Stable Modifiable Walking Pattern Algorithm with Constrained Optimized Central Pattern Generator

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Abstract In this paper, stable modifiable walking pattern algorithm is proposed using evolutionary optimized central pattern generator (CPG). Sensory feedback pathways in CPG are proposed, which use force sensing resistor (FSR) signals. For the optimization of CPG parameters, two-phase evolutionary programming (TPEP) is employed. Modifiable walking pattern generator (MWPG) generates position trajectory of center of mass (COM) of humanoid robot and CPG generates sagittal swing foot position trajectory. 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.

Key words: Modifiable walking pattern generator (MWPG), central pattern generator (CPG).

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]-[4]. 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, A 3-D linear inverted pendulum model (3-D LIPM) is one of popular schemes [5]– [8]. The 3-D LIPM decouples the sagittal and lateral center of mass (COM) motion equations in single support phase. A modifiable walking pattern generator (MWPG) extends the conventional 3-D LIPM for the zero moment point (ZMP) variation by the closed form functions and allows the bipedal robot to modify the walking pattern in real-time while walking [9], [10]. In the latter, central pattern generator (CPG) is widely used [11]-[14]. It can generate rhythmic output signals without rhythmic central input or sensor signal. Also, it can alter generated signals to deal with environmental disturbance using sensor feedback.

This paper proposes a stable MWPG algorithm with constrained optimized CPG. The proposed scheme generates position trajectory of the humanoid robot's COM using the MWPG. Also, to minimize the disturbance by the COM position error, the CPG generates the sagittal swing foot position trajectory and sensor feedback in CPG modifies the generated sagittal swing foot position trajectory. The sensor feedback gets the disturbance information using signals of force sensing resistor (FSR) sensors attached on the sole of foot. To optimize the parameters of the CPG, two-phase evolutionary programming (TPEP) is employed considering equality constraints [15], [16]. 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, stable MWPG using constrained 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 MWPG using constrained optimized CPG. In this paper, to generate the trajectory of COM, the MWPG is employed [9], [10]. The bipedal walking is composed of single and double support phases. In the single support phase, the primary dynamics of the bipedal robot is modeled as a 3-D LIPM [5]. The MWPG extends the conventional 3-D LIPM for the ZMP variation by the closed form functions and allows the bipedal robot to modify the walking pattern in real-time while walking. Meanwhile, the sagittal swing foot position trajectory is generated by the constrained optimized CPG for stable bipedal walking.

2.1 Neural Oscillator

In this paper, the neuron is developed to generate rhythmic signal for humanoid robots. The neuron is biologically inspired to generate a rhythmic signal, defined as follows (Fig. 1) [17]:

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

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

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

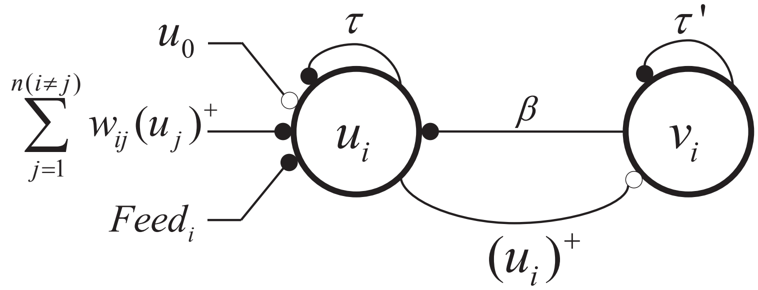


Fig. 1 Neuron structure. The lines ending with black and white circles are inhibitory and excitatory connections, respectively.

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 neurons, 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. In this paper, the neural oscillator 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 [17]. The CPG structure generates the rhythmic signal as follows (Fig. 2):

$$\tau \dot{u}_1^e = -u_1^e - w(u_1^f)^+ - \beta v_1^e + u_0 + Feed_1^e, \tag{4}$$
$$\tau' \dot{v}_1^e = -v_1^e + (u_1^e)^+ \tag{5}$$
$$\tau \dot{u}_1^f = -u_1^f - w(u_1^e)^+ - \beta v_1^f + u_0 + Feed_1^f, \tag{6}$$
$$\tau' \dot{v}_1^f = -v_1^f + (u_1^f)^+ \tag{7}$$
$$o_1 = (u_1^e)^+ - (u_1^f)^+ \tag{8}$$

where the superscripts e and f denote the EN and the FN, respectively.

2.2 Swing Foot Trajectory Generation by CPG

Using the NO, the sagittal foot trajectory is generated as follows:

$$x_{foot} = -S^{pre} + \frac{S + S^{pre}}{2A_1} o_1 \tag{9}$$

where x_{foot} is the sagittal position of the swing foot. S and S^{pre} are the sagittal step lengths at the present footstep and previous footstep, respectively. A_1 is the

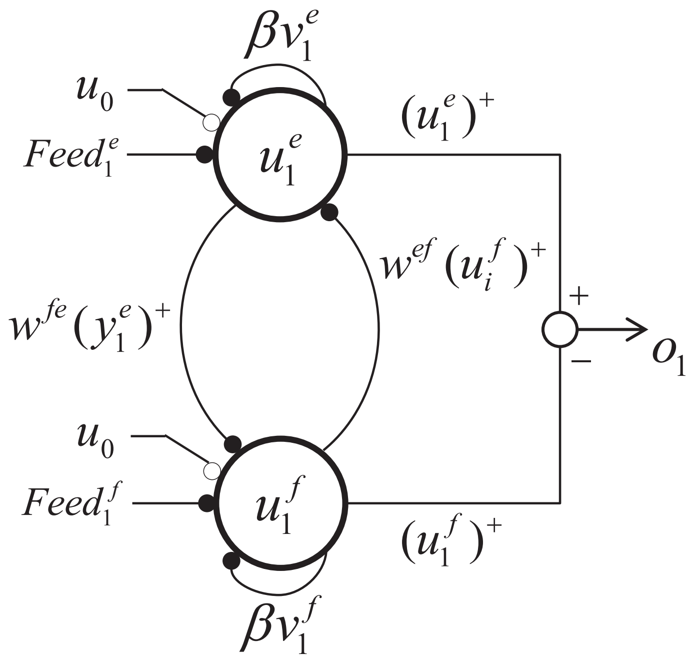


Fig. 2 CPG structure.

amplitude of o_1. o_1 should become minimum value $-A_1$ at beginning single support phase and o_1 should become maximum value A_1 at end single support phase to satisfy step length.

The sensor feedback of the NO alters x_{foot} to compensate the disturbance by the COM position error. The sensor feedback gets the information from four FSRs of each foot, which are attached to each corner of the sole of the foot. The sensory feedback is designed as follows:

$$Feed_1^e = k_f|x_{zmp}^d - x_{zmp}^r| \tag{10}$$

$$Feed_1^f = -Feed_1^e \tag{11}$$

with

$$x_{zmp}^r = \frac{\sum_{i=1}^4 (f_i^l x_i^l + f_i^r x_i^r)}{\sum_{i=1}^4 (f_i^l + f_i^r)}$$

where k_f is the scaling factor. x_{zmp}^d is the desired sagittal ZMP and x_{zmp}^r is the real sagittal ZMP [18]. f_i^r and f_i^l are the ground reaction forces (GRFs) measured at the right and left feet, respectively, by FSRs. x_i^l and x_i^r are the sagittal positions of FSRs on left and right soles.

2.3 Constrained Optimization for CPG

The objective of this optimization is to obtain the desired output signals and to minimize the oscillation of the ZMP while bipedal walking. To obtain the desired output signals, time constants of the CPG should be optimized. When the magnitude of the NO output signal generated by the CPG reaches the minimum (maximum) value, the time T_1^{min} (T_1^{max}) should be equal to time at beginning (ending) single support phase. Thus, $T_1^{max} - T_1^{min}$ should be equal to the single support time T_{ss}. When the magnitude of output signal reaches zero, the time T_1^0 should be equal to the middle value of T_{ss}. To satisfy the objective and these constraints, the following objective function is defined to obtain the time constants and the scaling factors in the sensory feedback, by the TPEP [16]:

$$\text{Minimize } f = f_x + P \tag{12}$$

subject to

$$\begin{aligned} (T_1^{max} - T_1^{min}) - T_{ss} = 0 \\ T_1^0 - \frac{T_{ss}}{2} = 0 \end{aligned}$$

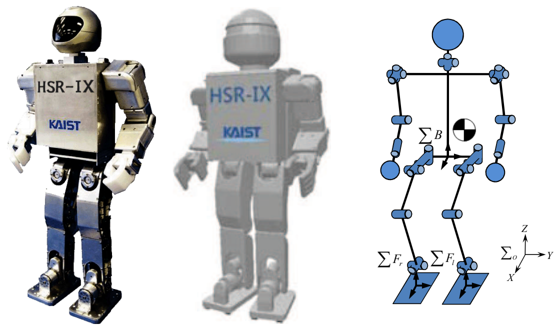
with

$$f_x = \sum_{T=0}^{T_s s} |x_{zmp}^d - x_{zmp}^r|$$

where P is the penalty which is given if humanoid robot loses its balance and collapses. f_x means the sum of the differences between the desired ZMP and the real ZMP while bipedal walking.

3 Simulations

The effectiveness of the proposed algorithm was demonstrated by computer simulations with the Webots model of a 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 [19].



(a) (b) (c)

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

Table 1 The parameters setting for TPEP.

Single support time (s)	T_{ss}	0.8
Double support time (s)	T_{ds}	0.4
Penalty	P	∞

Table 2 Initial values of inner states and self-inhibition states.

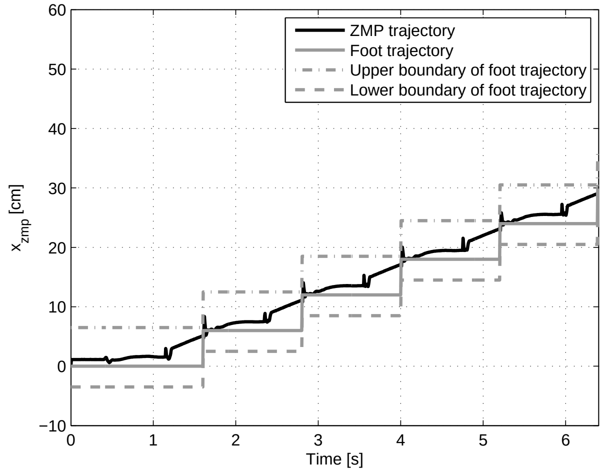
u_1^e (s)	-0.0068	u_1^f	0.9723
v_1^e (s)	0.1902	v_1^f	0.7771

Table 3 Constrained optimized parameters by TPEP.

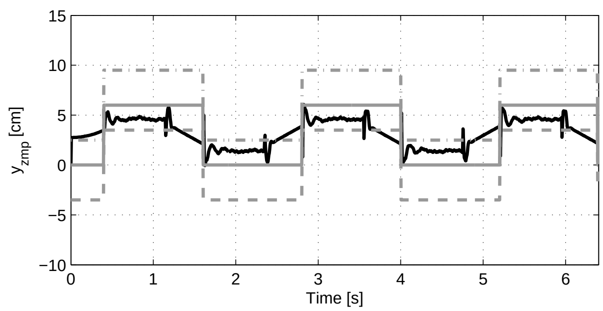
Time constants	τ	0.315
	τ'	0.207
Scaling factor	k_f	-3.21

3.1 CPG Parameters Setting using TPEP

In the simulation, Z_c was set as 23.35cm. The self inhibition weight, β, and the input signal, u_0 were set as 2.5 and 2.9, respectively. The connecting weights were set as 2.5 to make the phase difference between EN output and FN output to π [17]. Table 1 shows the parameter settings for the constrained optimization by TPEP. The initial values of inner states and self-inhibition states were set as Table 2 to make initial value of o_1 to the minimum value at beginning of single support phase. For the constrained optimization of the CPG, the simulation model of HSR-IX modeled by Webots, was employed. The constrained optimized parameters were obtained by TPEP as Table 3.



(a)



(b)

Fig. 4 The measured ZMP while bipedal walking with sensor feedback.

3.2 Walking Simulation using CPG

In this simulation, to increase the oscillation of the ZMP, the error term Δx was added to the generated sagittal COM position trajectory by MWPG while bipedal walking. When Δx increased by 0.5cm, f_x increased by 30.3% without sensor feedback and 27.27% with sensor feedback compared at $\Delta x = 0$. In this result, the increment of f_x caused Δx was reduced by 10.6% using the CPG with sensor feedback. Fig. 4 shows the measured ZMP trajectory. As shown in the figure, the ZMP trajectories were within the allowable ZMP variation region. It means the HSR-IX could walk stably with the proposed algorithm.

4 Conclusion

This paper proposed a stable MWPG algorithm with constrained optimized CPG. The MWPG was employed to generate COM position trajectory. The sagittal swing foot position trajectory was generated using CPG. Also, for stable bipedal walking, sensor feedback in CPG modified generated signals to deal with the disturbance. Sensor feedback got the disturbance information using FSRs. TPEP was employed to optimize parameters of CPG considering some constraints. In order to demonstrate the performance of the proposed scheme, computer simulations were carried out with the Webots model of the small sized humanoid robot, HSR-IX developed in the RIT Lab., KAIST.

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