Abstract—In recent decades, the locomotion control has been a main research field in robotics. In locomotion control problems, understanding the relationship between neuroscience and robotics is very important. In this work, a bio-inspired method for the gait generation and transition of a biped robot is implemented. This method uses a Central Pattern Generator (CPG), which is a neural network responsible for generating rhythmic output signals without sensory information. Humans and animals have the ability to produce various gaits by CPG according to the environmental conditions. The 4-cell CPG model proposed by Golubitsky et al. and symmetry in this model are used for walk and run gaits generation. In this work, Transitions from walk to skip and from run to skip are achieved by changing coupling weights of walk and run. The Morris-Lecar oscillator is used as the oscillator of each cell. The numerical simulations of periodic signals corresponding to the five-link bipedal walk and run gaits and transitions from walk to skip and run to skip are shown in the 4-cell CPG model. The periodic signals resulting of this model can be used as joint angles of hip and knee joints of a five-link biped robot. The results obtained in this work show the feasibility of using CPG-based methods to generate five-link biped locomotion and transitions between different gaits.

Keywords—Central Pattern Generator; five-link biped robot; gait transition

I. INTRODUCTION

Locomotion is one of the most important features of humans and animals, since it allows them to move on irregular ground to avoid predators or to look for food and so on. Locomotion is a complex mechanism and requires the coordination of a variety of muscles.

The most frequent method for gait generation is the trajectory-based methods, such as stability criteria known as Zero-Moment Point (ZMP) [1, 2]. However, this method requires the exact model of the robot dynamics and it is not adaptable to various environments. Therefore, new control methods based on Central Pattern Generators (CPGs) are being proposed.

CPGs are neural networks that produce rhythmic patterns of neural activity without receiving rhythmic inputs [3]. These networks are found in both invertebrate and vertebrate animals and humans. Fig. 1 shows the control system of the human locomotion. In this figure, the Central Nervous System (CNS) is the part of the nervous system consisting of the brain and the spinal cord. The human locomotion is controlled by the CNS. The CPG provides a series of periodic signals for each part of the locomotor. This information is transferred to muscles by a network of motor neurons for locomotion. The modulation of CPG patterns by sensorial information from environment results in the most stable locomotion in complex terrain [4].

The CPG model for locomotion control was first proposed by Wilson in 1961 for studying the flight patterns. Cohen in 1980s [5] presented the discussion through the researches on the dissection of a lamprey spinal cord. Afterwards, in 2007 Ijspeert et al. [6] showed how transition occurs from walking to swimming by modulating the electrical stimulation of the Mesencephalic Locomotor Region (MLR) in salamander CPG model. CPG models recently have been widely used in robotic systems such as quadruped locomotion [7, 8, 9], snake robot [10], and biped locomotion [11, 12].

A set of identical systems of differential equations is used for the CPG modeling [13]. Humans and animals have the ability to produce various gaits by CPGs according to the environmental conditions. Chen et al. [14] studied smooth gait transition of a hexapod robot by a CPG algorithm, which is constructed by a series of oscillators with adjustable phase lag. Wu et al. [15] studied gait transition and added a transition state in the CPG network to enhance the static balance of the robot.

Wang et al. [16] presented the CPG inspired control for adaptive walking of biped robots. Their proposed control strategy is able to generate adaptive online joint control Signals to realize biped adaptive walking. They also had previously proposed adaptive locomotion control for AIBO quadruped robot [17].

![Fig. 1. Control system of the human locomotion.](image-url)
Cristiano et al. [18] proposed a locomotion control system for biped robots by using a network of CPGs. They used feedback signals for controlling the robot’s posture and resetting the phase of the locomotion pattern in order to prevent the robot from falling down whenever a risk situation arises. Santos et al. [19] proposed a bio-inspired robotic controller capable of locomotion generation that easily switches between different type of gaits. In their method, generated trajectories by CPG are modulated by a drive signal. Nandi et al. [20] developed an adaptive module active leg for amputees. Pinto and Golubitsky [21] studied two models for biped locomotion. One that was proposed by Golubitsky is a 4-cell model for the legs of a biped animal, and the other is a 8-cell model for the arm-leg model. Afterwards, they studied the CPG model for modular generation of a hexapod robot’s movements, using a biological approach [22]. They used the network of twelve coupled CPG-units, each of which consists of two motor primitives.

Although many researches have been done on CPG modeling, the generation of the parameters of the CPG models is still one of the most interesting fields in this area. Therefore, in this study, the 4-cell Morris-Lecar model is proposed with appropriate parameters to implement in the biped robot gait generation and transition.

This paper is organized as follows. First of all, the CPG models will be reviewed and a 4-cell CPG model and symmetry in this model for gait generation of biped will be presented. In Section III, The Morris-Lecar oscillators are used as internal dynamics of cells. Then, in Section IV, results and discussions are presented. Conclusions and future works are provided in Section V.

II. CPG MODEL FOR GAIT GENERATION OF BIPED

In this section, a CPG model for gait generation and transition of biped will be introduced. It is based on the work done by Golubitsky et al [23]. They proposed a CPG model in order to generate the rhythmic movements for animals with 2n legs, which is shown in Fig. 2. Physiological studies show that the Locomotion in animals and human is controlled by joints of each leg and joints are controlled by flexor and extensor muscle groups. In this paper, we choose the 4-cell CPG network model for gait generation and transition of a biped robot.

The four-cell model can be used for producing the rhythms of bipedal gaits of walk, run, skip, among other gaits. As mentioned earlier, some works have implemented the symmetry property to generate the gaits in robots. The symmetry is related to phase relations between legs [21, 23]. The symmetry property of model is shown in Fig. 3.

CPGs are modeled as sets of identical systems of differential equations. It is assumed that all neurons (or cells) in CPG are modeled by the same system of ODEs. Right Hip (RH) and Right Knee (RK) cells send signals to the Right leg, and Left Hip (LH) and Left Knee (LK) cells send signals to the right leg (as shown in Fig. 4). The different arrows between cells present the different coupling weights.

The coupling weights matrixes can be represented by the following form (1)

\[
W_{coupling} = \begin{bmatrix}
1 & wa_2 & wb_2 & wc_2 \\
2 & wa_1 & 0.0 & wc_2 & wb_2 \\
3 & wb_1 & wc_1 & 0.0 & wa_2 \\
4 & wc_1 & wb_1 & wa_1 & 0.0
\end{bmatrix}
\]

In walk and run, both legs receive same signals with a phase shift. For producing the walk the 4-cell CPG uses two signals per leg with a half-period phase difference. These models can produce run gait by sending two in phase signals to one leg and other two in phase signals to the other leg. These models send two different signals to one leg and the same signals to another leg with a half-period phase difference in order to produce skip gait.

![Fig. 2. The 2D schematic of a 2n-legged CPG model [23].](image)

![Fig. 3. A 4-cell CPG model with coupling weights](image)
III. MORRIS-LECAR OSCILLATOR NEURON MODEL

In order to implement the cells of a CPG, several types of nonlinear oscillators have been used. In this paper, we use neural oscillator model proposed by Catherine Morris and Harold Lecar [24]. This model is defined in (2-6). The Morris-Lecar neuron model is a two-dimensional reduced dynamical model for the membrane potential of a neuron.

\[
\dot{v} = f_1(v, w) = -g_{ca} m(v)(v - v_{ca}) - g_l (v - v_l) - g_k (v - v_k) + i
\]

\[
\dot{w} = f_2(v, w) = -\varphi r(v)(n(v) - w)
\]

Where

\[
m(v) = \frac{1}{2} (1 + \text{tanh}(\frac{v - v_1}{v_2}))
\]

\[
n(v) = \frac{1}{2} (1 + \text{tanh}(\frac{v - v_1}{v_4}))
\]

\[
r(v) = (\text{cosh}(\frac{v - v_1}{v_2}))
\]

Here, \(i\) is the applied current (\(\mu\text{A/cm}^2\)), \(v\) is the membrane potential (mV), \(v_1\), \(v_2\), \(v_3\) and \(v_4\) are the equilibrium potentials. \(v_1\), \(v_2\), \(v_3\) and \(v_4\) are parameters chosen to fit voltage-clamp data and \(w\) indicates the Potassium variable.

The parameter values of the Morris–Lecar equations in the numerical simulations for producing the periodic signals are presented in Table I.

For example, the odes of the cell, \(Osc_{1}\), are defined in (7) and (8). [16].

\[
\dot{y}_{11} = f_1(y_{11},y_{21},y_{31},y_{41}) = f_1(y_{11},y_{12})
\]

\[
-\omega_a h (y_{11},y_{21}) - \omega_b h(y_{11},y_{31}) - \omega_c h(y_{11},y_{41})
\]

\[
\dot{y}_{12} = f_2(y_{11},y_{12}) = f_2(y_{11},y_{12})
\]

We choose diffusive coupling between cells. In Eq. 8, \(h(y_i,y_j) = y_i \cdot y_j\) is the function that shows the diffusive coupling between cells and \(\omega_a\), \(\omega_b\) and \(\omega_c\) are the coupling weights between cells, where \(n = 1, 2\).

This 4-cell CPG model with coupling strengths is shown in Fig. 3.

IV. RESULTS AND DISCUSSIONS

The advantages of the CPG control method motivated us to simulate the 4-cell model with diffusive coupling for a bipedal robot. We used the Morris-Lecar equations as oscillator of each cell. The symmetry concept in CPG model is used for gait generation. We present the values of the initial conditions and the coupling weights, which correspond to the walk, run, transition between walk to skip and transition between run to skip (Table II and Table III). We can obtain the transition from walk to skip and from run to skip by changing the coupling weights of walk and run gaits.

We plot the periodic signals of the 4-cell CPG network identify walk, run and skip gaits. The signals of 4-cell model can be used as joint angles of hip and knee joints of a five-link biped robot as shown in Fig. 4.

As it is observed in fig 5-9, 4-cell CPG can produce the represented phases difference that are related to walk, run and skip gaits.

The periodic signals of 4-cell model for walk and run gaits are shown in Fig. 5-6. According to these diagrams, we can use the first variables from the signal of each oscillator, \(y_{11}, i = 1,2,3,4\), as joint angles of a five-link biped robot.

As shown on Fig. 5, the 4-cell CPG generates two signals per leg with a half-period phase difference to generate the walk. Fig. 6 illustrates that 4-cell CPG send two in phase signal to each leg in order to produce run gait.

The phase diagram related to walk gait for the 4-cell model has been depicted in Fig. 7. According to this diagram, the signals converge to a limit cycle and this shows the ability of this model to generate the gaits for biped.

The periodic signals of 4-cell model for walk to skip transition and run to skip transition are shown in Fig. 8-9. The transition from walk to skip is obtained by increasing \(w_{b1}\) parameter in the walk gait from -0.2 to 0.04, also transition from run to skip is obtained by decreasing \(w_{c2}\) parameter in the run gait from 0.1 to -0.15 (as mentioned in Table III). The stick diagram of the biped robot’s walking during one half-step is depicted in Fig. 10.

![Fig. 4. The CPG outputs for hip and knee joints of a five-link Biped robot.](Image)
### TABLE II. THE VALUES OF INITIAL CONDITIONS OF CELLS

<table>
<thead>
<tr>
<th>Gait</th>
<th>Initial Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk</td>
<td>[0.304 0.163 -0.169 0.229 -0.169 0.229 0.304 0.163]</td>
</tr>
<tr>
<td>Run</td>
<td>[0.050 -0.100 -0.110 0.329 0.050 -0.100 -0.110 0.329]</td>
</tr>
<tr>
<td>Walk-skip</td>
<td>[-0.091 0.568 -0.086 -0.229 0.298 0.233 -0.234 0.060]</td>
</tr>
<tr>
<td>Run-skip</td>
<td>[0.097 0.197 0.211 0.134 -0.115 0.033 0.124 0.156]</td>
</tr>
</tbody>
</table>

### TABLE III. THE VALUES OF COUPLING STRENGTHS BETWEEN CELLS

<table>
<thead>
<tr>
<th>Gait</th>
<th>Coupling Weights Matrixes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk</td>
<td>0.0 -0.1 -0.2 0.1 -0.1 0.0 0.1 -0.2 -0.1 0.0</td>
</tr>
<tr>
<td>Run</td>
<td>0.0 -0.3 0.19 0.09 -0.3 0.09 0.19 0.19 0.09 -0.3 0.09 -0.3 0.09 -0.3 0.09 -0.3 0.09 -0.3 0.09</td>
</tr>
<tr>
<td>Walk-Skip</td>
<td>0.0 -0.1 -0.2 0.1 -0.1 0.0 0.1 -0.2 0.1 0.04 0.1 0.0 -0.1 0.04 -0.1 0.0</td>
</tr>
<tr>
<td>Run-Skip</td>
<td>0.0 -0.3 0.19 -0.15 -0.3 0.0 -0.15 0.19 0.09 0.0 -0.3 0.09 0.0 -0.3 0.09 0.0 -0.3 0.09 0.0</td>
</tr>
</tbody>
</table>

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Fig. 5. The periodic signals of a 4-cell model for walk.

Fig. 6. The periodic signals of a 4-cell model for run.

Fig. 7. Phase diagram for biped walking, generated by the 4-cell model.

Fig. 8. The periodic signals of a 4-cell model for skip obtained by changing coupling weights of walk gait.
of walk and run gaits. This method is inspired by gait generation and transitions in animals and humans achieved by changing CPGs networks. The output of the oscillators was used as the joint angles of the robot. Simulation results show that the periodic signals of the 4-cell model converge very fast to a limit cycle in state space. This reveals the ability of this model to generate the gaits for biped.

The design of a physical prototype to verify presented method for gait generation and transition will be the subject of future work. In the meantime, we intend to obtain more transitions between gaits by changing the other parameters of model.

REFERENCES


