Stable Modifiable Walking Pattern Generator with Arm Swing Motion Using Evolutionary Optimized Central Pattern Generator

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Abstract. In this paper, a stable modifiable walking pattern generator (MWPG) is proposed by a employing arm swing motion. The arm swing motion is generated by a central pattern generator (CPG) which is optimized by a constraint evolutionary algorithm. In this scheme, the MWPG generates a position trajectory of center of mass (COM) of humanoid robot and the CPG generates the arm swing motion. A sensory feedback in the CPG is designed, which uses a inertial measurement unit (IMU) signal. For the optimization of the CPG parameters, a two-phase evolutionary programming (TPEP) is employed. The effectiveness of the proposed scheme is demonstrated by simulations using a Webots dynamic simulator for a small sized humanoid robot, HSR-IX, developed in the Robot Intelligence Technology (RIT) Lab, KAIST.

1 Introduction

These days many humanoid robots have been developed [1]-[4]. However, their control algorithms still need 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.

There are two typical approaches to bipedal walking of humanoid robot, such as dynamic model based approach and biologically inspired approach. In the former, a 3-D linear inverted pendulum model (3-D LIPM) is one of popular schemes [5]– [8]. A modifiable walking pattern generator (MWPG) extends the conventional 3-D LIPM for a zero moment point (ZMP) variation by the closed form functions and can modify the humanoid robot's walking pattern in real-time while walking [9], [10]. In the latter, a central pattern generator (CPG) is widely used [11]-[14]. It can generate rhythmic output signals and modify generated signals to deal with environmental disturbance using a sensory feedback. Also, for stable bipedal walking, the methods about controlling upper body were developed. The process was presented to generate whole body motions for a biped humanoid robot from captured human motion [15]. A method to generate whole body motion of a humanoid robot considering linear/angular momentum was presented [16].

This paper proposes a stable MWPG with a arm swing motion using a constrained evolutionary optimized CPG. The proposed scheme generates a position trajectory of the humanoid robot's COM using the MWPG. Also, to stable walking, the CPG generates the arm swing motion and a sensory feedback in the CPG modifies the generated arm swing motion. Generated arm swing motion is proportional to the sagittal step length like human. The sensory feedback gets a inertial measurement unit (IMU) signal. To optimize the parameters of the CPG, a two-phase evolutionary programming (TPEP) is employed considering equality constraints [17], [18]. The effectiveness of the proposed scheme is demonstrated by computer simulations with the Webots model of a small sized humanoid robot HSR-IX developed in the Robot Intelligence Technology (RIT) Lab., KAIST.

This paper is organized as follows. In Section II, the arm swing motion planning using constrained evolutionary optimized CPG is proposed. In Section III, simulation results are presented and finally concluding remarks follow in Section IV.

2 Stable MWPG using CPG

This section presents the proposed stable modifiable walking pattern algorithm with the arm swing motion using constrained evolutionary optimized CPG. In this paper, to generate the trajectory of COM, the MWPG is employed [9], [10]. Meanwhile, the arm swing motion is generated by the constrained evolutionary optimized CPG for stable bipedal walking.

2.1 Neural Oscillator

In this paper, a neural oscillator (NO) is employed to generate a rhythmic signal for the humanoid robot. The NO is composed of two neurons, each of which consists of two mutually excited neurons: an extensor neuron (EN) and a flexor neuron (FN) to generate rhythmic signal. Each neuron is defined as follows (Fig. 1) [19]:

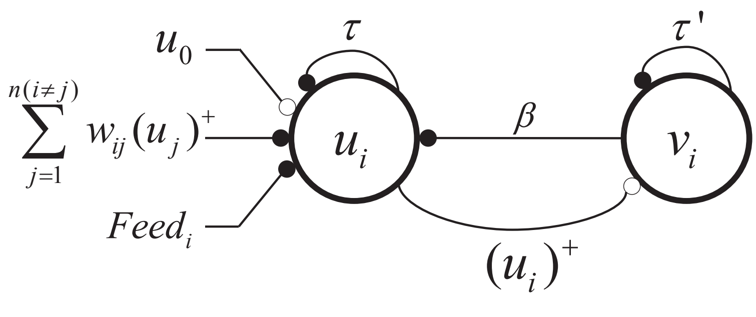


Fig. 1. Neuron structure. The lines ending with black and white circles are inhibitory and excitatory connections, respectively.

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

$$\tau' \dot{v}_i = -v_i + (u_i)^+ \tag{2}$$

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

where u_i, v_i and $(u_i)^+$ are a inner state, a self-inhibition state and a output signal of the ith neuron, respectively. u_0 is a constant input signal, w_{ij} is a connecting weight between ith and jth neurons, τ and τ' are time constants, β is a weight of the self-inhibition, and $Feed_i$ is a sensory feedback signal which is necessary for stable biped locomotion, of the ith neuron. Using EN and FN, the NO is defined as follows (Fig. 2):

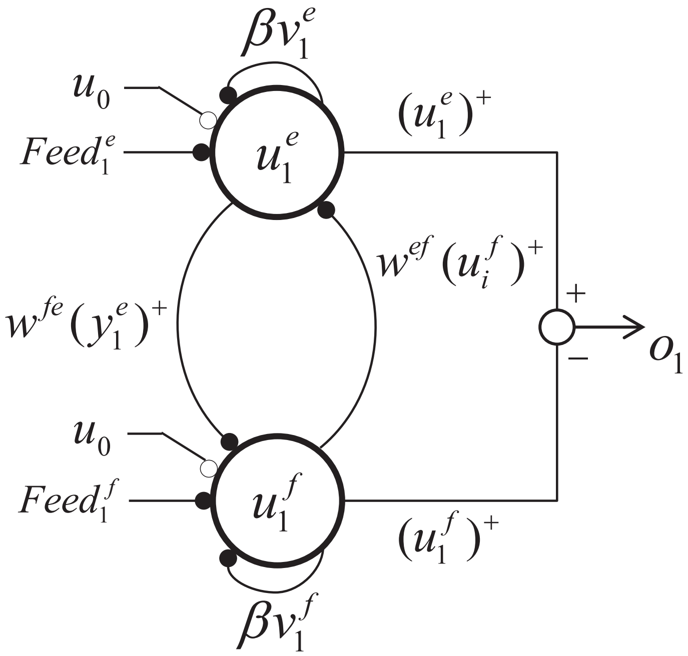


Fig. 2. Neural oscillator.

$$\tau \dot{u}_1^e = -u_1^e - w(u_1^f)^+ - \beta v_1^e + u_0 + Feed_1^e, \tag{4}$$

$$\tau' \dot{v}_1^e = -v_1^e + (u_1^e)^+ \tag{5}$$

$$\tau \dot{u}_1^f = -u_1^f - w(u_1^e)^+ - \beta v_1^f + u_0 + Feed_1^f, \tag{6}$$

$$\tau' \dot{v}_1^f = -v_1^f + (u_1^f)^+ \tag{7}$$

$$o_1 = (u_1^e)^+ - (u_1^f)^+ \tag{8}$$

where the superscripts e and f denote the EN and the FN, respectively. o_i is output signal of ith NO.

2.2 Arm Swing Motion by CPG

Human generates the arm swing motion while walking. The arm swing motion decreases yawing momentum and help to keep humanoid robot's balance while walking. Using the NO, the arm trajectory is generated as follows for stable walking like human:

$$p_{arm}^{l} = \begin{cases} k_{arm}(-S^{pre} + \frac{S + S^{p}re}{2A_1}(o_1 + A_1)), & \text{if support leg is left} \\ k_{arm}(S^{pre} + \frac{S + S^{pre}}{2A_1}(o_1 - A_1)), & \text{otherwise} \end{cases} \tag{9}$$

$$p_{arm}^{r} = -p_{arm}^{l} \tag{10}$$

where $p_{arm}^{l/r}$ is a sagittal distance between the left/right elbow and the center of the humanoid robot's body. k_{arm} is a scaling factor. S and S^{pre} are sagittal step lengths at the present and the previous footstep, respectively. A_1 is a amplitude of o_1. When support leg is left/right, o_1 should become $-A_1/A_1$ at beginning single support phase and o_1 should become $A_1/-A_1$ at end double support phase to make like human.

The sensory feedback of the NO alters p_{arm}^{l} and p_{arm}^{r} for stable walking. For stable walking, the sensory feedback of the NO should minimize slip while walking. The sensory feedback gets the information from the yawing angle of the humanoid robot's body using IMU signal. The sensory feedback is designed as follows:

$$Feed_1^{e} = k_f(\theta_y - \theta_y^{d}) \tag{11}$$

$$Feed_1^{f} = -Feed_1^{e} \tag{12}$$

where k_f is the scaling factor. θ_y and θ_y^{d} are the real and desired yawing angles of the center of humanoid robot's body, respectively.

2.3 Evolutionary Optimization for CPG

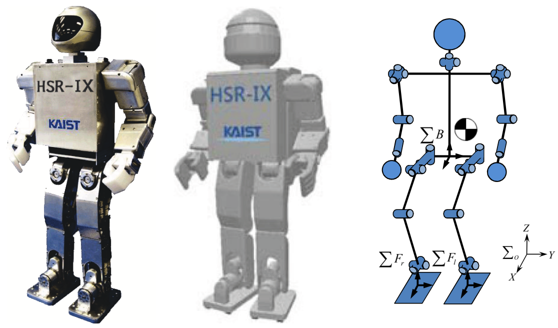
The objective of this evolutionary optimization is to obtain the desired output signal of the NO and to minimize slip by the yawing moment. To obtain the desired output signal of the NO, time constants of the NO should be optimized. If support leg is left, when the magnitude of the output signal of the NO reaches the minimum (maximum) value, the time T_1^{min} (T_1^{max}) should be equal to time at beginning single (end double) support phase. Thus, $T_1^{max} - T_1^{min}$ should be equal to the single support time $T_{ss} + T_{ds}$. Also, when the magnitude of output signal reaches zero, the time T_1^{0} should be equal to the middle value of $T_{ss} + T_{ds}$. To minimize slip by the yawing moment, the scaling factor in the sensory feedback should be optimized. To satisfy these constraints and the objective, the following objective function considering equality constraints is defined to obtain the time constants and the scaling factor in the sensory feedback by the TPEP [18]:

$$\text{Minimize } f = f_{yawing} + P \tag{13}$$

subject to

$$(T_1^{max} - T_1^{min}) - (T_{ss} + T_{ds}) = 0$$

$$T_1^{0} - \frac{T_{ss} + T_{ds}}{2} = 0$$



(a) (b) (c)

Fig. 3. (a) HSR-IX. (b) Simulation model. (c) Configuration.

with

$$f_{yawing} = \sum |\theta_y - \theta_y^d|$$

where P is the penalty which is given if humanoid robot loses its balance and collapses. f_{yawing} is the sum of $|\theta_y - \theta_y^d|$ while walking.

3 Simulations

The effectiveness of the proposed algorithm was demonstrated by computer simulations with the Webots model of the small sized humanoid robot, HSR-IX (Fig. 3). HSR-IX is the latest one of HSR-series. HSR is a small-sized humanoid robot that has been in continual redesign and development in RIT Lab, KAIST. Its height and weight are 52.8cm and 5.5kg, respectively. It has 26 DOFs that consist of 14 RC servo motors in the upper body and 12 DC motors with harmonic drives for reduction gears in the lower body. Webots is the 3-D robotics simulation software. Users can conduct the physical and dynamical simulation using Webots [21].

3.1 CPG Parameters Setting using TPEP

In the simulation, Z_c was set as 23.35cm. β and u_0 were set as 2.5 and 2.5, respectively. The connecting weight, w, was set as 2.5 to make the phase difference between EN output and FN output to π [19]. The initial values of inner states, u_1 and u_2, and the self-inhibition states, v_1 and v_2, were set as -0.0042, 0.8372, 0.1834 and 0.6501, respectively, to make initial value of o_1 to the minimum value at beginning of single support phase. T_{ss} and T_{ds} were set as 0.8s and 0.4s, respectively. P in the objective function was set as ∞. For the constrained evolutionary optimization of the CPG, the simulation model of HSR-IX modeled by Webots, was employed. The constrained evolutionary optimized parameters were obtained by TPEP as Table 1.

Table 1. Constrained evolutionary optimized parameters by TPEP.

Time constants	τ	0.4676
	τ'	0.3089
Scaling factor	k_{arm}	0.6023
	k_f	3.2140

Table 2. A list of commanded step lengths.

Steps	S (cm)	L (cm)	Support foot
1^{st}	4.0	6.0	Left
2^{nd}	4.0	-6.0	Right
3^{rd}	6.0	6.0	Left
4^{th}	4.0	-6.0	Right
5^{th}	7.0	6.0	Left
6^{th}	5.0	-6.0	Right
7^{th}	2.0	6.0	Left
8^{th}	6.0	-6.0	Right
9^{th}	7.0	6.0	Left
10^{th}	0.0	-6.0	Right

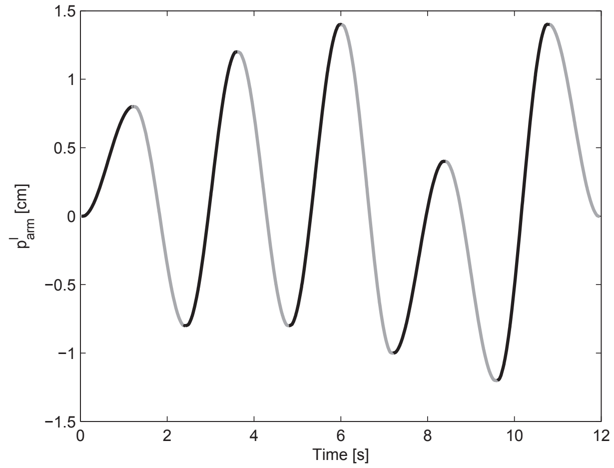
3.2 Walking Simulation using CPG

In this simulation, the simulation model of HSR-IX by Webots was used. Table 2 shows the list of step lengths used for the simulation.

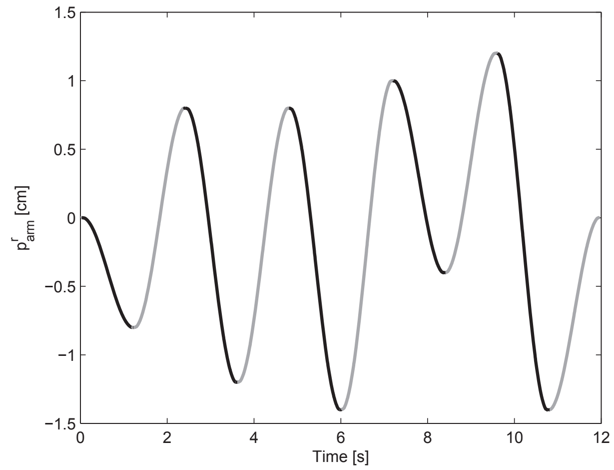
Fig. 4 shows the trajectories of p^l_{arm} and p^r_{arm} while walking. As shown in the figure, the amplitudes of p^l_{arm} and p^r_{arm} were proportional to the sagittal step length like human. Fig. 5 and Fig. 6 show the measured yawing momentums while walking without the arm swing motion and with the arm swing motion using the proposed CPG, respectively. As shown in the figure, the amplitude of yawing momentum was decreased by the arm swing motion using the proposed CPG. It means HSR-IX could walk stably with the proposed algorithm.

4 Conclusion

This paper proposed a stable MWPG algorithm with the constrained evolutionary optimized CPG. The MWPG was employed to generate COM position trajectory. The arm swing motion was generated using the CPG. To minimize yawing momentum while walking, the sensory feedback in the CPG modified generated signals. The sensory feedback got the disturbance information using IMU sensor. TPEP was employed to optimize parameters of the CPG considering some constraints. In order to demonstrate the performance of the proposed scheme, computer simulations were carried out with



(a)



(b)

Fig. 4. Position trajectories of left and right arms. The thick and thin lines represent the trajectories when support leg is left and when support leg is right, respectively.

the Webots model of the small sized humanoid robot, HSR-IX developed in the RIT Lab., KAIST. In the simulation, the amplitude of yawing momentum was decreased by the arm swing motion using the proposed CPG.

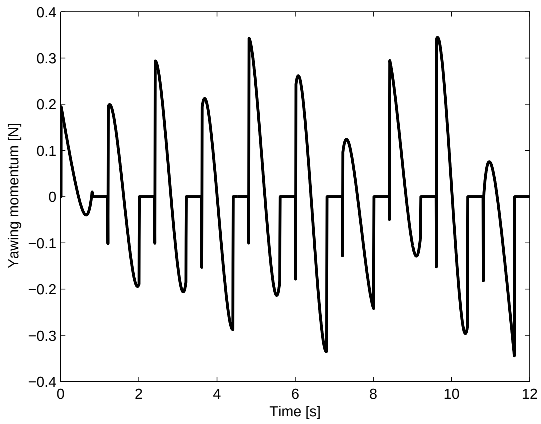


Fig. 5. The measured yawing momentum while bipedal walking without the arm swing motion.

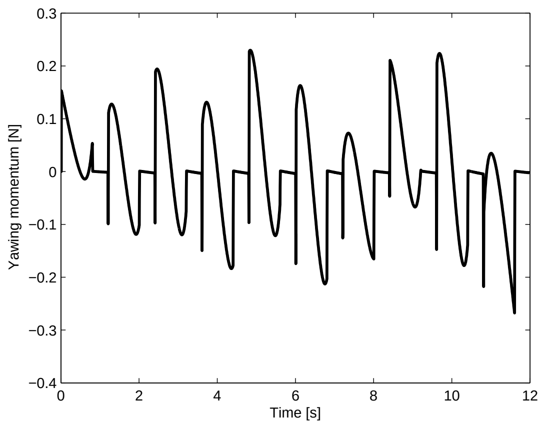


Fig. 6. The measured yawing momentum while bipedal walking with the arm swing motion.

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