P_Z = lsin\theta$. Thus, the desired phase difference between ankle's vertical and horizontal oscillations should be $\pi/2$.

For stable biped locomotion along the lateral direction, the distance between the supported leg and the center of hip along the lateral direction is controlled to be minimum using neural oscillator. When humanoid robot is double supported, the position of the center of hip is given as the center position of both ankles along the lateral direction. When P_Z increases, the distance between the center of hip and the supported leg is designed to decrease such that P_{COH_Y} increases. On the other hand, when P_Z decreases, the distance between the center of hip and the supported leg is designed to increase such that P_{COH_Y} decreases. Consequently, phase difference between P_Z and P_{COH_Y} should be zero.

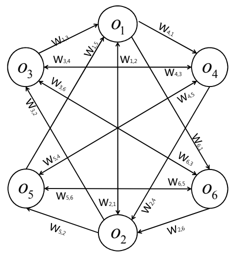


Fig. 2. The neural oscillator

Neural oscillators are designed for stable biped locomotion, as shown in Fig. 2, where $w_{1,2} = w_{2,1} = 2.0$, $w_{3,4} = w_{4,3} = w_{5,6} = w_{6,5} = 1.5$, $w_{1,3} = w_{1,4} = w_{2,4} = w_{2,6} = 0.25$, $w_{3,2} = w_{5,2} = w_{4,1} = w_{6,1} = 0.5$, $w_{3,6} = w6,3 = w_{4,5} = w_{5,4} = 0.5$ are used to satisfy phase difference conditions derived in this section.

2.3 Sensory Feedback Design

When humanoid robot walks using CPG, its balance is maintained using sensory feedback. For sensory feedback, the information on humanoid robot's body posture is needed such that FSR sensors are attached on the sole of foot to collect the information. The sensory feedback pathways are designed as follows:

$$Feed_1 = k_1((F_{L_f} - F_{L_b}) - (F_{R_f} - F_{R_b})), \tag{9}$$
$$Feed_2 = -Feed_1, \tag{10}$$
$$Feed_3 = k_2(F_L - F_R), \tag{11}$$
$$Feed_4 = -Feed_3, \tag{12}$$
$$Feed_5 = k_3((F_{L_l} - F_{L_r}) + (F_{R_l} - F_{R_r})), \tag{13}$$
$$Feed_6 = -Feed_5 \tag{14}$$

where F_L and F_R are left and right foot's vertical reaction forces, respectively, F_{L_f}, F_{R_f}, F_{L_b} and F_{R_b} are left and right foot's front and back vertical reaction forces, respectively, and F_{L_l}, F_{R_l}, F_{L_r} and F_{R_r} are left and right foot's left and right vertical reaction force, respectively.

2.4 Evolutionary Optimization for CPG Algorithm

The proposed CPG-based walking pattern generator has 8 parameters. In this paper, these parameters are evolutionary optimized by employing Quantum-inspired Evolutionary Algorithm (QEA) [14]. The goal to optimize the parameters is to make the humanoid robot approach the destination as soon as possible and to maintain its balance as stable as possible. The objective function is defined as follows:

$$f = \frac{k_x T_1}{d|_{t=T_1}} + k_y \sum_{kT=0}^{T_1} |P_{err}[kT]| + B_P \tag{15}$$

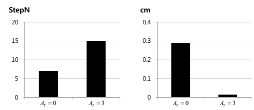
where k_x and k_y are constants and $T_1/d|_{t=T_1}$ is the speed of biped locomotion for T_1, which corresponds to the fitness function for fast biped locomotion. Also, $\sum_{kT=0}^{kT_1} |P_{err}[kT]|$ is the sum of position error along the lateral direction for T_1, which corresponds to the fitness function for decreasing position error along the lateral direction. When stability of biped locomotion increases, position error decreases. Therefore, decreasing position error means that stability of biped locomotion is improved. The last term is the penalty which is to be given if humanoid robot loses its balance and collapses, where B_P is assigned a priori as a constant value. .

3 Simulations and Experiment

The effectiveness of the proposed algorithm was demonstrated by computer simulations with the Webot model of a small sized humanoid robot, HSR-IX in a dynamic environment and real experiments with HSR-IX. In each simulation, if the humanoid robot walks n steps without falling down to the ground and n is lower than 15 steps, total number of steps is n steps, else total number of steps is 15 steps. $\tau/\tau' = 0.105/0.132$ and $\tau = 0.105A_\tau$ were used. The parameters on the CPG were optimized by QEA.

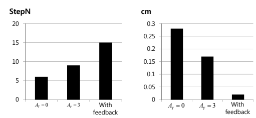
3.1 Effectiveness of Generating Trajectory of Position along the Lateral Direction

Fig. 3 shows the effectiveness of generating trajectories of the position of the center of hip along the lateral direction in addition to the position of left and right ankles, respectively, along the sagittal and vertical directions. $A_X = 2.0$, $A_\tau = 1.5$ and $A_Z = 1.0$ were used. When CPG-based walking pattern generator generated trajectories the position of the center of hip along the lateral direction in addition to the trajectories of the position of the left and right ankles, respectively, along the sagittal and vertical directions, total number of steps increased and position error along the lateral direction decreased. This result shows that it improves stability of biped locomotion if trajectory of the position of the center of hip along the lateral direction is generated using CPG in addition to the position of ankles along the sagittal and vertical directions.



(a) (b)

Fig. 3. Effectivness of generating trajectory of position along the lateral direction. (a) Total number of steps. (b) Position error along the lateral direction.



(a) (b)

Fig. 4. Effect of sensory feedback pathways. (a) Total number of steps. (b) Position error along the lateral direction.

3.2 Effectiveness of Sensory Feedback Pathways

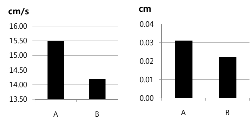
Fig. 4 shows the effectiveness of including sensory feedback pathways. $A_X = 3.0$, $A_\tau = 1.5$ and $A_Z = 1.2$ were used. In this simulation, humanoid robot's walking speed was faster than that in Sec. 3.1, such that it was hard to maintain balance without sensory feedback pathways. Generating trajectory of the position with sensory feedback pathways, total number of steps increased and position error along the lateral direction decreased. This result shows that sensory feedback based on FSR sensor maintains humanoid robot's balance and prevents it from falling down to the ground.

3.3 Effectiveness of Evolutionary Optimization

In Fig. 5, the velocity and position error along were plotted, when k_x was fixed as 500, and k_y was changed. When k_y increased, the walking velocity was slower, but the position error along the lateral direction decreased. This result illustrates that when k_y decreases, the optimization of the parameters makes the humanoid robot walk faster, when k_y increases, the optimization of the parameters makes the biped locomotion more stable.

3.4 Experiment

Experiment was carried out with the actual humanoid robot, HSR-IX. $\tau/\tau' = 0.105/0.132$, $\tau = 0.105A_\tau$, $A_\tau = 4$, $A_x = 2.0$, $A_y = 3.0$ and $A_z = 0.5$ were used. For stable biped locomotion in real experiments, the parameters, $k_1 \sim k_3$, in sensory feedback pathways of the CPG, were evolutionary optimized using the computer simulation of



(a) (b)

Fig. 5. Effectiveness of evolutionary optimization. A is $k_x = 500$, $k_y = 100$ and B is $k_x = 500$, $k_y = 200$. (a) The velocity. (b) Position error along the lateral direction.

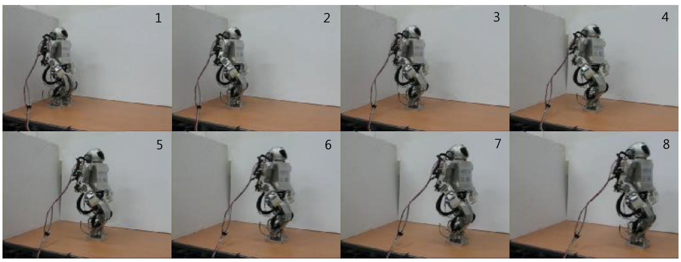


Fig. 6. Shapshots of experiment using HSR-IX

HSR-IX model by Webot. Then these parameters were tuned for proper walking by trial and error. Fig. 6 shows the humanoid robot achieved stable walking.

4 Conclusion

This paper proposed a walking pattern generator for stable biped locomotion based on evolutionary CPG. The neural oscillators in the CPG were developed to generate rhythmic signals. The proposed CPG-based walking pattern generator generated trajectory of the position of the center of hip along lateral direction in addition to trajectories of the position of ankles along the sagittal and vertical directions for stable biped locomotion in 3D space. The sensory feedback pathways in CPG were designed using FSR signals. Quantum-inspired Evolutionary Algorithm (QEA) was employed to optimize parameters of CPG for stable and fast biped locomotion. In order to demonstrate the performance of the proposed scheme, computer simulations were carried out with the Webot model of the small sized humanoid robot, HSR-IX in a dynamic environment and real experiments were carried out with HSR-IX developed in the RIT Lab., KAIST.

Acknowledgments

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References

1. Hirai, K., Hirose, M., Haikawa, Y., Takenaka, T.: The development of honda humanoid robot. In: Proc. IEEE Int. Conf. on Robotics and Automations, Leuven, Belgium, pp. 1321–1326 (May 1998)
2. Ogura, Y., Aikawa, H., Shimomura, K., Kondo, H., Morishima, A., Lim, H.-O., Takanishi, A.: Development of a new humanoid robot WABIAN-2. In: Proc. IEEE Int. Conf. on Robotics and Automations,Orlando, Florida, pp. 76–81 (May 2006)
3. Akachi, K., Kaneko, K., Kanehira, N., Ota, S., Miyamori, G., Hirata, M., Kajita, S., Kanehiro, F.: Development of humanoid robot HRP-3P. In: Proc. IEEE-RAS Int. Conf. On Humanoid Robots, Tsukuba, Japan, pp. 50–55 (December 2005)
4. Park, I.-W., Kim, J.-Y., Lee, J., Oh, J.-H.: Online free walking trajectory generation for biped humanoid robot KHR-3(HUBO). In: Proc. IEEE Int. Conf. on Robotics and Automations, Orlando, Florida, pp. 1231–1236 (May 2006)
5. Kim, J.-H., Lee, K.-H., Kim, Y.-D., Lee, B.-J., Yoo, J.-K.: The origin of artificial species: Humanoid robot HanSaRam. In: Proc. 2nd International Conference on HNICEM 2005, Manila, Philippines (March 2005)
6. Kajita, S., Kanehiro, F., Kaneko, K., Fujiwara, K., Yokoi, K., Hirukawa, H.: A Realtime Pattern Generator for Biped Walking. In: Proc. IEEE Int. Conf. on Robotics and Automation, Washington, DC, pp. 31–37 (May 2002)
7. Lee, B.-J., Stonier, D., Kim, Y.-D., Yoo, J.-K., Kim, J.-H.: Modifiable Walking Pattern of a Humanoid Robot by Using Allowable ZMP Variation. IEEE Transaction on Robotics 24(4), 917–925 (2008)
8. Lee, B.-J., Stonier, D., Kim, Y.-D., Yoo, J.-K., Kim, J.-H.: Modifiable Walking Pattern of a Humanoid Robot by Using Allowable ZMP Variation. IEEE Transactions on Robotics 24(4), 917–923 (2008)
9. Grillner, S., et al.: Neural networks that co-ordinate locomotion and body orientation in lamprey. Trends in NeuroSciences 18(6), 270–279 (1995)
10. Taga, G.: Emergence of bipedal locomotion through entrainment among the neuro-musculo-skeletal system and the environment. Physica D: Nonlinear Phenomena 75(1.3), 190–208 (1994)
11. Endo, G., Morimoto, J., Matsubara, T., Nakanishi, J., Cheng, G.: Learning CPG Sensory Feedback with Policy Gradient for Biped Locomotion for a Full-body Humanoid. In: Proc. The 20th National Conference on Artificial Intelligence, vol. 3, pp. 1267–1273 (2005)
12. Hase, K., Yamazaki, N.: Computer simulation of the ontogeny of biped walking. Anthropological Science 106(4), 327–347 (1998)
13. Mori, T., Nakamura, Y., Sato, M., Ishii, S.: Reinforcement learning for a cpg-driven biped robot. In: Nineteenth National Conference on Artificial Intelligence, pp. 623–630 (2004)
14. Han, K.-H., Kim, J.-H.: Genetic quantum algorithm and its application to combinatorial optimization problem. In: Proc. 2000 Congress on Evolutionary Computation, vol. 2, pp. 1354–1360. IEEE Press, Piscataway (July 2000)
15. Matsuoka, K.: Sustained oscillations generated by mutually inhibiting neurons with adaptation. Biol. Cybern. 52(6), 367–376 (1985)