# Gait Generation for a Bipedal System By Morris-Lecar Central Pattern Generator

Sahar Farshbaf rashidi [1], Mohammad-Reza Sayyed Noorani [2], Maryam Shoaran[3], Ahmad Ghanbari[4]
Department of Mechatronics Engineering, University of Tabriz, Tabriz, Iran
Email: sahar.farshbaf@yahoo.com (Corresponding author)
Email: smrs.noorani@tabrizu.ac.ir
Email: m.shoaran@tabrizu.ac.ir
Email: a-ghanbari@tabrizu.ac.ir

**Abstract**

*The ability to move in complex environments is one of the most important features of human beings and animals. In this work, we exploit a bio-inspired method to generate different gaits in a bipedal locomotion system. We used the 4-cell CPG model developed by Pinto [21]. This model has been established on symmetric coupling between the cells which are responsible for generating oscillatory signals. These signals are served as activation signals sent to muscle groups. We used the Morris-Lecar equations as internal nonlinear dynamics of the cells, and considered a diffusive type to model couplings between the cells. We succeeded to obtain periodic solutions corresponding to the bipedal gaits of walk, run, two legged jump, and two legged hop, extracted from the 4-cell CPG model, by numerical simulations. In fact, gait generation is done by the adjustment of the coupling weights which are justifying correct phase differences between the oscillatory outputs of the cells. Moreover, in order to optimize the performance of the produced gaits, a non-dominated sorting genetic algorithm is utilized to adjust the coupling weights.*

**Keywords**: Gait Generation, Central Pattern Generator, 4-Cell Model, Diffusive Coupling, Morris-Lecar Oscillator

## 1- Introduction

Locomotion is one of the most important features of human beings and animals, since it allows them to move on irregular terrains to avoid predators or to look for food and so on. A locomotion system in animals is a complex biomechanical mechanism called neuro-musculoskeletal system in which coordination between varieties of muscles is performed.

The most frequent method in generation of legged gaits for bio-inspired robots, e.g. bipeds and quadrupeds, is established upon a stability criteria known as Zero Moment Point (ZMP) [1, 2]. However, this method requires an exact model of the robot dynamics and it is not adaptable for various environments. Therefore, a free model method, to generate and control the locomotion gaits, is introduced that is inspired from Central Pattern Generator (CPG).

It is a neural network that produces 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 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 to study the flight patterns [5]. Cohen in 1980s [6] presented the discussion through the researches on the dissection of a lamprey spinal cord. Afterwards, in 2007 Ijspeert et al. [7] 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 [8-10], snake robot [11], and biped locomotion [12, 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 oscillations with adjustable phase lag.

Wu et al. [15] studied gait generation and 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]. 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.

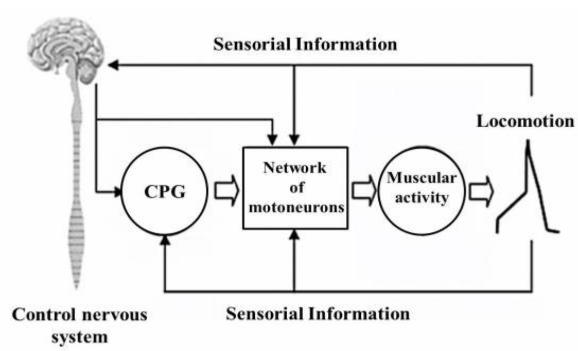


**Fig.1.** Control system of the human locomotion [4]

Santos et al. [19] proposed a bio-inspired robotic controller capable of locomotion generation that easily switches between different types 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 an 8-cell model for the arm-leg model. Then, Pinto and Santos [22] investigated the CPG model for gait generation and transition in two-legged animals. They could produce various gaits by Manual adjustment of 4-cell CPG model coupling weights. Afterwards, they studied the CPG model for modular generation of a hexapod robot's movements, using a biological approach [23]. They used the network of twelve coupled CPG-units, each of which consisted 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 model with appropriate parameters is proposed to generate gaits for a bipedal system. The NSGA-II algorithm will be used here to search for the coupling weights between oscillators in producing patterns of different gaits. It is worth mentioning that in the previous studies [22, 24], these parameters were adjusted manually.

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 3, The Morris-Lecar oscillators are used as internal dynamics of cells. In, Section 4, we briefly review a non-dominated sorting genetic algorithm (NSGA-II) to find the coupling weights of the model in order to produce walk, run, two legged jump and two legged hop gaits. Then, in Section 5, results and discussions are presented. Conclusions and future works are provided in Section 6.

## 2- Modeling Four-Cell CPG Model

In this section, a CPG model for gait generation of biped will be introduced. It is based on the work done by Golubitsky et al [25]. They proposed a CPG model in order to generate the rhythmic movements for animals with 2n legs. 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 chose the 4-cell CPG network model for gait generation of a bipedal system. The 4-cell model can be used to produce the rhythms of bipedal gaits of walk, run, two legged jump, two legged Hop among other gaits.

As mentioned earlier, some works have implemented the symmetry property to generate the gaits in robots [21, 25]. The symmetry property of the model is shown in Fig. 2.

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 Flexor (RF) and Right Extensor (RE) cells send signals to the Right leg, and Left Flexor(LF) and Left Extensor(LE) cells send signals to the right leg (as shown in Fig. 2). The different arrows between cells present the different coupling weights.

We used the relation between the phases of flexor and extensor muscles in the leg to produce different gaits [20]. In walk and run, both legs receive same signals with a phase shift. To produce the walk, the 4-cell CPG uses two signals per leg with a half-period phase difference. These models can produce run gaits by sending two in phase signals to one leg and other two in phase signals to the other leg. The right and left legs move simultaneously in two-legged hops and two-legged jumps. Producing two-legged hop gaits requires in phase signals sent to the muscles of both legs and in two-legged jump, the signals sent to each leg are in-phase.

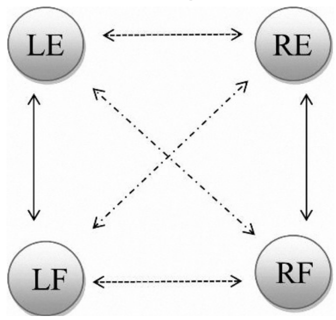


**Fig. 2.** The 4-cell CPG model for biped

### 3- Morris-Lecar Oscillator model

In order to implement the cells of a CPG, several types of nonlinear oscillators have been used. In this paper, we used the neural oscillator model proposed by Catherine Morris and Harold Lecar [26]. This model is defined in (1-5). The Morris-Lecar neuron model is a two-dimensional reduced dynamical model for the membrane potential of a neuron.

$$\dot{v} = f_1(v, w) = -g_{ca}\, m(v)(v - v_{ca}) - g_l(v - v_l) - g_k(v - v_K) + i \quad (1)$$

$$\dot{w} = f_2(v, w) = -\varphi\tau(v)(n(v) - w) \quad (2)$$

*Where*

$$m(v) = \frac{1}{2}\left(1 + tanh\left(\frac{v - v_1}{v_2}\right)\right) \quad (3)$$

$$n(v) = \frac{1}{2}\left(1 + tanh\left(\frac{v - v_3}{v_4}\right)\right) \quad (4)$$

$$\tau(v) = \left(cosh\left(\frac{v - v_1}{v_2}\right)\right) \quad (5)$$

Here, i is the applied current ($\mu A/cm^2$), v is the membrane potential (mV), $v_l$, $v_{ca}$ and $v_k$ 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 1.

For example, the odes of the cell, $C_i$, are defined in (6) and (7) [21].

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

$$\dot{y}_{i1} = F_1(y_{i1}, y_{j1}, y_{k1}, y_{l1}) = f_1(y_{i1}, y_{i2}) - wa_n h(y_{i1}, y_{j1}) - wb_n(y_{i1}, y_{k1}) - wc_n(y_{i1}, y_{l1}) \quad (6)$$

$$\dot{y}_{i2} = F_2(y_{i1}, y_{i2}) = f_2(y_{i1}, y_{i2}) \quad (7)$$

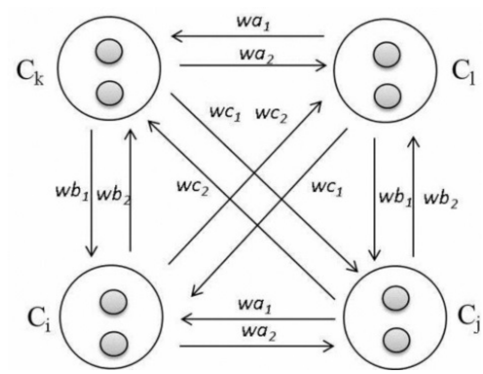


**Fig. 3.** 4-cell CPG model with coupling constants

**Table.1.** The values of oscillator parameters

| Parameter | Value | Parameter | value |
|---|---|---|---|
| $v_1$ | 0.010 | $g_k$ | 2.00 |
| $v_2$ | 0.145 | $v_k$ | -0.70 |
| $v_3$ | 0.100 | $v_l$ | -0.50 |
| $v_4$ | 0.150 | $v_{ca}$ | 1.00 |
| $g_l$ | 0.500 | $g_{Ca}$ | 0.899 |
| $i$ | 0.229 | $\varphi$ | 0.254 |

## 4- Regulation of CPG Parameters Using Non-Dominated Sorting Genetic Algorithm

Non-dominated sorting genetic algorithm (NSGA-II), introduced by Deb in 2000 [27], is one of the mostly known and commonly used optimization algorithms in the field of multi-objective optimization. In this paper we used NSGA-II to search for the coupling weights ($wa_1$, $wa_2$ and $wa_3$) between oscillators in producing rhythmic patterns of walk, run, two legged jump and two legged hop gaits. In this algorithm, ranking and crowding distance concepts were used to sort the population. Two-point crossover and mutation methods were used to generate two new offspring chromosomes. The relations between the phases of oscillators in producing walk, run, two legged jump and two legged hop gaits are shown in Fig.4. We define the fitness functions according to these phase relations between cells of model.

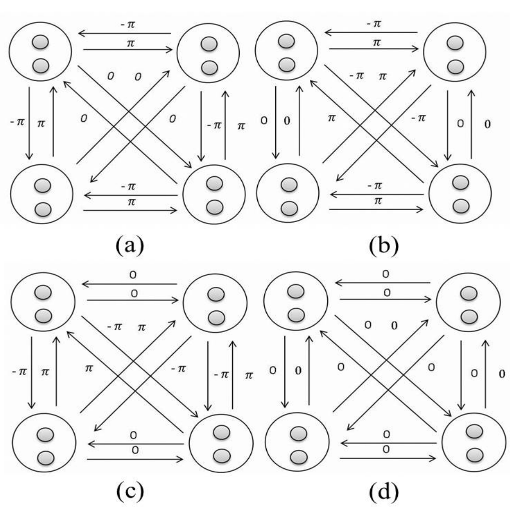


**Fig. 4.** Relations between the phases of the oscillators in: (a) walk, (b) run, (c) two-legged jump, and (d) two-legged hop

## 5- Results and Discussion

The advantages of the CPG control method motivated us to simulate the 4-cell model with diffusive coupling for a bipedal system. We used the Morris-Lecar equations as internal dynamics of cells. We present the values of the initial conditions and the coupling weights that are obtained from NSGA-II and correspond to the walk, run, two-legged hop and two-legged jump gaits (Table. 2 and Table. 3). We plot the periodic solutions of the 4-cell CPG network identify walk, run, two-legged hop and two-legged jump gaits. The periodic solutions of 4-cell model can be used as angles of flexor and extensor muscles of a bipedal system.

**Table.2.** The values of initial conditions

| Gait | Initial Conditions |
|---|---|
| Walk | [ 0.280 0.277 -0.197 0.159 -0.197 0.159 0.280 0.277 ] |
| Run | [ -0.304 0.163 0.169 0.229 -0.304 0.163 0.169 0.229 ] |
| Two-Legged Jump | [ -0.046 0.398 -0.046 0.398 0.327 0.253 0.327 0.253 ] |
| Two-Legged Hop | [ -0.059 0.255 -0.059 0.255 -0.059 0.255 -0.059 0.255] |

**Table.3.** The values of coupling weights between cells of model

| Gait | $wa_1$ | $wa_2$ | $wb_1$ | $wb_2$ | $wc_1$ | $wc_2$ |
|---|---|---|---|---|---|---|
| Walk | 0.39 | 0.39 | -0.68 | -0.68 | 0.49 | 0.49 |
| Run | -0.94 | -0.94 | 1.00 | 1.00 | 0.65 | 0.65 |
| Two-Legged Jump | 0.98 | 0.98 | -0.01 | -0.01 | -0.22 | -0.22 |
| Two-Legged Hop | 0.36 | 0.36 | 0.33 | 0.33 | -0.02 | -0.02 |

The periodic solutions of 4-cell model for walk, run, two-legged hop and two-legged jump gaits are shown in Figs. 5-8. According to this diagram, we can use the first variables from the signal of each oscillator, $y_{i1}$, i = 1,2,3,4, as angles of a muscles of bipedal system.

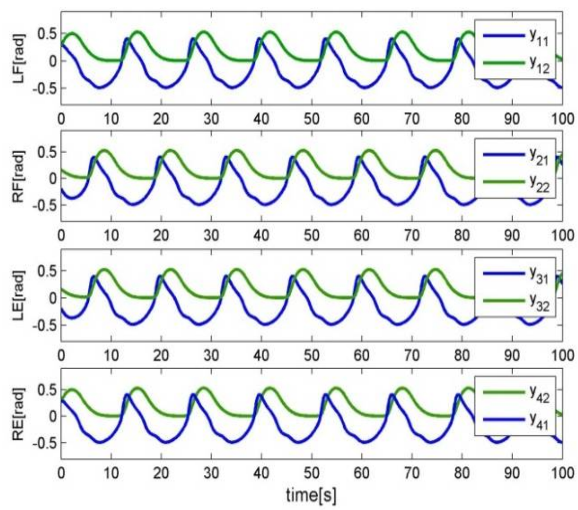


**Fig. 5**.The periodic solutions of the 4-cell model for walk

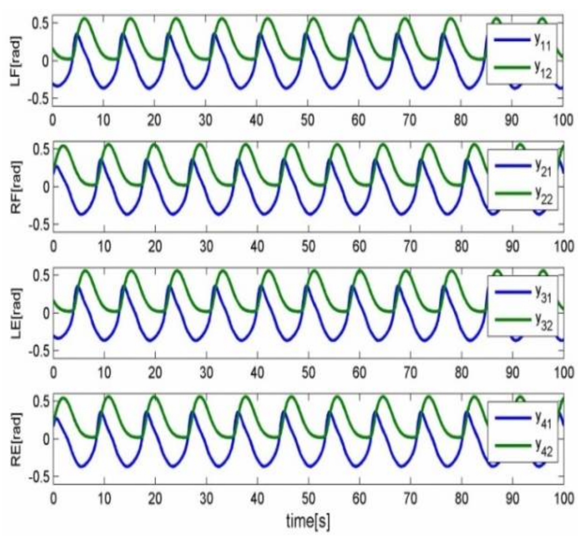


**Fig. 6.** The periodic solutions of the 4-cell model for Run

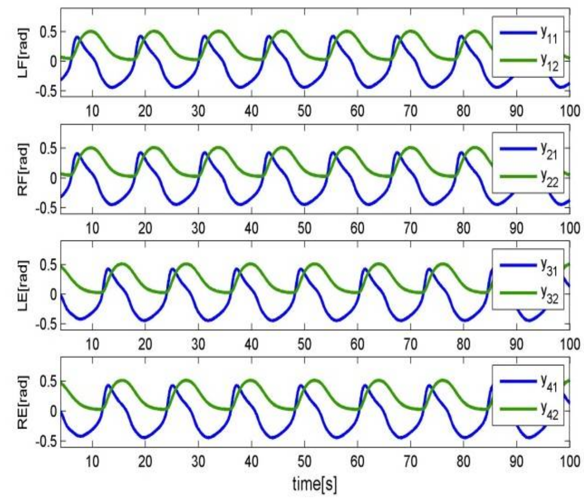


**Fig. 7.** The periodic solutions of the 4-cell for Two-Legged Jump

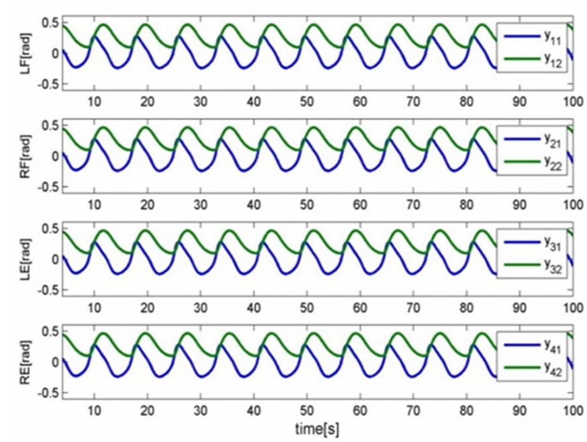


**Fig. 8.** The periodic solutions of the 4-cell model for Two-Legged Hop

For instance, the phase diagram of walk gait is shown in Figure 9. According to this diagram, signals of walk gait after starting from the initial state and elapsing a short time converge to a limited cycle, which shows the capability of this approach in producing rhythmic gaits.

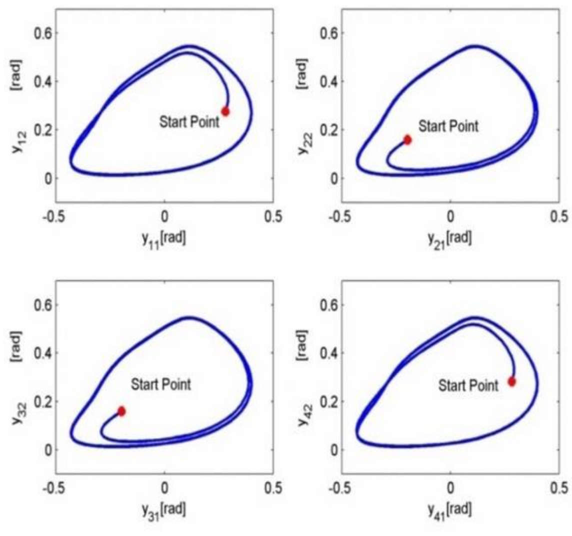


**Fig.9**. Limit cycle diagrams of Coupled System of oscillators in walk

## 6- Conclusion

In this paper, a simple gait generation method has been proposed for bipedal locomotion using a 4-cell CPG model with diffusive coupling between cells. In this model, the Morris-Lecar equations were used as oscillator of cells. Furthermore, the symmetry property and phase relations between cells were implemented for walk, run, two legged jump and two legged hop gaits generations. The different periodic signals were generated by changing coupling weights for the new locomotion gaits. Non dominated sorting genetic algorithm (NSGAII) was used to search for optimal weights of model. Simulation results show that the periodic signals of the 4-cell model converge fast to a limited cycle in state space. This reveals the ability of this model to generate rhythmic patterns of gaits to be biped. The design of a physical prototype to verify the presented method for gait generation will be the subject of future work. In the meantime, we intend to produce more gaits by transition from these.

## References


[1] P. Sardain and G. Bessonnet, "Forces acting on a biped robot. Center of pressure-zero moment point," Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, 2004, vol. 34, pp. 630-637.

[2] K. Erbatur and O. Kurt, "Natural ZMP trajectories for biped robot reference generation," Industrial Electronics, IEEE Transactions on, 2009, vol. 56, pp. 835-845.

[3] A. J. Ijspeert, "Central pattern generators for locomotion control in animals and robots: a review," Neural Networks, 2008, vol. 21, pp. 642-653.

[4] P. Arena, L. Fortuna, M. Frasca and G. Sicurella, "An adaptive, self-organizing dynamical system for hierarchical control of bio-inspired locomotion," Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on, 2004, vol. 34, pp. 1823-1837.

[5] D. M. Wilson, "The central nervous control of flight in a locust," *J. exp. Biol,* 1961, vol. 38, pp. l-490.

[6] A. H. Cohen, P. J. Holmes and R. H. Rand, "The nature of the coupling between segmental oscillators of the lamprey spinal generator for locomotion: a mathematical model," Journal of mathematical biology, 1982, vol. 13, pp. 345-369.

[7] A. J. Ijspeert and A. Crespi, "Online trajectory generation in an amphibious snake robot using a lamprey-like central pattern generator model," in ICRA, 2007, pp. 262-268.

[8] K. Nakada, T. Asai and Y. Amemiya, "An analog CMOS central pattern generator for interlimb coordination in quadruped locomotion," Neural Networks, IEEE Transactions on, 2003, vol. 14, pp. 1356-1365.

[9] K. Matsuoka, "Mechanisms of frequency and pattern control in the neural rhythm generators," Biological cybernetics, 1987, vol. 56, pp. 345-353.

[10] Y. Fukuoka, H. Kimura and A. H. Cohen, "Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts," The International Journal of Robotics Research, 2003, vol. 22, pp. 187-202.

[11] X. Wu and S. Ma, "CPG-based control of serpentine locomotion of a snake-like robot," Mechatronics, 2010, vol. 20, pp. 326-334.

[12] T. Reil and P. Husbands, "Evolution of central pattern generators for bipedal walking in a real-time physics environment," Evolutionary Computation, IEEE Transactions on, 2002, vol. 6, pp. 159-168.

[13] C. Liu, D. Wang and Q. Chen, "Central Pattern Generator Inspired Control for Adaptive Walking of Biped Robots," IEEE transactions on systems, man, and cybernetics. Systems, 2013, vol. 43, pp. 1206-1215.
[14] W. Chen, G. Ren, J. Zhang and J. Wang, "Smooth transition between different gaits of a hexapod robot via a central pattern generators algorithm," Journal of Intelligent & Robotic Systems, 2012, vol. 67, pp. 255-270.
[15] X. Wu, L. Teng, W. Chen, G. Ren, Y. Jin and H. Li, "CPGs With Continuous Adjustment of Phase Difference for Locomotion Control," International Journal of Advanced Robotic Systems, 2013, vol. 10.
[16] J. Wang, J. Wen, W. Chen, H. Yue and D. Liu, "A gait generating algorithm with smooth speed transition for the locomotion of legged robots," Transactions of the Institute of Measurement and Control, 2013.
[17] C. Liu, Q. Chen and D. Wang, "CPG-inspired workspace trajectory generation and adaptive locomotion control for quadruped robots," Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on, 2011, vol. 41, pp. 867-880.
[18] J. Cristiano, D. Puig and M. A. García, "Locomotion Control of a Biped Robot through a Feedback CPG Network," in ROBOT2013: First Iberian Robotics Conference, 2014, pp. 527-540.
[19] C. P. Santos and V. Matos, "Gait transition and modulation in a quadruped robot: A brainstem-like modulation approach," Robotics and Autonomous Systems, 2011, vol. 59, pp. 620-634.
[20] G. C. Nandi, A. J. Ijspeert, P. Chakraborty and A. Nandi, "Development of Adaptive Modular Active Leg (AMAL) using bipedalrobotics technology," Robotics and Autonomous Systems, 2009, vol. 57, pp. 603-616.
[21] C. M. Pinto and M. Golubitsky, "Central pattern generators for bipedal locomotion," Journal of mathematical biology, 2006, vol. 53, pp. 474-489.
[22] C. M. Pinto and A. P. Santos, "Modelling gait transition in two-legged animals," Communications in Nonlinear Science and Numerical Simulation, 2011, vol. 16, pp. 4625-4631.
[23] C. M. Pinto, D. Rocha, and C. P. Santos, "Hexapod robots: new CPG model for generation of trajectories," J. Numer. Anal. Ind. Appl. Math, 2012, vol. 7, pp. 15-26.
[24] S. F. Rashidi, M.-R. S. Noorani, M. Shoaran, and A. Ghanbari, "Gait generation and transition for a five-link biped robot by Central Pattern Generator," in Robotics and Mechatronics (ICRoM), 2014 Second RSI/ISM International Conference on, 2014, pp. 852-857.
[25] M. Golubitsky, I. Stewart, P.-L. Buono, and J. Collins, "Symmetry in locomotor central pattern generators and animal gaits," Nature, 1999, vol. 401, pp. 693-695.
[26] C. Morris and H. Lecar, "Voltage oscillations in the barnacle giant muscle fiber," Biophysical journal, 1981, vol. 35, p. 193.
[27] K. Deb, S. Agrawal, A. Pratap, and T. Meyarivan, "A fast elitist non-dominated sorting genetic algorithm for multi-objective optimization: NSGA-II," Lecture notes in computer science, 2000, vol. 1917, pp. 849-858.