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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 paper 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

Introduction

Recent studies on stimulation for movement, such as walking, swimming and running have shown that the basic locomotors patterns of biological systems are produced by a central nervous system, referred to as the Central Pattern Generator (CPG) (Larsen; Sillar, 1996). Central Pattern Generators are biologically inspired networks of nonlinear oscillating neurons that are cable 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 rhythmic commands for the muscles (Brown, 1911); (Ijspeert, 2008); (Ijspeert, Crespi, Ryczko, &Cabelguen, 2007); (Sproewitz, Moeckel, Maye, &Ijspeert, 2008). 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&Ijspeert, 2000).

Generally speaking, CPGs are considered a set of nonlinear oscillators and each of the set of nonlinear 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 (Bucher, Haspel, Golowasch, & Nadim, 2000); (Casasnovas&Meyrand, 1995); (Van Vreeswijk, Abbott, &Ermentrout, 1994).

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 neuronal network, where the CPG gives signals to each joint (Amrollah&Henaff, 2010; Ijspeert, 2008). Experiments reveal that there is a tight coupling between sensory feedback and CPGs. The reflexes are phase-dependent,theywillhave different effects depending on the timing within locomotorscycle (Pearson, 1995).Various models of CPG used for controlling the biped locomotion in human robots have been introduced (for details, see, Aoi& Tsuchiya, 2005; Endo et al., 2005; (Taga, 1998); (Taga, Yamaguchi, & Shimizu, 1991). 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; Inagaki, Yuasa, & Ari, 2003). CPGs have been also used to control swimming robots, such as swimming lamprey or eel robots (see, Arena, 2001; Crespi, &Ijspeert, 2008; Ijspeert, &Crespi, 2007; Inagaki et al., 2006), as well as to control Quadruped robots (for details, see, Billard&Ijispeert, 2000; Brambilla, Buchli, &Jispeert, 2006; Fukuoka, Hikmura, & Cohen, 2003). This paper summarizes the kinematics model used for simulations and gaits design, explains the Uncouple, Unidirectional and Bidirectional two CPGs structures, and analyze stability of the

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mode. It also explores how optimized Central Pattern Generator structures may be adapted to robotic systems that perform one-leg movement, and gives suggestions for future research.

Kinematic Model

Kinematic model is designed to perform basic analysis. Figure1 shows the flight and stance modes of the leg structure, whereL_1,L_2 represent the lengths of the thigh and the calf leg respectively, and θ_1,θ_2 show the angular positions of the hip and the knee. Let us also assume that (x_A, y_A) denotes the first coordinate of the hip, and (x_f, y_f) 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.

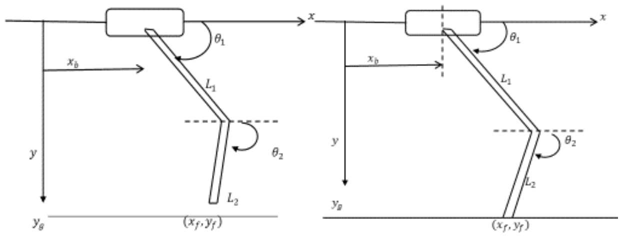

Figure 1: Leg System in Swing and Stance Mode

As Figure 1 shows, we have two cases: The first case is when the leg is in stance mode, the Kinematic Model has one degree of freedom. The hip joint angleθ_1 is also calculated with respect to knee angle θ_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 equations are

$$x_A = x_b + L_1 cos\theta_1,\ x_f = x_b + L_1 cos\theta_1 + L_2 cos\theta_2,$$
$$y_A = L_1 sin\theta_1 \text{ and } y_f = L_1 sin\theta_1 + L_2 sin\theta_2$$

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 neutrals in robotic structures. These neutrals 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 formula ((Larsen)(Ijspeert & Crespi, 2007); (Ijspeert et al., 2007); (Sproewitz et al., 2008),

$$\left.\begin{aligned} \dot{\varphi}_i &= 2\pi v_i + \sum_j r_j w_{ij} \sin\left(\varphi_j - \varphi_i - \emptyset_{ij}\right) \\ \ddot{r}_i &= a_i\left(\frac{a_i}{4}(R_i - r_i) - \dot{r}_i\right) \\ \theta_i &= r_i(1 + \cos(\varphi_i)) \end{aligned}\right\} \quad (1)$$

where θ_i is the output of oscillator i, which has amplitude r_i. Both the amplitude and the output are angles expressed either in radians or in degrees, which are subsequently sent to the motor controllers of the robot. By deriving the equation (1), we obtain three types of CPGs, Uncoupled, Unidirectional and Bidirectional CPGs respectively.

$$\left.\begin{aligned} \dot{\varphi}_1 &= 2\pi v_1 \\ \ddot{r}_1 &= a_1\left(\frac{a_1}{4}(R_1 - r_1) - \dot{r}_1\right) \\ \dot{\varphi}_2 &= 2\pi v_2 \\ \ddot{r}_2 &= a_2\left(\frac{a_2}{4}(R_2 - r_2) - \dot{r}_2\right) \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} \dot{\varphi}_1 &= 2\pi v_1 + r_2 w_{12} \sin(\varphi_2 - \varphi_1 - \emptyset_{12}) \\ \ddot{r}_1 &= a_1\left(\frac{a_1}{4}(R_1 - r_1) - \dot{r}_1\right) \\ \dot{\varphi}_2 &= 2\pi v_2 \\ \ddot{r}_2 &= a_2\left(\frac{a_2}{4}(R_2 - r_2) - \dot{r}_2\right) \end{aligned}\right\} \quad (3)$$

$$\left.\begin{aligned} \dot{\varphi}_1 &= 2\pi v_1 + r_2 w_{12} \sin(\varphi_2 - \varphi_1 - \emptyset_{12}) \\ \ddot{r}_1 &= a_1\left(\frac{a_1}{4}(R_1 - r_1) - \dot{r}_1\right) \\ \dot{\varphi}_2 &= 2\pi v_2 + r_1 w_{21} \sin(\varphi_1 - \varphi_2 - \emptyset_{21}) \\ \ddot{r}_2 &= a_2\left(\frac{a_2}{4}(R_2 - r_2) - \dot{r}_2\right) \end{aligned}\right\} \quad (4)$$

The output of the systems gives $\theta_1 = r_1(1 + \cos(\varphi_1))$ and $\theta_2 = r_2(1 + \cos(\varphi_2))$, where θ_1 and θ_2 (defined previously) are said to represent the angular joints of the hip and the knee respectively, and the state variables φ_i and r_i equally represent the phase and the amplitude.

The CPG will converge if isolated by v_i and R_i. 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 $\emptyset_{ij}$, 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, see, (Amrollah & Henaff, 2010); (Parker & Smith, 1990). Figure 2 shows one CPG in Simulink block.

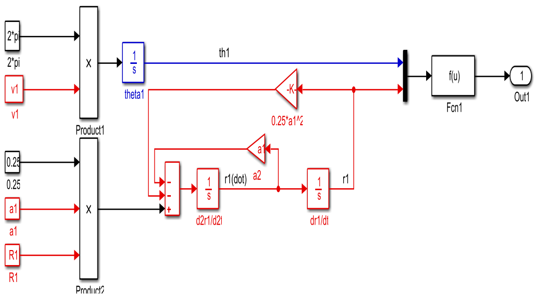

Figure 2: Internal Dynamics of one CPG (Uncoupled)

Stability

It is a clear for the first case uncoupled two CPGs thatthere is no bifurcation, and that the first and the second CPGs are independent of each other and they are always oscillators. As for the second case, Unidirectional Two CPGs, where $\emptyset = \varphi_2 - \varphi_1$ denotes the phase difference, r_1 and r_2 converge asymptotically to R_1 and R_2 respectively. The time evolution of the phase difference is determined by

$$\dot{\emptyset} = f(\emptyset) = \dot{\varphi}_2 - \dot{\varphi}_1 = 2\pi(v_2 - v_1) - r_2 w_{12} \sin(\emptyset - \emptyset_{12})$$

If the oscillators synchronize, they will do so at the fixed points $\emptyset_\infty$. We obtain these points when $\dot{\emptyset} = 0$.
Now, when $f(\emptyset_\infty) = 0, it$ gives us

$$\emptyset_\infty = \arcsin\left(\frac{2\pi(v_2 - v_1)}{R_2 w_{12}}\right) + \emptyset_{12}$$

Note that there is no fixed-point if

$$\left|\frac{2\pi(v_2 - v_1)}{R_2 w_{12}}\right| > 1.$$

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

$$\left|\frac{2\pi(v_2 - v_1)}{R_2 w_{12}}\right| = 1,$$

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

$$\left|\frac{2\pi(v_2 - v_1)}{R_2 w_{12}}\right| < 1,$$

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

$$\frac{df(\emptyset_\infty)}{d\emptyset} = -R_2 w_{12} \cos(\emptyset_\infty - \emptyset_{12}).$$

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 $\emptyset_{12} = -\emptyset_{21}, w_{12} = -w_{21} = -w$, and $R_1 = R_2=1$. Then, as $t \to \infty$ we will have $r_1 \to R_1$ and $r_2 \to R_2$.

$$\dot{\varphi}_1 = 2\pi v_1 - w\sin(\varphi_2 - \varphi_1 - \emptyset_{12})$$
$$\dot{\varphi}_2 = 2\pi v_2 + w\sin(\varphi_1 - \varphi_2 - \emptyset_{21})$$

Also, for $\emptyset = \varphi_2 - \varphi_1$ which denotes the phase difference, the time evolution of the phase difference is determined by

$$\dot{\emptyset} = f(\emptyset) = \dot{\varphi}_2 - \dot{\varphi}_1 = 2\pi(v_2 - v_1).$$

Now, if $f(\emptyset_\infty) = 0$, 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 $\emptyset_{12} = -\emptyset_{21}$, $w_{12} = w_{21} = w$ and $R_1 = R_2=1$. Then,

$$\dot{\emptyset} = f(\emptyset) = \dot{\varphi}_2 - \dot{\varphi}_1 = 2\pi(v_2 - v_1) - 2w\sin(\emptyset - \emptyset_{12}).$$

Now, $f(\emptyset_\infty) = 0$ gives us

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

If the oscillators synchronize, they will do so at the fixed points $\emptyset_\infty$. 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, 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 $\emptyset_\infty = \frac{\pi}{2} + \emptyset_{12}$ when $v_2 > v_1$, and $\emptyset_\infty = -\frac{\pi}{2} + \emptyset_{12}$ when $v_2 < v_1$.
This solution is asymptotically stable, and the two oscillators will synchronize with that phase difference. Finally, if

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

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

$$\frac{df(\emptyset_\infty)}{d\emptyset} = -w\cos(\emptyset_\infty - \emptyset_{12}).$$

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 withthat phase difference.
Case 3:
Let us assume that $\emptyset_{12} = -\emptyset_{21}$ and $R_1 = R_2=1$. Then

$$\dot{\emptyset} = \dot{\varphi}_2 - \dot{\varphi}_1 = 2\pi(v_2 - v_1) - (w_{21} + w_{12})\sin(\emptyset - \emptyset_{12})$$

and $f(\emptyset_\infty) = 0$ leads to the fixed point

$$\emptyset_\infty = \arcsin\left(\frac{2\pi(v_2 - v_1)}{w_{21} + w_{12}}\right) + \emptyset_{12}.$$

Note that there is no fixed-point if

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

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

$$\left|\frac{2\pi(v_2 - v_1)}{w_{21} + w_{12}}\right| = 1$$

then, there is a single fixed point

$$\emptyset_\infty = \frac{\pi}{2} + \emptyset_{12} \text{ when } v_2 > v_1, \text{ and}$$
$$\emptyset_\infty = -\frac{\pi}{2} + \emptyset_{12} \text{ when } v_2 < v_1.$$

This solution is asymptotically stable, and the two oscillators will synchronize with that phase difference. Finally, if

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

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

$$\frac{df(\emptyset_\infty)}{d\emptyset} = -(w_{21} + w_{12})\cos(\emptyset_\infty - \emptyset_{12})$$

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 $\emptyset_{12} = -\emptyset_{21}$.In this case,we have

$$\dot{\emptyset} = \dot{\varphi}_2 - \dot{\varphi}_1 = 2\pi(v_2 - v_1) - (R_1 w_{21} + R_2 w_{12})\sin(\emptyset - \emptyset_{12})$$

and $f(\emptyset_\infty) = 0$results in

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

Note that there is no fixed-point if

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

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

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

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

$$\left|\frac{2\pi(v_2 - v_1)}{R_1 w_{21} + R_2 w_{12}}\right| < 1$$

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

$$\frac{df(\emptyset_\infty)}{d\emptyset} = -(R_1 w_{21} + R_2 w_{12})\cos(\emptyset_\infty - \emptyset_{12})$$

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.

Optimizing Gait Generation

In this section, 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 below:

$P_1 = \{a_1, v_1, R_1, a_2, v_2, R_2\}$. Uncoupled Case

$P_2 = \{a_1, v_1, R_1, a_2, v_2, R_2, w_{12}, \emptyset_{12}\}$. Unidirectional case

$P_3 = \{a_1, v_1, R_1, w_{12}, \emptyset_{12}, a_2, v_2, R_2, w_{21}, \emptyset_{21}\}$. Bidirectional case.

(Nolfi & Floreano, 2000) and (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.

$$J = -C_1 \sum_{k=1}^{n} x_b(k) + C_2[\sum_{k=1}^{n}(\theta_1^2(k) + \theta_2^2(k))]/N, \quad (5)$$

$C_1, C_2 \in [0,1]$, 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 $C_1 C_2 \neq 0$, 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). 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 $0 \leq \theta_1, \theta_2 \leq \pi$. Figures 3 through 5 below 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 the Figure 3.a, 3.b and 3.c

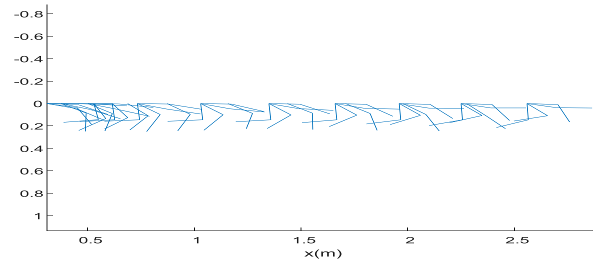

Figure 3a: Simulation of Walking Gait with Constraints

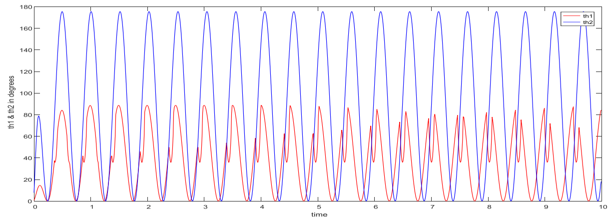

Figure 3b: Joint angles against Time

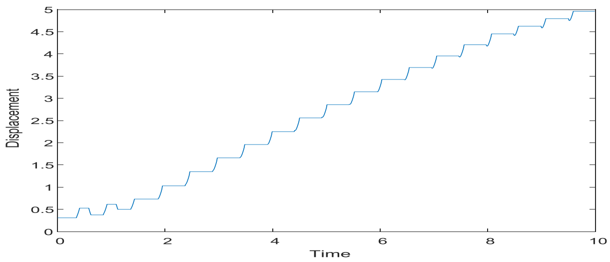

Figure 3c: Displacement against Time

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 Figure 4.a, 4.b and 4.c

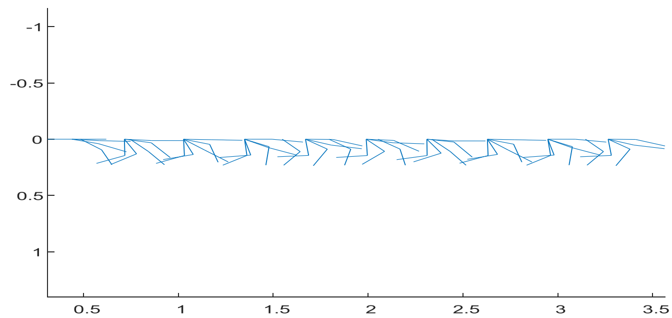

Figure 4a: Simulation of Walking Gait with Constraints

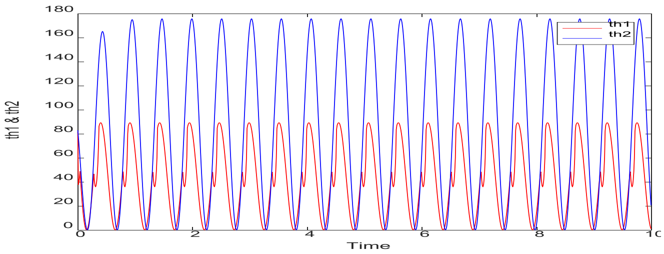

*Figure 4b:*Joint angles against Time

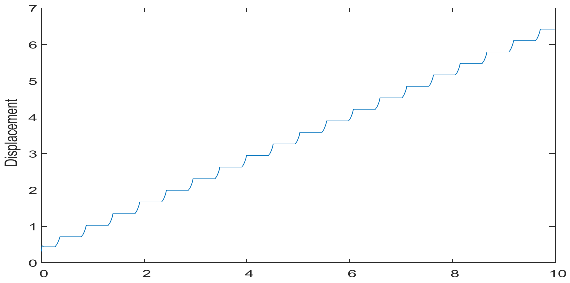

Figure 4c: Displacement against Time

Finally, by optimizing gait we obtain movement by means of using the cost function J for the case of the bidirectional two CPGs, figure 5.a, and 5.b show this results

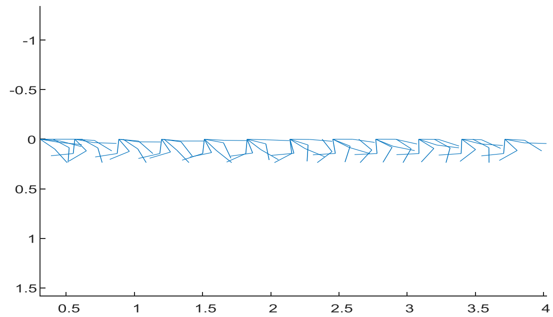

Figure 5a: Simulation of Walking Gait with Constraints

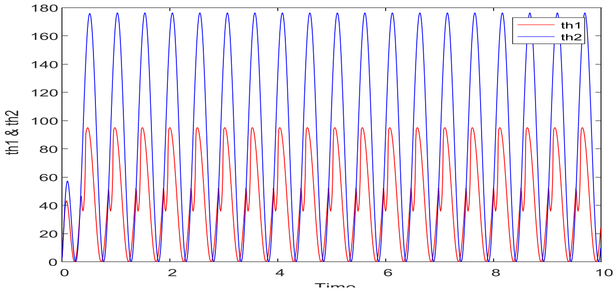

Figure 5b: Joint angles against Time

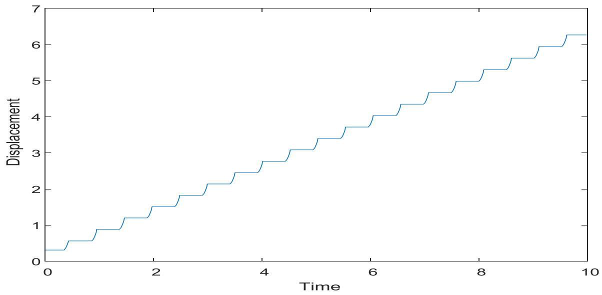

Figure 5c: Displacement against Time

Table 1 and 2 below 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 parametersR_1 and R_2 are the smallest values in both Tables. A close look at table 1and 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 seconds

Start at initial points	Uncoupled, Unidirectional and Bidirectional Two CPGs in unbounded in 10 seconds				
	Parameters values	Fval	Xb	Optimization type	E
30.3617 28.5861 0.8646 20.3022 14.2796 1.2199	30.7363 28.5866 0.8628 20.3314 14.2796 1.2202	-2.3849e+004	47.8770	GA & Hybridfcn at fmincon to uncoupled	3.0341
30.7363 28.5866 0.8628 20.3314 14.2796 1.2202	30.6689 28.5866 0.8629 20.3406 14.2796 1.2202	-1.1924e+004	47.8777	GA & Hybridfcn at fmincon to uncoupled	3.0343
13.2211 27.9674 0.8541 23.3678 20.0000 1.2259 47.6153 50.7133	17.2865 40.4284 0.9287 28.0195 33.3458 1.2273 52.0449 50.3126	-2.8213e+004	112.8684	GA & Hybridfcn at patternsearch to unidirectional	2.9301
59.3216 34.6978 0.8072 8.6457 1.1144 59.4932 34.2898 1.2267 12.0076 6.7790	61.4180 34.8193 0.8691 8.8225 1.0938 61.9136 34.4234 1.3595 12.1180 6.7896	-6.8743e+004	138.4982	GA & Hybridfcn at fmincon to Bidirectional	3.6014
61.4180 34.8193 0.8691 8.8225 1.0938 61.9136 34.4234 1.3595 12.1180 6.7896	62.4355 34.8369 0.8565 8.9123 1.1130 61.9463 34.4603 1.3678 12.1621 6.8044	-3.4536e+004	139.0181	Hybridfcn at fmincon unidirectional	3.6486
17.2865 40.4284 0.9287 28.0195 33.3458 1.2273 52.0449 50.3126	17.5270 40.6125 1.0038 27.1307 33.3437 1.2270 51.1525 50.1892	-5.7859e+004	116.9131	GA & Hybridfcn at patternsearch to unidirectional	3.0240

Table 2:
Optimizing Uncoupled, Unidirectional and Bidirectional Two CPGs in bounded region in 10 sec

By optimizing of two CPGs		Optimizing Uncoupled, Unidirectional and Bidirectional Two CPGs in bounded region in 10 sec				
		Parameter's values	Fval	xb	Optimization type	E
D & E	Two Uncoupled without constraints	33.7958 1.9992 1.4355 68.5282 1.9857 3.2592	-1.1020e+03	4.4082	GA	18.4589
D & E	Two Uncoupled with constraints	18.6883 1.9928 0.7746 46.4124 1.9604 1.5327	-1.3260e+03	4.9613	GA & Hybrid function at pattern search	4.1004
D	Two Uncoupled with constraints	35.3887 1.9955 0.7564 26.4992 1.9606 1.5707	-2.7312e+03	4.9856	GA & Hybrid function at fmincon	4.2406
E	Two Uncoupled with constraints	0.0613 0.0426 0.0070 0.0309 0.0429 0.0263	9.3082e-09	0.3100	GA & Hybrid function at pattern search	9.3175e-09
D & E	Unidirectional Two CPGs	50.0000 1.9850 0.7804 13.1020 1.9230 1.5356 2.0000 -0.3699	-1.7074e+03	6.4220	GA & Hybrid function at pattern search	4.2509
D	Unidirectional Two CPGs	20.2328 1.9347 0.7369 25.6692 -1.9619 1.5424 -0.3227 3.2986	-3.0227e+03	5.5084	GA & Hybrid function at fmincon	4.1719
D & E	Bidirectional Two CPGs	48.2175 1.9592 0.8301 1.9690 -0.5784 31.8414 1.9616 1.5398 1.7346	-1.6230e+03	6.2665	GA & Hybrid function at pattern search	4.2799
D	Bidirectional Two CPGs	9.5946 1.9499 0.8009 1.2422 5.5546 48.1560 1.9717 1.2744 1.9235	-3.1376e+03	6.1787	GA & Hybrid function at fmincon	2.9796

Where E= Energy, D= Displacement, Fval= objective Function and xb=Displacement in meter

Conclusion and Future Directions

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

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