Journal of Engineering and Applied Sciences 12 (5): 1164-1172, 2017
ISSN: 1816-949X

Optimization of Central Patterns Generators

[1]Abdalftah Elbori, [2]Mehmet Turan and [3]Kutluk Bilge Arikan
[1]Department of Modes, [2]Department of Mathematics,
[3]Department of Mechatronics Engineering,
Atilim University, 06836 Ankara, Turkey

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.

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

NTRODUCTION

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) (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; Righetti and Ijspeert, 2006; Ijspeert *et al*., 2007; Sproewitz *et al*., 2008; Cho and Jeon, 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 (Bucher *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 neuronal 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 locomotors 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 Ijispeert, 2000; Brambilla *et al*., 2006; Fukuoka *et al*., 2003). This study summarizes the kinematics model used for simulations and gaits design, explains the uncouple, unidirectional and bidirectional two CPGs structures and analyzes stability of the mode. It also explores how optimized

Corresponding Author: Abdalftah Elbori, Department of Modes, Atilim University, 06836 Ankara, Turkey

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. Figure1 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 θ_1, θ_2 show the angular positions of the hip and the knee. Let us also assume that (X_A, y_f) 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.

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 θ_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 equation 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 Equaton (Larsen) (Ijspeert and Crespi, 2007; Ijspeert *et al*., 2007; Sproewitz *et al*., 2008):

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

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 Eq. 1 we obtain three types of CPGs, uncoupled, unidirectional and bidirectional CPGs, respectively:

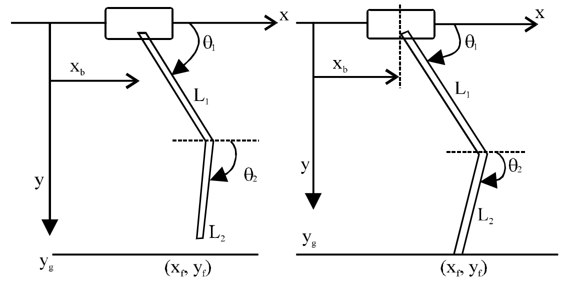

Fig. 1: Leg system in swing and stance mode

$$\left.\begin{aligned} \dot{\varphi}_1 &= 2\pi v_1 \\ \ddot{r}_1 &= a_1\left(\frac{a_1}{4}\left(R_1 -_r 1\right) - \dot{r}_1\right) \\ \dot{\varphi}_2 &= 2\pi v_2 \\ \ddot{r}_2 &= a_2\left(\frac{a_2}{4}\left(R_2 - r_2\right) - \dot{r}_2\right) \end{aligned}\right\} \quad (2)$$

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

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

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 variablesφ_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 α_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 φ_{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 Henaff, 2010; Parker and Smith, 1990). Figure 2 shows one CPG in simulink block.

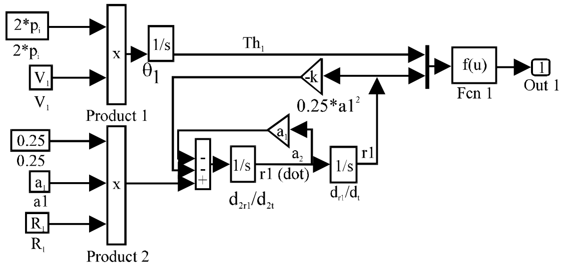

Fig. 2: Internal dynamics of one CPG (uncoupled)

Stability: It is a clear for the first case uncoupled two CPGs that there 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 $\varnothing = \varphi_2 - \varphi_1$ denotes the phase difference, r_1 and r_2 converge asymptotically to R and R, respectively. The time evolution of the phase difference is determined by:

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

If the oscillators synchronize they will do so at the fixed points $\varnothing\infty$. We obtain these points when $\varnothing = 0$. Now when $f(\varnothing\infty) = 0$ it gives us:

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

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 weight w_{12} multiplied by the R_2 amplitude of the oscillator 2 the oscillators do not synchronize and are said to drift. If:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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:

$$\frac{df(\varnothing\infty)}{d\varnothing}=-w\cos(\varnothing\infty-\varnothing_{12})$$

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, then the two oscillators will remain synchronized with that phase difference.

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

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

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

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

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

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

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:

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

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 $\varnothing_{12} = -\varnothing_{21}$ In this case, we have:

$$\dot{\varnothing}=\dot{\varphi}_2-\dot{\varphi}_1=2\pi(v_2-v_1)-(R_1w_{21}+R_2w_{12})\sin(\varnothing-\varnothing_{12})$$

and $f(\varnothing\infty) = 0$ results in:

$$\varnothing\infty=\arcsin\left(\frac{2\pi(v_2-v_1)}{R_1w_{21}+R_2w_{12}}\right)+\varnothing_{12}$$

Note that there is no fixed-point if:

$$\left(\frac{2\pi(v_2-v_1)}{R_1w_{21}+R_2w_{12}}\right)>1$$

That is when the difference of intrinsic frequencies is too large compared to the coupling weight multiple by amplitude $R_1w_{21}+R_2w_{12}$ the oscillators do not synchronize and are said to drift. If:

$$\left(\frac{2\pi(v_2-v_1)}{R_1w_{21}+R_2w_{12}}\right)=1$$

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

$$\left(\frac{2\pi(v_2-v_1)}{R_1w_{21}+R_2w_{12}}\right)<1$$

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:

$$\frac{df(\varnothing\infty)}{d\varnothing}=-(R_1w_{21}+R_2w_{12})\cos(\varnothing\infty-\varnothing_{12})$$

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:

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

Unidirectional case:

$$P_3 = \{a_1, v_1, R_1, w_{12}, \varnothing_{12}, a_2, v_2, R_2, w_{21}, \varnothing_{21}\}$$

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 Irfanoglu, 2011):

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

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 $0 \le \theta_1$, $\theta_2 \le \pi$. 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.

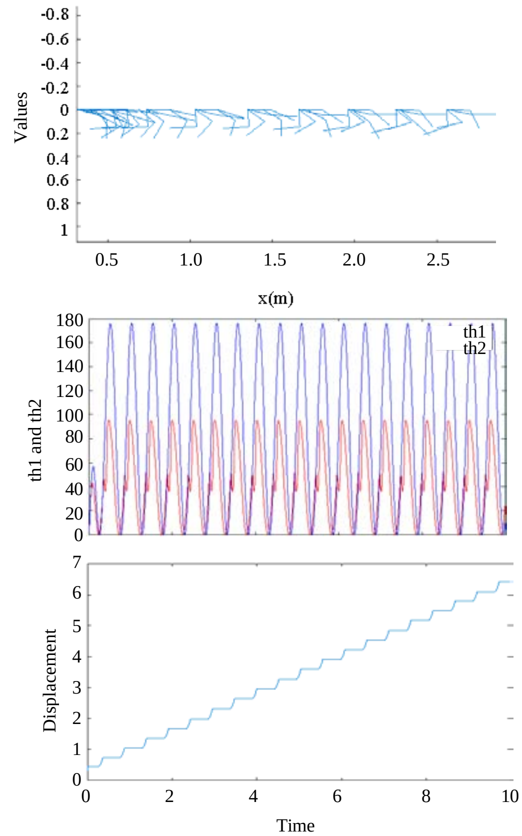

Fig. 3: a) Simulation of walking gait with constraints; b) Joint angles against time; c) Displacement against time

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 Fig. 4a-c. Finally by optimizing gait we obtain movement by means of using the cost function J for the case of the

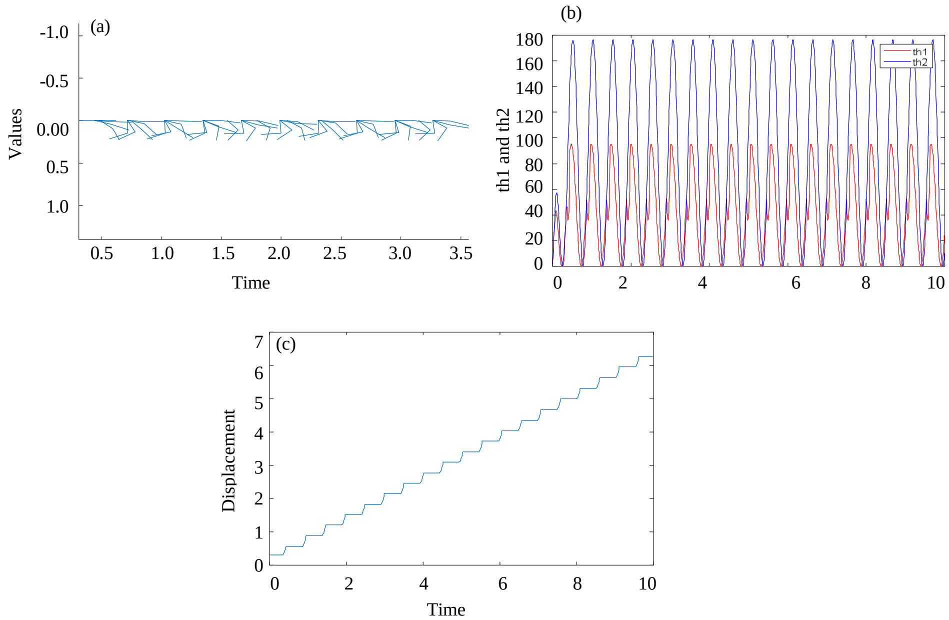

Fig. 4: a) Simulation of walking with constraints; b) Joint angles against time; c) Displacement against time

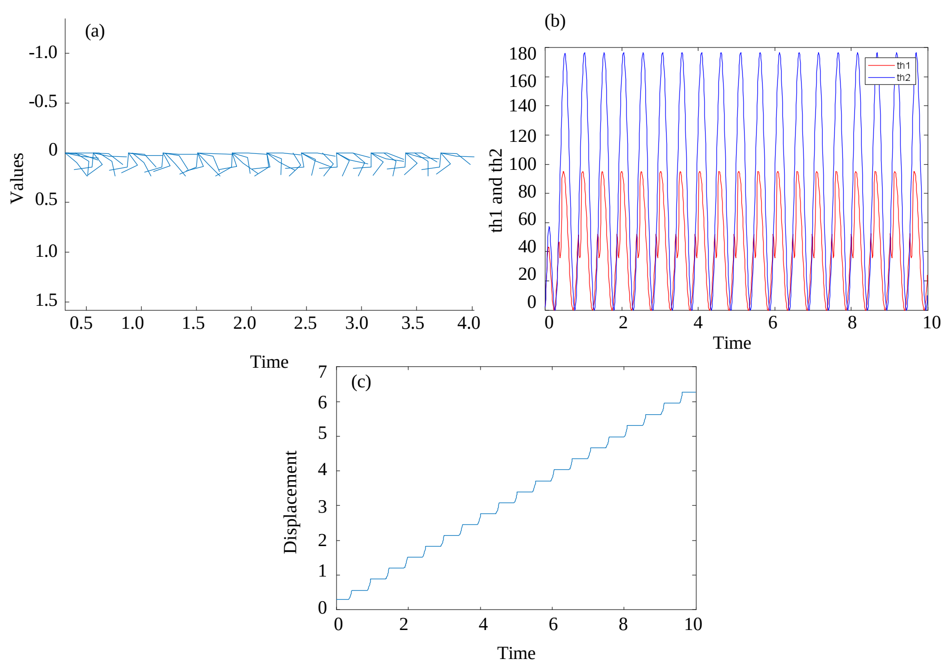

Fig. 5: a) Simulation of walking gait with constraints; b) Joint angles against time of optimizing gait; c) Displacement against time of optimizing gait

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

	Uncoupled, Unidirectional and bidirectional two CPGs in unbounded in 10 sec				
Start at initial points	Parameters values	F-values	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 and 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 and 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 and 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 and 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 and hybridfcn at patternsearch to unidirectional	3.0240

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

		Optimizing uncoupled, unidirectional and bidirectional two CPGs in bounded region in 10 sec				
By optimizing of two CPGs		Parameter's values	F-values	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 and 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 and 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 and 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 and hybrid function at pattern search	4.2509
D	Unidirectional two CPGs 25.6692, -1.9619, 1.5424,	20.2328, 1.9347, 0.7369, -0.3227, 3.2986	-3.0227e+03	5.5084 at fmincon	GA and hybrid function	4.1719
D&E	Bidirectional two CPGs 1.9690, -0.5784, 31.8414,	48.2175, 1.9592, 0.8301, 1.9616, 1.5398, 1.7346	-1.6230e+03	6.2665 at pattern search	GA and hybrid function	4.2799
D	Bidirectional two CPGs 1.2422, 5.5546, 48.1560,	9.5946, 1.9499, 0.8009, 1.9717, 1.2744, 1.9235	-3.1376e+03	6.1787 at fmincon	GA and hybrid function	2.9796

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

Alexander, R.M., 1996. Optima for Animals. Princeton University Press, Princeton, New Jersey,.

Alexander, R.M., 2003. Principles of Animal Locomotion. Princeton University Press, Princeton, New Jersey, ISBN:10:978-654-321, Pages: 377.

Amrollah, E. and P. Henaff, 2010. On the role of sensory feedbacks in Rowat-Selverston CPG to improve robot legged locomotion. Front. Neurorob., 4: 113-113.

Aoi, S. and K. Tsuchiya, 2005. Locomotion control of a biped robot using nonlinear oscillators. Auton. Robots, 19: 219-232.

Arena, P., L. Fortuna, M. Frasca and G. Sicurella, 2004. An adaptive, self-organizing dynamical system for hierarchical control of bio-inspired locomotion. IEEE. Trans. Syst. Man Cybern. B. (Cybern.), 34: 1823-1837.

Arikan, K.B. and B. Irfanoglu, 2011. A test bench to study bioinspired control for robot walking. J. Control Eng. Appl. Inf., 13: 76-80.

Billard, A. and A.J. Ijspeert, 2000. Biologically inspired neural controllers for motor control in a quadruped robot. Proceedings of the IEEE-INNS-ENNS International Joint Conference on Neural Networks Vol. 6, July, 27, 2000, IEEE, Los Angeles, California, ISBN:0-7695-0619-4, pp: 637-641.

Brambilla, G., J. Buchli and A.J. Ijspeert, 2006. Adaptive four legged locomotion control based on nonlinear dynamical systems. Proceedings of the International Conference on Simulation of Adaptive Behavior, September 25-29, 2006, Springer, Berlin, Germany, pp: 138-149.

Brown, T.G., 1911. The intrinsic factors in the act of progression in the mammal. Proc. Royal Soc. London. Ser. B. Containing Pap. Biol. Charact., 84: 308-319.

Bucher, D., G. Haspel, J. Golowasch and F. Nadim, 2000. Central Pattern Generators. John Wiley & Sons, Hoboken, New Jersey,.

Buschges, A., 2005. Sensory control and organization of neural networks mediating coordination of multisegmental organs for locomotion. J. Neurophysiol., 93: 1127-1135.

Casasnovas, B. and P. Meyrand, 1995. Functional differentiation of adult neural circuits from a single embryonic network. J. Neurosci., 15: 5703-5718.

Cho, T.H. and G.M. Jeon, 2016. A method for detecting man-in-the-middle attacks using time synchronization one time password in interlock protocol based internet of things. J. Appl. Phys. Sci., 2: 37-41.

Crespi, A. and A.J. Ijspeert, 2008. Online optimization of swimming and crawling in an amphibious snake robot. IEEE. Trans. Rob., 24: 75-87.

Endo, G., J. Nakanishi, J. Morimoto and G. Cheng, 2005. Experimental studies of a neural oscillator for biped locomotion with QRIO. Proceedings of the 2005 IEEE International Conference on Robotics and Automation, April 18-22, 2005, IEEE, Kyoto, Japan, ISBN:0-7803-8914-X, pp: 596-602.

Fukuoka, Y., H. Kimura and A.H. Cohen, 2003. Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts. Intl. J. Rob. Res., 22: 187-202.

Ijspeert, A.J. and A. Crespi, 2007. Online trajectory generation in an amphibious snake robot using a lamprey-like central pattern generator model. Proceedings of the 2007 IEEE International Conference on Robotics and Automation, April 10-14, 2007, IEEE, Lausanne, Switzerland, ISBN:1-4244-0601-3, pp: 262-268.

Ijspeert, A.J., 2008. Central pattern generators for locomotion control in animals and robots: A review. Neural Networks, 21: 642-653.

Ijspeert, A.J., A. Crespi, D. Ryczko and J.M. Cabelguen, 2007. From swimming to walking with a salamander robot driven by a spinal cord model. Sci., 315: 1416-1420.

Inagaki, S., H. Yuasa and T. Arai, 2003. CPG model for autonomous decentralized multi-legged robot system-generation and transition of oscillation patterns and dynamics of oscillators. Rob. Auton. Syst., 44: 171-179.

Inagaki, S., H. Yuasa, T. Suzuki and T. Arai, 2006. Wave CPG model for autonomous decentralized multi-legged robot: Gait generation and walking speed control. Rob. Auton. Syst., 54: 118-126.

Maizir, H., R. Suryanita and H. Jingga, 2016. Estimation of pile bearing capacity of single driven pile in sandy soil using finite element and artificial neural network methods. Int. J. Appl. Phys. Sci., 2: 45-50.

Marbach, D., 2004. Evolution and online optimization of central pattern generators for modular robot locomotion. Master Thesis, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland.

Matsuoka, K., 1987. Mechanisms of frequency and pattern control in the neural rhythm generators. Biol. Cybern., 56: 345-353.

Nolfi, S. and D. Floreano, 2000. Evolutionary Robotics: The Biology, Intelligence and Technology of Self-Organizing Machines. MIT Press, Cambridge, Massachusetts, ISBN:978-0262-640565, Pages: 321.

Parker, G.A. and J.M. Smith, 1990. Optimality theory in evolutionary biology. Nat., 348: 27-33.

Pearson, K.G., 1995. Proprioceptive regulation of locomotion. Current Opin. Neurobiol., 5: 786-791.

Righetti, L. and A.J. Ijspeert, 2006. Programmable central pattern generators: An application to biped locomotion control. Proceedings of the 2006 IEEE International Conference on Robotics and Automation, May 15-19, 2006, IEEE, Lausanne, Switzerland, ISBN:0-7803-9505-0, pp: 1585-1590.

Sillar, K.T., 1996. The development of central pattern generators for vertebrate locomotion. Adv. Psychol., 115: 205-221.

Sproewitz, A., R. Moeckel, J. Maye and A.J. Ijspeert, 2008. Learning to move in modular robots using central pattern generators and online optimization. Intl. J. Rob. Res., 27: 423-443.

Taga, G., 1998. A model of the neuro-musculo-skeletal system for anticipatory adjustment of human locomotion during obstacle avoidance. Biol. Cybern., 78: 9-17.

Taga, G., Y. Yamaguchi and H. Shimizu, 1991. Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. Biol. Cybern., 65: 147-159.

Vreeswijk, C., L.F. Abbott and E.G. Bard, 1994. When inhibition not excitation synchronizes neural firing. J. Comput. Neurosci., 1: 313-321.