Optimization of Central Patterns Generators

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Abstract: The issue of how best to optimize Central Patterns Generators (CPG) for locomotion to generate motion for one leg with two degrees of freedom has inspired many researchers to explore the ways in which rhythmic patterns obtained by genetic algorithms may be utilized in uncoupled, unidirectional and bidirectional two CPGs. This study takes as its assumption that the focus on stability analysis to decrease variation between steps brings about better results with respect to the gait locomotion and argues that controlling the amplitude and frequency may lead to more robust results viz., stimulation for movement.

Keywords: Central Patterns Generators (CPGs), kinematic model of one leg, stability, optimizing gait generation, assumption

INTRODUCTION

Recent studies on stimulation for movement such as walking, swimming and running have shown that the basic locomotor patterns of biological systems are produced by a central nervous system, referred to as the Central Pattern Generator (CPG) (stillar, 1996). Central pattern generators are biologically inspired networks of nonlinear oscillating neurons that are capable of producing rhythmic patterns without sensory feedback. Localized in the spinal cord of animals, the CPG sends signals from the brainstem to produce a periodic activity and hence generates rhythmical commands for the muscles (Brown, 1911; Ijspeert, 2008; Righetti and Ijspeert, 2006; Ijspeert et al., 2007; Spowewitz et al., 2008; Cho and Jeeon, 2016; Maizir et al., 2016). Recent studies on human body have shown that many functions that cannot be controlled by the human body consciously are controlled by the CPGs such as breathing and digestion (Billard and Ijspeert, 2000).

Generally speaking, CPGs are considered a set of nonlinear oscillators and each of the set of non linear oscillators is forced by the output of a sensor which gives a time-index to the first-order information on the motion (Ijspeert, 2008). A neural oscillator is formed by two neurons with inhibitive connections between them and the responses of two neurons of a neural oscillator suppress each other in such a way that one of them is extensor neuron and the other is flexor neuron (Buchel et al., 2000; Casasnovas and Meyrand, 1995; Vreeswijk et al., 1994; Buschges, 2005; Matsuoka, 1987; Pearson, 1995).

Interestingly, many physical structures of the limbs and arms have been modeled and the control systems have been copied to regenerate the same move patterns in the robots as seen in nature. CPGs always synchronize with body movement and accordingly burst rhythmic patterns to motor neurons at an appropriate time in a movement cycle (Ijspeert, 2008). In legged locomotion, each leg is controlled by distinct neural network where the CPG gives signals to each joint (Amrollah and Henaff, 2010; Ijspeert, 2008). Experiments reveal that there is a tight coupling between sensory feedback and CPGs. The reflexes are phase-dependent they will have different effects depending on the timing within locomotor cycle (Pearson, 1995). Various models of CPG used for controlling the biped locomotion in human robots have been introduced (Aoi and Tsuchiya, 2005; Endo et al., 2005; Taga, 1998; Taga et al., 1991; Marbach, 2004). Different modes of locomotion have been controlled by Models of CPGs such as the CPG models used with octopod and hexapod robots inspired by insect locomotion (Arena et al., 2004; Inagaki et al., 2006; 2003; Nolfi and Floreano, 2000). CPGs have been also used to control swimming robots such as swimming lamprey or eel robots (Arena et al., 2004; Crespi and Ijspeert, 2008; Ijspeert and Crespi, 2007; Inagaki et al., 2006) as well as to control Quadruped robots (Billard and Ijspeert, 2000; Brambilla et al., 2006; Fukuda et al., 2003). This study summarizes the kinematics model used for simulations and gait design, explains the uncouple, unidirectional and bidirectional two CPGs structures and analyzes stability of the mode. It also explores how optimized...

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central pattern generator structures may be adapted to robotic systems that perform one-leg movement and gives suggestions for future research.

**MATERIALS AND METHODS**

**Kinematic model:** Kinematic model is designed to perform basic analysis. Figure 1 shows the flight and stance modes of the leg structure where \( L_1 \), \( L_2 \) represent the lengths of the thigh and the calf leg respectively and \( \theta_1, \theta_2 \) show the angular positions of the hip and the knee. Let us also assume that \((x_H, y_H)\) denotes the first coordinate of the hip and \((x_K, y_K)\) denotes the second coordinate of the knee. Now, if the tip of the second link touches the ground the leg will behave like a revolute joint. This indicates that a zero slip is considered between the tip of the link and ground surface. As such the body will move along \( x \)-direction only in stance mode.

We have two cases: the first case is when the leg is in stance mode, the kinematic model has one degree of freedom (Fig. 1). The hip joint angle \( \theta_1 \) is also calculated with respect to knee angle \( \theta_2 \), which is determined by the CPG. The second case is when the leg is in swing mode, we obtain leg with 2 DOF. The hip and knee joint angles are calculated by uncoupled, unidirectional and bidirectional two CPGs. The kinematic equation are:

\[
\begin{align*}
    x_H &= x_H + L_1 \cos \theta_1, \\
    y_H &= L_1 \sin \theta_1 \\
    x_K &= x_K + L_2 \cos \theta_2, \\
    y_K &= L_1 \sin \theta_1 + L_2 \sin \theta_2
\end{align*}
\]

**Central Pattern Generators (CPGs):** As defined previously, CPGs are biologically inspired networks of nonlinear oscillating neurons that are cable of producing rhythmic patterns without sensory feedback. Recently, a plethora of applications have been implemented using different neurons in robotic systems. These neurons are implemented by software methods called CPGs where the CPG unit is responsible for generating required angular references for the hip and knee joints. The mathematical differential equations present the CPGs in general Equation (Larsen) (Ijspeert and Crespi, 2007; Ijspeert et al., 2007; Sproewitz et al., 2008):

\[
\begin{align*}
    \phi_i &= 2\pi v_i + \sum_{i=1}^{n} \omega_i \sin (\phi_j - \phi_i - \theta_i) \\
    \dot{\xi}_i &= a_i \left( \frac{1}{4} (R_i - \xi_i) - \xi_i \right) \\
    \theta_i &= \xi_i (1 + \cos (\phi_i))
\end{align*}
\]

where, \( \theta_i \) is the output of oscillator \( i \) which has amplitude \( r_i \). Both the amplitude and the output are angles expressed in radians or in degrees which are subsequently

Fig. 1: Leg system in swing and stance mode

sent to the motor controllers of the robot. By deriving the Eq 1 we obtain three types of CPGs, uncoupled, unidirectional and bidirectional CPGs, respectively:

\[
\begin{align*}
    \phi_1 &= 2\pi v_1 \\
    \dot{\xi}_1 &= a_1 \left( \frac{1}{4} (R_1 - \xi_1) - \xi_1 \right) \\
    \theta_1 &= \xi_1 (1 + \cos (\phi_1)) \\
    \phi_2 &= 2\pi v_2 \\
    \dot{\xi}_2 &= a_2 \left( \frac{1}{4} (R_2 - \xi_2) - \xi_2 \right) \\
    \theta_2 &= \xi_2 (1 + \cos (\phi_2)) \\
    \phi_3 &= 2\pi v_3 + r_i w_{12} \sin (\phi_2 - \phi_1 - \theta_1) \\
    \dot{\xi}_3 &= a_3 \left( \frac{1}{4} (R_3 - \xi_3) - \xi_3 \right) \\
    \theta_3 &= \xi_3 (1 + \cos (\phi_3))
\end{align*}
\]

The output of the systems gives \( \theta_1 = r_1 (1 + \cos (\phi_1)) \) and \( \theta_2 = r_2 (1 + \cos (\phi_2)) \) where \( \theta_1 \) and \( \theta_2 \) (defined previously) are said to represent the angular joints of the hip and the knee respectively and the state variables \( \phi_i \) and \( r_i \) equally represent the phase and the amplitude. The CPG will converge if isolated by \( v_i \) and \( R \). The constant \( a_i \) determines how fast the amplitude \( r_i \) will converge to \( R_i \). When multiple CPGs exist they are coupled together by the coupling weights \( w_{ij} \) and phase biases \( \phi_{ij} \) where \( i, j = 1, 2 \) and \( i \neq j \). Certain forms of outputs are possible by changing the numerical values of parameters (for more details about different CPGs (Amrollah and Hanafi, 2010; Parker and Smith, 1990). Figure 2 shows one CPG in simulink block.
then there are two fixed points; one of them is stable and the other one is unstable. The stability of the fixed point is determined by the sign of:

$$\frac{d\phi}{d\varnothing} = -R_2 w_{12} \cos(\varnothing - \varnothing_{12})$$

The fixed point is stable if this quantity is negative and unstable if it is positive. If the initial phase difference is the unstable fixed point the two oscillators will remain synchronized with that phase difference hence there is no bifurcation. The third case is bidirectional two CPGs. Let us consider four different cases.

**Case 1:** Let us assume that $\varnothing_{12} = -\varnothing_{12}$, $w_{12} = w_{12} = w$ and $R_1 = R_2 = 1$. Then, as $t \to \infty$ we will have $r_1 \to R_1$ and $r_2 \to R_2$:

$$\phi_1 = 2\pi v_1 - w \sin(\varnothing - \varnothing_{12})$$
$$\phi_2 = 2\pi v_2 + w \sin(\varnothing - \varnothing_{12})$$

Also, for $\varnothing = \varnothing_{12}$, which denotes the phase difference the time evolution of the phase difference is determined by:

$$\dot{\varnothing} = f(\varnothing) = \phi_2 - \phi_1 = 2\pi(v_2 - v_1)$$

Now, if $f(\varnothing) = 0$ then $v_2 = v_1$, which means there is no fixed point. In this case it is said to drift.

**Case 2:** Let us assume that $\varnothing_{12} = -\varnothing_{12}$, $w_{12} = w_{12} = w$ and $R_1 = R_2 = 1$. Then:

$$\dot{\varnothing} = f(\varnothing) = \phi_2 - \phi_1 = 2\pi(v_2 - v_1) - 2w \sin(\varnothing - \varnothing_{12})$$

Now, $f(\varnothing) = 0$ gives us:

$$\varnothing_{12} = \arcsin\left(\frac{\pi(v_2 - v_1)}{w}\right) + \varnothing_{12}$$

If the oscillators synchronize, they will do so at the fixed points $\varnothing_{12}$. Note that there is no fixed-point if:

$$\left|\frac{\pi(v_2 - v_1)}{w}\right| > 1$$

That is when the difference of intrinsic frequencies is too large compared to the coupling weight $w_{12}$ multiplied by the $R_2$ amplitude of the oscillator 2 the oscillators do not synchronize and are said to drift. If:

$$\left|\frac{\pi(v_2 - v_1)}{w}\right| < 1$$

then there is a single fixed point $\varnothing_{12} = \pi/2 + \varnothing_{12}$ when $v_2 > v_1$ and $\varnothing_{12} = \pi/2 + \varnothing_{12}$ when $v_2 < v_1$. This solution is asymptotically stable and the two oscillators will synchronize with that phase difference. Finally, if:

$$\left|\frac{\pi(v_2 - v_1)}{w}\right| = 1$$

That is when the difference of intrinsic frequencies is too large compared to the coupling weight $w$ the oscillators do not synchronize and are said to drift. If, on the other hand:

$$\left|\frac{\pi(v_2 - v_1)}{w}\right| > 1$$
then there is a single fixed point $\Omega = \pi/2 + \Omega_{12}$ when $v_1 > v_2$ and $\Omega = -\pi/2 + \Omega_{12}$ when $v_1 < v_2$. This solution is asymptotically stable and the two oscillators will synchronize with this phase difference. Finally, if:

$$\frac{\pi(v_1 - v_2)}{w} < 1$$

then there are two fixed points; one of them is stable and the other one is unstable. The stability of the fixed point is determined by the sign of:

$$\frac{df(\Omega)}{d\Omega} = -(w_{21} + w_{12}) \cos(\Omega - \Omega_{12})$$

The fixed point is stable if this quantity is negative and unstable if it is positive. If the initial phase difference is the unstable fixed point, then the two oscillators will remain synchronized with that phase difference.

**Case 3:** Let us assume that $\Omega_{12} = -\Omega_{12}$ and $R_1 = R_2 = 1$. Then:

$$\dot{\Omega} = \phi_2 - \phi_1 = 2\pi(v_2 - v_1) - (w_{21} + w_{12}) \sin(\Omega - \Omega_{12})$$

and $f(\Omega) = 0$ leads to the fixed point:

$$\Omega = \arcsin\left(\frac{2\pi(v_2 - v_1)}{R_1 w_{21} + R_2 w_{12}}\right) + \Omega_{12}$$

Note that there is no fixed-point if:

$$\frac{2\pi(v_2 - v_1)}{w_{21} + w_{12}} > 1$$

That is when the difference of intrinsic frequencies is too large compared to the coupling weight $w_{21} + w_{12}$, the oscillators do not synchronize and are said to drift. If:

$$\frac{2\pi(v_2 - v_1)}{R_1 w_{21} + R_2 w_{12}} = 1$$

then there is a single fixed point $\Omega = \pi/2 + \Omega_{12}$ when $v_1 > v_2$ and $\Omega = \pi/2 + \Omega_{12}$ when $v_1 < v_2$. This solution is asymptotically stable and the two oscillators will synchronize with this phase difference. Finally, if:

$$\frac{2\pi(v_2 - v_1)}{w_{21} + w_{12}} < 1$$

then there are two fixed points; one of them is stable and the other one is unstable. The stability of the fixed point is determined by the sign of:

$$\frac{df(\Omega)}{d\Omega} = -(w_{21} + w_{12}) \cos(\Omega - \Omega_{12})$$

Again, the fixed point is stable if this quantity is negative and unstable if it is positive. If the initial phase difference is the unstable fixed point then the two oscillators will remain synchronized with that phase difference.

**Case 4:** Let us take $\Omega_{12} = -\Omega_{12}$. In this case, we have:

$$\dot{\Omega} = \phi_2 - \phi_1 = 2\pi(v_2 - v_1) - (R_1 w_{21} + R_2 w_{12}) \sin(\Omega - \Omega_{12})$$

and $f(\Omega) = 0$ results in:

$$\Omega = \arcsin\left(\frac{2\pi(v_2 - v_1)}{R_1 w_{21} + R_2 w_{12}}\right) + \Omega_{12}$$

Note that there is no fixed-point if:

$$\frac{2\pi(v_2 - v_1)}{R_1 w_{21} + R_2 w_{12}} > 1$$

That is when the difference of intrinsic frequencies is too large compared to the coupling weight multiple by amplitude $R_1 w_{21} + R_2 w_{12}$, the oscillators do not synchronize and are said to drift. If:

$$\frac{2\pi(v_2 - v_1)}{R_1 w_{21} + R_2 w_{12}} = 1$$

then there is a single fixed point $\Omega = \pi/2 + \Omega_{12}$ when $v_1 > v_2$ and $\Omega = \pi/2 + \Omega_{12}$ when $v_1 < v_2$. This solution is asymptotically stable and the two oscillators will synchronize with that phase difference. Finally, if:

$$\frac{2\pi(v_2 - v_1)}{w_{21} + w_{12}} < 1$$

There are two fixed points, one of them is stable and the other one is unstable. The stability of the fixed point is determined by the sign of:

$$\frac{df(\Omega)}{d\Omega} = -(w_{21} + w_{12}) \cos(\Omega - \Omega_{12})$$
The fixed point is stable if this quantity is negative and unstable if it is positive. As such when the initial phase difference is the unstable fixed point the two oscillators will remain synchronized with that phase difference.

RESULTS AND DISCUSSION

Optimizing gait generation: In this study, we will consider three cases where each pattern generator outputs angular patterns for each joint. To evaluate gait generation, we need to find the optimal parameter sets by using central pattern generators which explains how the angular of the hip and the knee should vary with time to generate motion along x-direction. For each case, parameter sets for the central pattern of each joint is given:

\[ P_1 = \{ a_1, v_1, R_1, a_2, v_2, R_2 \} \]

Uncoupled case:

\[ P_2 = \{ a_1, v_1, a_2, v_2, R_1, R_2, w_{12}, \varphi_{12} \} \]

Unidirectional case:

\[ P_3 = \{ a_1, v_1, R_1, w_{12}, \varphi_{12}, a_2, v_2, R_2, w_{21}, \varphi_{21} \} \]

Bidirectional case: Nolfi and Floreano (2000), Alexander (1996) used genetic algorithms to find the optimal parameter sets. In this study there is only one cost function utilized the different walking patterns depend on this cost function (Arikan and Ifranoglu, 2011):

\[ J = -C_1 \sum_{k=1}^{n} x_k(k) + C_2 \sum_{k=1}^{n} (\theta_1(k) + \theta_2(k)) / N \]

where, \( C_1, C_2 \in [0, 1] \) with \( C_1 + C_2 = 1 \), n is the number of elements of position vector in simulation and N is the length of the time. To maximize the displacement or the velocity, we should minimize J if \( C_2 = 0 \) then the aim is to maximize the displacement. However, if \( C_1, C_2 = 0 \) then there will be another cost function involving energy related terms in addition to the position. The goal is to minimize the energy while changing the position. Actually this fact is available in biological locomotion (Alexander, 1996, 2003). The angular positions of the hip and knee joints are shaped during the optimization. These cost functions result in two different walking patterns. The first cost function presents walking pattern with large variations in joint because only the displacement is emphasized in this function. However, the second one moves in +x direction with small angular variations of hip and knee joints.

Still there are two constraints \( 0 \leq \theta_1, \theta_2 \leq \pi \). Figure 3 through 5 show some gaits as a result of evolutionary optimization technique. Evolutionary optimization algorithms reveal the gait below in case constraints applied for joint angles. In this study, we used the hybrid function during the optimization. A hybrid function is an optimization function that runs after the genetic algorithm terminates in order to improve the value of the fitness function. The hybrid function uses the final point from the genetic algorithm as its initial point. You can specify a hybrid function in Hybrid function options. Specifically, we used optimization toolbox function at pattern search or fmincon, a constrained minimization function. The example first runs the genetic algorithm to find a point close to the optimal point and then uses that point as the initial point for pattern search or fmincon.

Following gait optimization, we may conclude that locomotion is achievable by using the cost function J for the case of the uncoupled two CPGs such as in Fig. 3a-c.

Again by utilizing gait optimization, stimulation of movement may be obtained using the cost function J for the case of the unidirectional two CPGs it is show by Fig. 4a-c. Finally by optimizing gait we obtain movement by means of using the cost function J for the case of the
Fig. 4: a) Simulation of walking with constraints; b) Joint angles against time; c) Displacement against time

Fig. 5: a) Simulation of walking gait with constraints; b) Joint angles against time of optimizing gait; c) Displacement against time of optimizing gait

Bidirectional two CPGs, Fig. 9-11 show this results. Table 1 and 2 summarize the results of the optimization in unbounded and bounded region. It is concluded that all parameters in three types of CPGs have positive values. The parameters $R_1$ and $R_2$ are the smallest values in both table. A close look at Table 1 and 2, we clearly realize that in Table 1 the displacement and the velocity increase too much hence it is not possible to be physically implemented, simply because optimization has been carried out in an unbounded region. By contrast in Table 2, optimization can be physically implemented. Moreover, the three cases reveal no bifurcation; better results come from bidirectional two CPGs, though.
Table 1: Uncoupled, unidirectional and bidirectional two CPGs in unbounded in 10 sec

<table>
<thead>
<tr>
<th>Start at initial points</th>
<th>Uncoupled, Unidirectional and bidirectional two CPGs in unbounded in 10 sec</th>
<th>F-values</th>
<th>Xb</th>
<th>Optimization type</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.3017, 28.3858, 0.86846, 20.3022, 14.2796, 1.2199</td>
<td>30.7356, 28.3868, 0.8628, 20.3314, 14.2796, 1.2202</td>
<td>-2.3849e+00</td>
<td>47.8770</td>
<td>GA and hybrid function at finicon to unbounded</td>
<td>3.0541</td>
</tr>
<tr>
<td>30.7363, 28.5866, 0.8682, 20.3314, 14.2796, 1.2202</td>
<td>30.6689, 28.5866, 0.8629, 20.3406, 14.2796, 1.2202</td>
<td>-1.1924e+00</td>
<td>47.8777</td>
<td>GA and hybrid function at finicon to unbounded</td>
<td>3.0543</td>
</tr>
<tr>
<td>13.2211, 27.4674, 0.8541, 23.3678, 20.0001, 22.1295, 47.6153, 50.7135</td>
<td>17.2865, 40.4284, 0.9287, 28.0195, 33.3458, 1.2273, 52.0449, 50.3126</td>
<td>-2.8213e+00</td>
<td>112.8604</td>
<td>GA and hybrid function at patternsearch to unidirectional</td>
<td>2.9801</td>
</tr>
<tr>
<td>59.3216, 34.6979, 0.8072, 8.6457, 1.1144, 59.4932, 34.2398, 1.2267, 12.0076, 6.7790</td>
<td>61.4180, 34.8193, 0.8691, 8.8225, 1.0938, 61.9136, 34.4234, 1.3595, 12.1180, 6.7896</td>
<td>-6.8743e+00</td>
<td>138.4982</td>
<td>GA and hybrid function at finicon to bidirectional</td>
<td>3.6014</td>
</tr>
<tr>
<td>61.4180, 34.8193, 0.8691, 8.8225, 1.0938, 61.9136, 34.4234, 1.3595, 12.1180, 6.7896</td>
<td>62.0355, 34.8369, 0.8565, 8.9123, 1.1130, 61.9643, 34.4603, 1.3678, 12.1021, 6.8944</td>
<td>-3.4536e+00</td>
<td>139.0181</td>
<td>Hybrid function at finicon to unidirectional</td>
<td>3.6846</td>
</tr>
<tr>
<td>17.2865, 40.4284, 0.9287, 28.0195, 33.3458, 1.2273, 52.0449, 50.3126</td>
<td>17.5270, 40.6125, 1.0388, 27.1307, 33.3437, 1.2270, 51.1525, 50.1892</td>
<td>-5.7859e+00</td>
<td>116.9131</td>
<td>GA and hybrid function at patternsearch to unidirectional</td>
<td>3.0240</td>
</tr>
</tbody>
</table>

Table 2: Optimizing uncoupled, unidirectional and bidirectional two CPGs in bounded region in 10 sec

<table>
<thead>
<tr>
<th>By optimizing of two CPGs</th>
<th>Parameter values</th>
<th>F-values</th>
<th>Xb</th>
<th>Optimization type</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&amp;E Two uncoupled without constraints</td>
<td>33.7956, 1.9992, 1.4355, 68.5282, 1.9857, 3.2592</td>
<td>-1.1020e+00</td>
<td>4.4082</td>
<td>GA</td>
<td>18.4589</td>
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<tr>
<td>D&amp;E Two uncoupled with constraints</td>
<td>18.6893, 1.9928, 0.7746, 46.4124, 1.9604, 1.5327</td>
<td>-1.3260e+03</td>
<td>4.9613</td>
<td>GA and hybrid function at pattern search</td>
<td>4.1004</td>
</tr>
<tr>
<td>D Two uncoupled with constraints</td>
<td>35.3887, 1.9955, 0.7564, 26.4992, 1.9605, 1.5707</td>
<td>-2.7312e+03</td>
<td>4.9856</td>
<td>GA and hybrid function at finicon</td>
<td>4.2406</td>
</tr>
<tr>
<td>E Two uncoupled with constraints</td>
<td>0.0613, 0.0426, 0.0670, 0.0630, 0.0420, 0.0623</td>
<td>9.3682e-09</td>
<td>0.3100</td>
<td>GA and hybrid function at pattern search</td>
<td>9.3175e-09</td>
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<tr>
<td>D&amp;E Unidirectional two CPGs</td>
<td>50.0000, 1.9850, 0.7804, 13.1020, 1.9230, 1.5356, 2.0000, -0.3699</td>
<td>-1.7074e+03</td>
<td>6.4220</td>
<td>GA and hybrid function at pattern search</td>
<td>4.2509</td>
</tr>
<tr>
<td>D Unidirectional two CPGs, 23.6492, -1.5619, 1.5424, 20.2528, 1.9347, 0.7369, -0.5227, 3.2986</td>
<td>-3.0227e+03</td>
<td>5.5084</td>
<td>GA and hybrid function at finicon</td>
<td>4.1719</td>
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<tr>
<td>D&amp;E Bidirectional two CPGs, 1.9690, -0.5781, 31.8414, 48.2175, 1.9592, 0.8301, 1.9616, 1.5398, 1.7346</td>
<td>-1.6230e+03</td>
<td>6.2665</td>
<td>GA and hybrid function at pattern search</td>
<td>4.2799</td>
<td></td>
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<tr>
<td>D Bidirectional two CPGs, 9.5546, 1.9490, 0.8009, 1.2422, 5.5546, 48.1509, 1.9717, 1.2744, 1.9235</td>
<td>-3.1376e+03</td>
<td>6.1787</td>
<td>GA and hybrid function at finicon</td>
<td>2.9796</td>
<td></td>
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</table>

E = Energy, D = Displacement, F-value = objective function and Xb = displacement in meter

CONCLUSION

To sum up in this study uncoupled, unidirectional and bidirectional two CPGs are used to generate motion for one leg with two degree of freedom. The study shows that when optimization is conducted in an unbounded region, the results are impossible to be implemented physically. Furthermore by using genetic algorithms and hybrid functions it seems that it is difficult to find a global region because there is no bifurcation for the parameters in the three cases above. However, when we consider the stability analysis presented above with the objective of decreasing the variation between steps it is vital that we control the amplitude and the frequency to obtain better results. Such results, we believe can be implemented physically. Most important the study reveals CPGs can control biped locomotion not only in animals but also in human beings.

SUGGESTION

Future research should investigate whether CPGs can control other functions in human bodies such as breathing, let alone the stimulation of the arm movement.

REFERENCES


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