Stable Modifiable Walking Pattern Generator with a Vertical Foot Motion by Evolutionary Optimized Central Pattern Generator

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Abstract. This paper proposes a stable modifiable walking pattern generator with a vertical foot motion generated by a central pattern generator that is obtained from the evolutionary constrained optimization. A modifiable walking pattern generator is employed which generates sagittal and lateral position trajectories of center of mass of humanoid robot and a CPG generates the vertical foot trajectory of swing leg. The oscillation of the ground reaction forces causes the external disturbance while walking. To decrease the oscillation of the ground reaction forces, sensory feedback in the CPG is designed, which uses force sensing resistor signals. For the optimization of parameters in the CPG, two-phase evolutionary programming is employed. The effectiveness of the proposed scheme is demonstrated by simulations using a Webots dynamic simulator for a small sized humanoid robot, HSR-X, developed in the Robot Intelligence Technology Lab, KAIST.

1 Introduction

Despite the complexity of high-DOF systems of humanoid robots, these days various humanoid robots have been developed [1]–[3]. Research on generation of stable walking patterns of humanoid robots plays one of the 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, which decouples the sagittal and lateral motion equations of central of mass (COM) with constant COM height in single support phase [4], [5]. A modiable walking pattern generator (MWPG) extends the 3-D LIPM for a zero moment point (ZMP) variation by the closed form functions. Thus, it can change the walking pattern of a humanoid robot in real-time while walking [6]–[8]. On the other hand, a central pattern generator (CPG) is widely used as a biologically inspired approach [9]–[14]. It can generate rhythmic output signals without rhythmic input signals and modify generated signals to deal with environmental disturbance by sensory feedbacks.

This paper proposes stable MWPG with a vertical foot motion using the CPG that is obtained from the evolutionary constrained optimization. The MWPG is employed and it generates position trajectory of COM of humanoid robot and the CPG generates vertical swing foot trajectory. To decrease ground reaction forces, a sensory feedback in the CPG is designed, which uses force sensing resistor (FSR) signals. For the optimization of parameters in the CPG, two-phase evolutionary programming (TPEP) is employed [15], [16]. The effectiveness of the proposed scheme is demonstrated by simulations using a Webots dynamic simulator for a small sized humanoid robot, HSR-X, developed in the Robot Intelligence Technology (RIT) Lab, KAIST.

2 Stable MWPG with CPG

This section presents the proposed stable MWPG with the vertical foot motion by the evolutionary optimized CPG. In this paper, the sagittal and lateral COM motions are generated by the MWPG. Meanwhile, the vertical foot motion is generated by the proposed CPG for stable bipedal walking.

2.1 Vertical Foot Motion by CPG

The vertical foot trajectory of the swing leg, z_{foot} is generated by a cycloid function in the previous MWPG as follows:

$$z_{foot}(t) = R(1 - (cos^2(\frac{\pi t}{T_{ss}}) - sin^2(\frac{\pi t}{T_{ss}}))) \tag{1}$$

where R denotes the radius of the cycloid circle and T_{ss} denotes the single support time. However, this method is hard to modify the generated vertical foot trajectory to deal with environmental disturbance. To solve this problem, this paper proposes the vertical foot motion generation by using the CPG obtained from the evolutionary constrained optimization.

The CPG generates rhythmic signals without a rhythmic sensory or central input. In this paper, to generate the rhythmic signals for the CPG, neural oscillator is employed and the neuron is represented as follows [17]:

$$\tau \dot{u}_i = -u_i - \sum_{j=1}^{n(j \neq i)} w_{ij} o_j - \beta v_i + u_0 + feed_i \tag{2}$$

$$\tau' \dot{v}_i = -v_i + o_i \tag{3}$$

$$o_i = max(u_i,\, 0) \tag{4}$$

where n is the number of neurons. u_i, v_i and y_i, $i = 1, \cdots, n$, are the inner state, the self-inhibition state and the output signal of the ith neuron, respectively. u_0 is the input signal that affects the output amplitude and w_{ij} is the connecting weight which determines the phase difference between the ith and jth neurons. τ and τ' are time constants, which influence on the shape and frequency of output signal. β is the weight of self-inhibition. $feed_i$ is the sensory feedback signal. A biological rhythmic locomotion is performed by the sequence of extension and flexion of muscles. For the modeling of this biological system, the CPG structure was devised [9]. In this structure, the rhythmic locomotion is assumed to be generated by the neural oscillators, each of which is composed of two neurons: an extensor neuron (EN) and a exor neuron (FN). The phase difference between EN and FN is π.

Using the CPG, the vertical foot trajectory of swing leg is generated as follows:

$$z_{foot} = R(1 - ((o_1 - o_2)^2 - (o_3 - o_4)^2)) \tag{5}$$

where o_1, o_2, o_3 and o_4 are the output signals of the neurons in the CPG. o_1 and o_3 perform the EN role, and o_2 and o_4 perform the FN role. The generated vertical foot trajectory by the CPG should be similar to the generated vertical foot trajectory by the cycloid circle. Thus, waveforms of $o_1 - o_2$ and $o_3 - o_4$ should be similar to the waveforms of $cos(\pi t/T_{ss})$ and $sin(\pi t/T_{ss})$, respectively. To satisfy these conditions, the time constants and connecting weights are optimized by TPEP.

While walking, the sum of the ground reaction forces (GRFs) on the feet oscillates around the weight of the robot, which causes the external disturbance. Thus, to improve the stability of the humanoid robot while walking, the sensory feedback in the CPG is designed to minimize the oscillation of the GRFs as follows:

$$feed_1 = k_f(F_L + F_R - mg) \tag{6}$$

$$feed_2 = -feed_1 \tag{7}$$

$$feed_3 = -feed_1 \tag{8}$$

$$feed_4 = -feed_3 \tag{9}$$

where k_f is the scaling factor and it is to be optimized by TPEP. F_L and F_R denote the GRFs on the left and right feet, respectively. They are obtained by FSRs attached to the sole of foot.

2.2 Evolutionary Optimization for CPG

The objective of this evolutionary optimization is to obtain the desired output signal of the neural oscillators and to improve the stability of the humanoid robot while walking. When the magnitude of $o_1 - o_2$ reaches the maximum (minimum) value, the magnitude of $o_3 - o_4$ should reach the zero. Also, when $o_3 - o_4$ is positive, the corresponding time T^+ should be a desired single support time T_{ss}. Meanwhile, to improve the stability of the humanoid robot while walking, the oscillation of GRFs should be minimized.

To satisfy these constraints and the objective, the following objective function considering equality constraints is defined to obtain the time constants and connecting weights in the neural oscillators, and scaling factor in the sensory feedback by the TPEP [15], [16]:

$$\text{Minimize } f = \sum |F_L + F_R - mg| + P \tag{10}$$

subject to equality constraints

c1 : $o_3 - o_4 = 0$ (when $o_1 - o_2$ reach the maximum value)
c2 : $o_3 - o_4 = 0$ (when $o_1 - o_2$ reach the minimum value)
c3 : $T^+ - T_{ss} = 0$

where P is the penalty which is given if humanoid robot loses its balance and collapses.

Fig. 1. HSR-X.

Table 1. The obtained parameter values of the designed CPG by the TPEP

τ	0.32	τ'	0.21
$w_{\pi/2}$	0.35	$w_{-\pi/2}$	0.35
k_f	6.6×10^{-3}		

3 Simulations

The proposed algorithm was implemented into a small-sized humanoid robot, HanSaRam-X (HSR-X) (Fig. 1) [18]. HSR-X is the latest one of HSR-series. HSR-series has been in continual redesign and development in the RIT Lab, KAIST. Its height and weight are 45.2 cm and 2.7 kg, respectively. It has 20 DOFs that consists of 8 DOFs in the upper body and 12 DOFs in the lower body. Computer simulation was carried out using the simulation model of HSR-X by Webots [19].

3.1 CPG Parameters Optimization by TPEP

In the simulation, Z_c set as 23.35cm. β and u_0 in the neural oscillators were set as 2.5 and 2.9, respectively. $w_{1,2}$, $w_{2,1}$, $w_{3,4}$ and $w_{4,3}$ were set as 2.5 to make the phase difference between EN and FN to π. Single and double support times were set as 0.8s and 0.4s, respectively. Also, the phase differences between o_1 and o_3, o_2 and o_4, o_4 and o_1 and o_3 and o_2 are all equal to $\pi/2$. Thus, $w_{1,3}$, $w_{2,4}$, $w_{4,1}$ and $w_{3,2}$ are set as $w_{\pi/2}$. In the same way, $w_{1,4}$, $w_{2,3}$, $w_{3,1}$ and $w_{4,2}$ are set as $w_{-\pi/2}$. The time constants, τ and τ', the connecting weights, $w_{\pi/2}$ and $w_{-\pi/2}$, and the scaling factor, k_f, were obtained by TPEP as shown in Table 1.

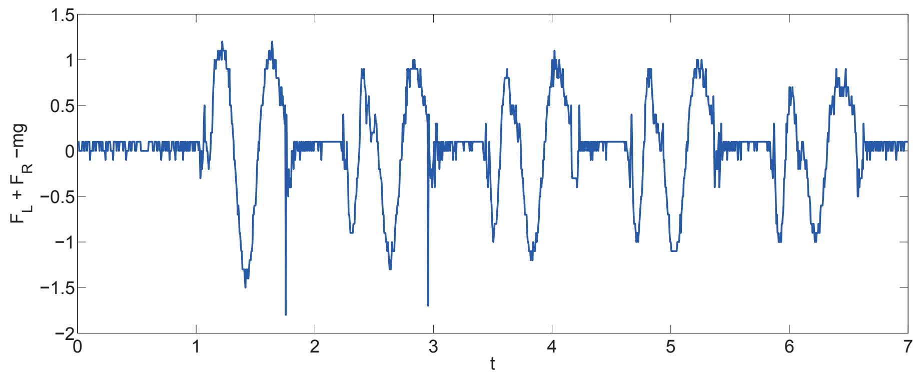

Fig. 2. Measured oscillation of the GRFs by the cycloid function

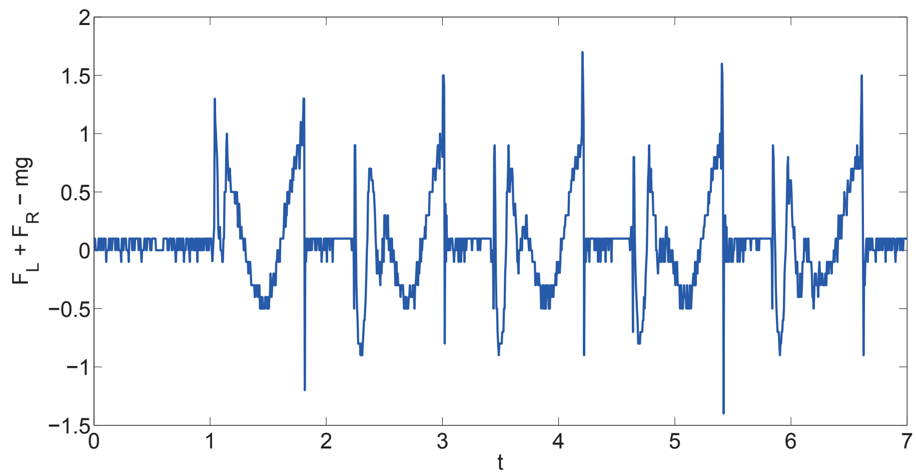

Fig. 3. Measured oscillation of the GRFs by the CPG

3.2 Simulation Result

In this simulation, the simulation model of HSR-IX by Webots was used. Figs. 2 and 3 show the measured oscillation of the GRFs while bipedal walking by the cycloid function and the proposed CPG, respectively, to generate vertical foot motion of swing leg. In this result, the sum of oscillation of the GRFs was reduced by 25.6% by the proposed CPG. It means the HSR-X could walk stably with the proposed algorithm.

4 Conclusion

This paper proposed stable MWPG with a vertical foot motion generated by the evolutionary optimized CPG. The MWPG was employed to generate the position trajectory of COM of humanoid robot. To improve the stability of humanoid robot while walking, the CPG was employed to generate the vertical swing foot trajectory. Also, the sensory feedback in the CPG was designed to minimize the oscillation of the GRFs, which used force sensing resistor (FSR) signals. For the optimization of parameters in the CPG, two-phase evolutionary programming (TPEP) was employed. The effectiveness of the proposed scheme was demonstrated by simulations using a Webots dynamic simulator for a small sized humanoid robot, HSR-X, developed in the Robot Intelligence Technology (RIT) Lab, KAIST.

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