Bipedal Robot Locomotion on a Terrain with Pitfalls

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ABSTRACT
In this paper a locomotion control system for bipedal robot is proposed to provide desirable walking on a terrain and skipping over a pitfall preventing the robot from falling in it. The proposed strategy is a combination of motion optimization based on particle swarm optimization algorithm and utilization of mode switching at the higher level controller. The model for bipedal robot is a compass gait model but the presented method is general and could be appropriately extended and generalized for other complicated models. Principles of minimalistic designs are also respected and simple central pattern generator and simple mechanical feedback control are used to produce and maintain desirable motion patterns of the robot.

KEYWORDS: Bipedal Robot Locomotion, Central Pattern Generator, Particle Swarm Optimization, Switching Controller, Compass Gait Model.

1. INTRODUCTION

Bipedal robots attract great amounts of researchers' interest because of their similarity to human general shape. To develop human-like robots, such those perform human tasks (specifically in dangerous or unknown environments like other planets) and also possible medical advantages (for example designing artificial limbs for disabled persons); modeling, simulation and control of bipedal robots are important subjects of study in the fields of robotics, control and intelligent systems, medical cybernetics, and even animation industry [1].

Many studies are published on the subject of bipedal robots which use different and diverse methods for stabilization, control and optimization of locomotion. Difference in environments in which the robot is moving, is also another topic in the field [2]. Both experimental studies [3] and simulations [2] of robot locomotion are carried on in previous works. Another approach to classify studies on bipedal robot motion is based on the type of robot drive. It may be passive locomotion [3] or locomotion with powered drive [2], or in some cases a combination of both [22]. Even though most of researches are focused on two dimensional sagittal locomotion of bipedal robots, some recent works have been done to investigate the three dimensional motion [4]. Robots with different numbers of degrees of freedom (DOF) are also studied in the literature [5].

Having a model for dynamics of the robot, one could work on designing a control method to stabilize and move the robot in a way that satisfies some desired objectives. Establishing stable walking patterns for a bipedal robot is often harder than in other types of legged robots because of highly instable and perturbable situation of bipedal motion. For periodic motions, it is accomplished by finding limit cycles in phase space of bipedal robots dynamics, which are related to periodic motions. So finding a stable pattern for one period could be sufficient for maintaining the whole walking as stable. With simple methods like PID control one may only expect to achieve slow walking patterns, and only for the cases with low degrees of freedom. In [1] different feedback control methods for the problem are studied. Some of methods are based on dynamics of inverted pendulum and zero moment point (ZMP) as used for example in [6]. In [7] a review of methods based on ZMP is presented.

Intelligent and soft computing based methods are also considered to control the motion of bipedal robots. In [8] fuzzy reinforcement learning is used to obtain the balance of bipedal robot. Utilization of fuzzy logic in bipedal robot modeling [9] and control [10, 11] are proposed in past studies. Neural networks are other types of intelligent systems which are used to control bipedal robots by learning adaptively the best control actions in various situations [12, 13]. Neuro-fuzzy systems are also utilized to trajectory modeling [14], gait synthesis [15, 16], and control [17] of bipedal robots.

One of the most common methods in robot locomotion design is to use a central pattern generation unit (CPG) [18]. In [19], Cellular Neural Network (CNN) is reviewed as a central pattern generator in locomotion of robot with worm or insect inspired structures. CPG network tuned by fuzzy logic principles is used in [20] to obtain adaptive optimal locomotion for robots of snake type. Utilization of CPG network composed of Matsuka oscillators [21] for locomotion of bipedal robot is proposed in [2]. In that study, mechanical feedback signals from joints of robot are taken to effect on oscillations of pattern generator network. Effects of changes in the smoothness of the environment (terrain) are also considered in that work. In [22], the problem of bipedal locomotion in a non-flat terrain is studied, and utilization of simple oscillators for a two-link robot motion is considered in both simulation and experimental evaluations. In that work, the robot may fall in some pitfalls and then come out, and no skipping over is assumed.

On the other hand, determining the parameter values for a CPG network is not a straightforward task, and due to numerous parameters of a CPG, one usually estimates the parameters using optimization algorithms. In [23] they have used genetic algorithm (GA), and in [24] particle swarm optimization (PSO) to search the parameter space. Utilization of online learning method is also proposed in [25].

In this paper, the problem of bipedal robot locomotion with possible skipping over pitfalls is studied. Following the work presented in [22], simple harmonic pattern generator for the compass gait model of bipedal robot is used. By applying some simple changes, general stabilized motion is achieved. Considering different modes of gait, appropriate parameters are obtained using PSO search method with appropriate objective functions for each mode. Finally by means of higher level switching control, safe locomotion of the robot in an environment with pitfalls is achieved. Minimal design is respected in the whole parts of the proposed control method.

The structure of next parts of this paper is as follows: In section 2 the model for bipedal robot based on compass gait and parameters of the model are presented. The units used to produce motion, stabilize and control the robot are presented in section 3. The overall method for determining specifications of different modes of gait based on PSO and switching control strategy are described in section 4. Simulation of the proposed method and the results of simulation are discussed in section 5, and concluding remarks are stated in section 6 of the paper.

2. BIPEDAL ROBOT MODEL

The model for bipedal robot used in this paper is based on compass gait model which is also used in the study presented in [22]. The model assumes two legs with no knees and heel joints. The two legs are joined in the hip joint and there is no upper body above the hip joint. These make the model simpler but harden the locomotion of the robot. The control method used here can be simply generalized and utilized for models with more complex dynamics.

When one of the legs is swinging and the other is in stance state, as shown in Figure 1, the swing dynamics governs the motion of robot. Two degrees of freedom in this dynamics are motions around the hip joint and around the support of stance leg contact point to the ground. The position can be described uniquely with the two angles of legs to the vertical direction as shown in Figure 1 as θ_t and θ_w. Index *t* indicates stance leg parameters and index *w* indicates swing leg parameters.

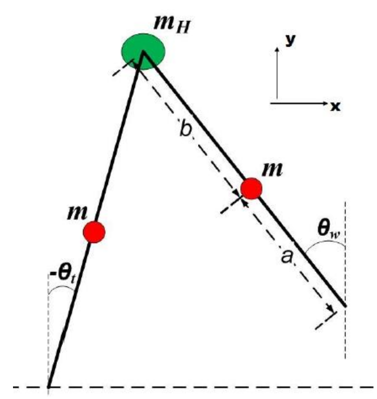

Fig. 1. Geometrical parameters of bipedal robot, swing dynamics of compass gait model

By considering the position variables of the system as $\boldsymbol{q} = \begin{bmatrix}\boldsymbol{\theta_t} \\ \boldsymbol{\theta_w}\end{bmatrix}$, dynamics of swing phase is governed by

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{q} + G(\boldsymbol{q}) = B\boldsymbol{u}\,, \quad (1)$$

in which

$$M(\boldsymbol{q}) = \begin{bmatrix} mb^2 & -mbl\cos(\theta_t-\theta_w) \\ -mbl\cos(\theta_t-\theta_w) & ma^2+ml^2+m_H l^2 \end{bmatrix},$$

$$C(\boldsymbol{q},\dot{\boldsymbol{q}}) = \begin{bmatrix} 0 & mbl\sin(\theta_t-\theta_w)\dot{\theta}_t \\ -mbl\sin(\theta_t-\theta_w)\dot{\theta}_w & 0 \end{bmatrix},$$

$$G(\boldsymbol{q}) = \begin{bmatrix} mgb\sin\theta_w \\ -mga\sin\theta_t - m_H gl\sin\theta_t - mgl\sin\theta_t \end{bmatrix},$$

$$B = \begin{bmatrix} 1 & 1 \\ 0 & -1 \end{bmatrix}.$$

In equations above, $l = a + b$ and $\boldsymbol{u}$ is the input torque which is inserted on the hip joint and we set here $\boldsymbol{u} = \begin{bmatrix} \boldsymbol{u_H} \\ \boldsymbol{0} \end{bmatrix}$.

When the swing leg touches the ground ($\theta_t + \theta_w = 0$), ongoing swing dynamics terminates and new swing phase begins with stance and swing legs changed. In Table 1 the values of parameters used in this paper are shown.

Table 1. Robot model parameters used for simulation in this paper

Parameter	Value
m	5 kg
m_H	5 kg
a	0.5 m
b	0.5 m
g	9.8 m/s^2

3. LOCOMOTION CONTROL UNITS

In this section the units for producing locomotion of the robot described by model in section 2 are discussed. Beside motion itself, its stability is also required for long duration of walking. As main goal of this research, the ability to control the motion patterns and specifically skipping over pitfalls has to be obtained by a higher level controller. So the locomotion control system is composed of three main parts: 1) Central pattern generation unit for producing motion of the robot, 2) Mechanical feedback control for maintaining the stability of motion, and 3) Higher level controller for switching between different modes of motion.

3.1. Central Pattern Generator

Natural central pattern generators are neural structures in both vertebrates and invertebrates which are considered as generators of rhythmic outputs in motion of the animal. By analogy, artificial CPG could be designed for different kinds of robots such as snakes, insects, and bipedal robots to exert torques on joints and producing some rhythmic motions such as walking on a plane [18].

To produce regular walking pattern for the robot model described in section 2, [22] used simple sinusoidal input torque which may differ for each step n with definition

$$\boldsymbol{u_{H_n}} = A_n \sin(2\pi f_n + \varphi_{n-1}). \tag{2}$$

In our study, the motion pattern of robot is more complicated in some modes such as skipping over pitfalls. So we utilize an input signal containing some other harmonics besides main one

$$\boldsymbol{u_H} = \sum_{h=0}^{h_{max}} A_h \sin(2\pi h f_1 + \varphi_h). \tag{3}$$

In (3), h stands for harmonic number. In contrast with [22] for a specific motion mode there is no difference between different steps input signal and it is only changed after switching between modes by higher level controller unit.

3.2. Mechanical feedback

To provide general stability of robot motion, we add a mechanical feedback to the hip joint. This unit exerts a negative term to input torque signal to the hip joint proportional to the angle between two legs. To prevent excess energy consumption by CPG unit, the mechanical negative feedback signal is exerted for angles greater than a θ_{max}:

$$u_f = \begin{cases} -K\theta & \theta > \theta_{max} \\ 0 & otherwise \end{cases}. \tag{4}$$

Looking Figure 1, it is clear that the angle between two legs is $\theta = |\theta_t| + |\theta_w|$. In the case of θ_{max}=0, the feedback input could be simply provided by a linear torsion spring.

3.3. Higher level switching control

Final goal of the proposed locomotion control system is to provide capability of skipping over pitfalls by the robot. To provide such behavior, the robot needs to be i) aware of the pitfall before confronting that , ii) capable of slowing down its walking a few steps before the pitfall, iii) capable of increasing its step length to skip over, and iv) capable of return to its normal walking after skipping over pitfall.

Different possible modes of motion are determined for the robot and the CPG parameters to produce appropriate input signals for motion pattern of each mode is obtained. The method for determining specifications of the mode and related CPG parameters will be presented in the next section. Here the main modes of motion are described:

1) Normal walking: In this mode the robot walks with regular steps of medium length (~0.3 m) on the surface of terrain.

2) Shortening the step length: When the robot observes a pitfall in front, it terminates its normal walking and shortens its step lengths to prevent possible fall in the pitfall and to provide appropriate situation for skipping over it.

3) Skipping over: When robot arrives close to the pitfall, chooses the suitable step length to pass over the pitfall.

4) Return: When the swing leg touches the ground after the pitfall, the robot updates its current step length in the return mode to provide appropriate situation to restart its normal walking again.
Three kinds of environmental information from robot sensory data are needed as inputs of higher level controller: 1) Recognition of the pitfall existence from a given distance, 2) getting close to the edge of pitfall, and 3) touching the ground over the pitfall by swing leg. Two first data could be obtained by means of optical and the latter one from mechanical sensors.

4. MOTION MODES SPECIFICATION BY PSO

Suitable parameters of CPG and mechanical feedback to produce appropriate signals for each motion mode needs to be determined for the system. A general strategy to determine those parameters is to optimize the motion pattern subject to defined constraints. There is infinite number of possible solutions and for every possible solution the objective values are calculated after simulation of resulting dynamics. This makes the utilization of swarm evolutionary optimization methods an appropriate choice, like PSO, for this problem. PSO can deal with continuous optimization problems better than similar methods such as genetic algorithm, and it is also faster in computational procedure [26]. Here a brief introduction to PSO is presented in section 4.1, and the procedure of its application for motion modes specification is described in section 4.2.

4.1. Particle Swarm Optimization

Particle Swarm Optimization is one of well-known meta-heuristic optimization methods which is introduced in [27] by modeling the movements of a swarm in a search space. The possible solutions of the problem are set to be the possible positions of particles in the search space, and the fitness function determines the fitness of each position. The particles have information sharing about their best experienced position. There is a memory for swarm to maintain the best experienced position from all particles in the swarm. Also, each particle has its own memory for its best experienced position. The velocity of a particle is determined from the sum of vectors from particle position pointed to best positions (Figure 5).

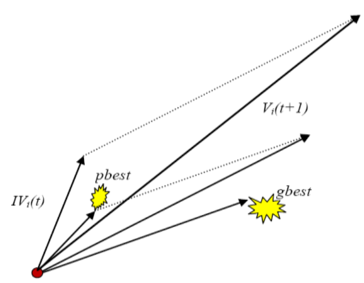

Fig. 2. Determining the velocity of particle in PSO

The new position of particle will be determined from this velocity and the procedure of updating the particle's velocity and position is iterated. The main procedure of PSO is as follows:

1- Initial positions and velocities of particles in search space are set randomly. For each particle the fitness of its position is determined by fitness function. The best fitting position among all swarm is set as global best position (*gbest*), and for *i*-th particle, its position is set for personal best position ($pbest_i$).
2- Velocity of *i*-th particle is updated as equation below

$$V_i(t+1) = I\,V_i(t) + r_1C_1(gbest - x_i(t)) + r_2C_2\big(pbest_i - x_i(t)\big), \qquad (5)$$

Where I is inertia factor, r_1 and r_2 are random numbers, and C_1 and C_2 are constant coefficients.
3- Position of *i*-th particle is updated also by

$$x_i(t+1) = x_i(t) + \delta\, V_i(t+1), \qquad (6)$$

In which the δ determines the time step.
4- Fitness values for the new positions are calculated by fitness function, *gbest* and *pbest* values are updated, and the procedure is iterated from stage 2.

After enough numbers of iterations, the swarm converges to the position with optimum fitness. This best position represents the optimum values for optimization variables.

4.2. Motion Modes Objectives

In utilization of PSO for determining appropriate parameters specification of different motion modes, suitable definition of objective functions (fitness functions) is necessary. The objective functions are based on desired behavior of the robot in corresponding mode and differ for different modes. Here we present objective functions of 4 main modes described in section 3.3 which are used in simulation. However, the choice of an objective function form is not unique.
Normal walking: In normal walking mode we desire the robot to have regular steps and stable walking pattern, and spend not too much energy. So it is appropriate to set a constant medium step length for the robot and force it to have minimum deviation from this value. The choice of medium length is due to lower energy consumption in normal walking. The objective function for normal walking with step length Δ is defined as

$$f_{NW} = MSE(\delta_s - \Delta), \qquad (7)$$

Where $\delta_s = |x_{t,s} - x_{w,s}|$ is the actual length of s-th step defined as the x direction distance between two heels at the end of that step. *MSE* indicates mean squared error operation. By minimization of f_{NW} to zero, the desired regular walking will be achieved.

Shortening the step length: In Shortening the step length from a distance to the edge of pitfall, it is appropriate for the robot to have short steps and to stop near the edge of pitfall. By choosing objective function as

$$f_{SD} = |\delta_s| + MSE(|x_h(t > t^*) - \gamma|), \qquad (8)$$

Where $x_h(t > t^*)$ is the x position of hip joint after time t^*, and γ is the distance of pitfall from the robot at the beginning of slow down phase.

Skip over: When robot tries to pass over the pitfall, it should change its step length from very short to very long. This phase happens in only one step, so it is suitable to define objective for only one step simulation and try to maximize

$$f_{SO} = |\delta_1| + x_h(t_{max}), \qquad (9)$$

Return: After passing the first leg over the pitfall, the robot should set its first step to a short length when in its initial state the legs are much apart. So the objective is defined as

$$f_{RE} = MSE(\delta_1 - \Delta), \quad when\ \delta_0 > M \qquad (10)$$

in which *M* is big step length.

5. SIMULATION RESULTS

In this section the simulation results of the whole system of biped robot, with gait dynamics described in section 2 and locomotion control system described in section 3, in an environment with pitfalls are presented.

In the first stage, different modes of motion are optimized by PSO as described in section 4. For each single mode, the objective values are obtained by simulating the motion in a few steps every time. The optimized values for parameters are shown in Table 2.

By means of PSO the normal walking parameters of CPG and mechanical feedback is determined. For this case, we set the desired normal walking step length $\Delta = 0.3$. For PSO algorithm population of 30 particles is used and the number of algorithm iterations is set to 250. After optimization, successive step lengths of the robot with parameters of obtained optimum solution are plotted in Figure 3. It is clear that the robot sets its step's lengths to 0.3 soon after beginning of motion. The angles of two legs are also shown in Figure 4. In Figures 5 and 6 the x position of hip and the exerted torque input on hip joint are depicted respectively.

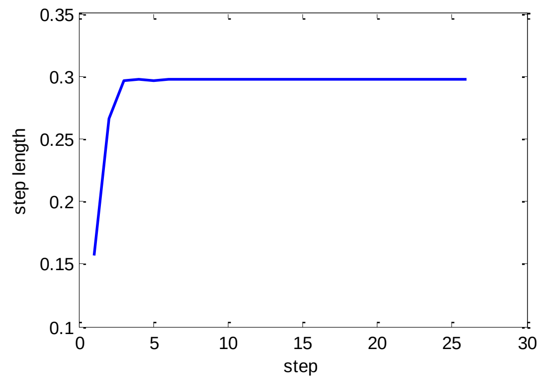

Fig. 3. Successive step lengths in optimized normal walking with $\Delta = 0.3$

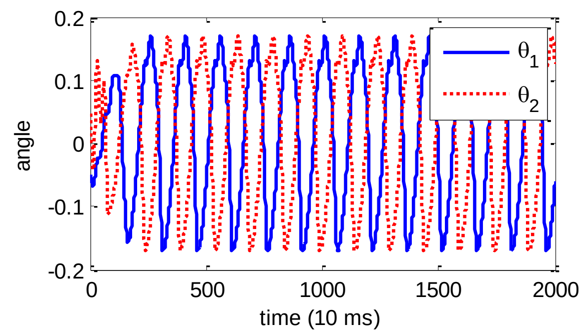

Fig. 4. Angles of two legs versus time in normal walking with $\Delta = 0.3$

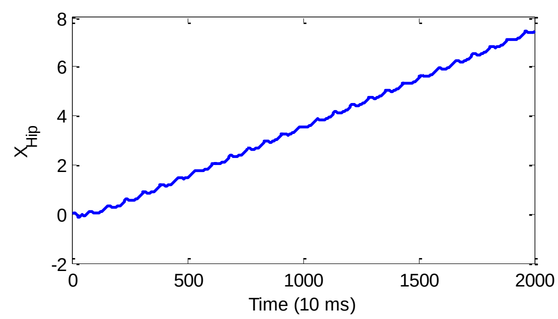

Fig. 5. x position of hip versus time in normal walking with $\Delta = 0.3$

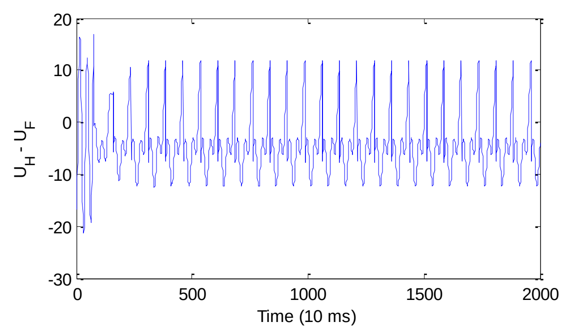

Fig. 6. Exerted torque on hip joint versus time in normal walking with $\Delta = 0.3$

In the second stage of work, slow down mode optimization is performed. The resulted step lengths after optimization are shown in Figure 7.

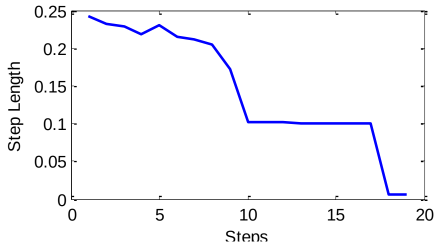

Fig. 7. Successive step lengths in optimized slowing down with $\gamma = 1$ and $t^* = 15$

In third and fourth stages skipping over and return modes are also optimized. Results of these two modes are not interesting for plotting because of their single step nature.
The parameters for CPG and mechanical feedback unit obtained for each mode are used for higher level controller. By utilization of higher level controller in switching between modes, the robot is simulated in a terrain with two pitfalls. The skipping over phase of the robot is shown in Figure 8.

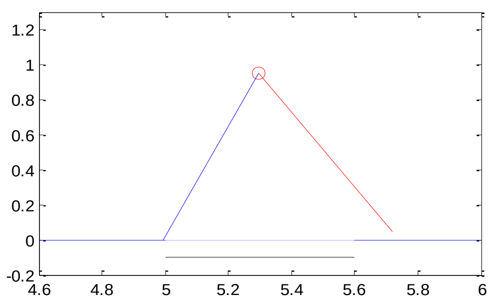

Fig. 8. Skipping over pitfall

Switching between modes is best illustrated by plot of step lengths for successive steps as shown in Figure 9. Different modes are clearly seen in the plot and also notated.

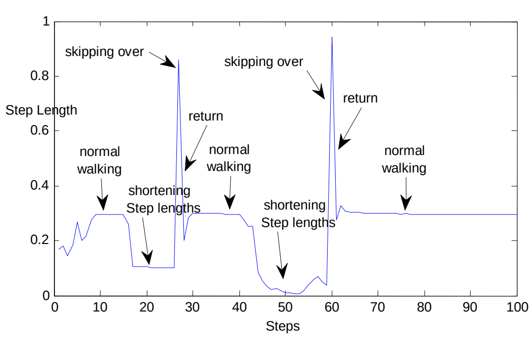

Fig. 9. Successive step lengths of simulated bipedal robot in a terrain with two pitfalls

Table 2. Optimized values for parameters of system for different modes.

Mode	Parameter	Value
Normal Walk	θ_{max}	0
	K	256
	$\{A_1, A_2, A_3, A_4, A_5, A_6\}$	{9.02,0,0,0,0,0}
	$\{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$	{-2.81,0,0,0,0,0}
	f_1	0.60
Shortening Steps	θ_{max}	0
	K	1398
	$\{A_1, A_2, A_3, A_4, A_5, A_6\}$	{6,1.38,2.68,6,0,0}
	$\{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$	{-2.9,0.69,-3.14,-0.4 , -0.4,0,0}
	f_1	0.78
Skip Over	θ_{max}	0.11
	K	145
	$\{A_1, A_2, A_3, A_4, A_5, A_6\}$	{26,0,0,7.45,25,25}
	$\{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$	{-0.34,0,0,3.14,-2.5, 2.2}
	f_1	0.09
Return	θ_{max}	0.08
	K	297
	$\{A_1, A_2, A_3, A_4, A_5, A_6\}$	{0,8,0.8,4.4,2.8,8.7}
	$\{\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6\}$	{0,-2.6,-3,-3.14, 3.14,-1.4}
	f_1	0.02

6. CONCLUSIONS

This paper proposed a locomotion control system for bipedal robot. The control system is consisted of three main units including central pattern generation, mechanical feedback stabilization, and higher level mode switching control. The proposed system extends previous works, mainly for its utilization of controller in passing over pitfalls in the terrain. We also found that using a simple mechanical feedback can provide general stability of motion. In all parts of the system minimalistic design and consumption was one of our concerns. The integrated strategy of this work combines advantages of PSO algorithm in motion optimization, central pattern generation, and switching control. The proposed methods are general, simple and therefore extendable for more complicated models.

REFERENCES

[1] E.R., Westervelt, J.W., Grizzle, C., Chevallereau, J.H., Choi, and B., Morris, **"Feedback control of dynamic bipedal robot locomotion"**, *CRC press Boca Raton*, 2007.

[2] G., Taga, Y., Yamaguchi, and H., Shimizu, **"Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment,"** *Biological cybernetics*, Vol. 65, No. 3, pp. 147–159, 1991.

[3] S., Collins, A., Ruina, R., Tedrake, and M., Wisse, **"Efficient bipedal robots based on passive-dynamic walkers,"** *Science*, Vol. 307, No. 5712, pp. 1082–1085, 2005.

[4] A.D., Ames , R.D., Gregg, **"Stably extending two-dimensional bipedal walking to three**

dimensions," in *American Control Conference, 2007. ACC'07*, pp. 2848–2854, 2007.

[5] F., Plestan, J.W., Grizzle, E.R., Westervelt, and G., Abba, **"Stable walking of a 7-DOF biped robot,"** *Robotics and Automation, IEEE Transactions on*, Vol. 19, No. 4, pp. 653–668, 2003.

[6] S., Kajita, F., Kanehiro, K., Kaneko, K., Fujiwara, K., Yokoi, and H., Hirukawa, **"A realtime pattern generator for biped walking,"** in *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, Vol. 1, pp. 31–37, 2002.

[7] M., Vukobratović , B., Borovac, **"Zero-moment point—thirty five years of its life,"** *International Journal of Humanoid Robotics*, Vol. 1, No. 01, pp. 157–173, 2004.

[8] C., Zhou , Q., Meng**, "Dynamic balance of a biped robot using fuzzy reinforcement learning agents,"** *Fuzzy sets and systems*, Vol. 134, No. 1, pp. 169–187, 2003.

[9] D., Kim, N.H., Kim, S.J., Seo, and G.T., Park, **"Fuzzy modeling of zero moment point trajectory for a biped walking robot,"** in *Knowledge-Based Intelligent Information and Engineering Systems*, pp. 716–722, 2004.

[10] Z., Liu, Y., Zhang, and Y., Wang, **"A type-2 fuzzy switching control system for biped robots,"** *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, Vol. 37, No. 6, pp. 1202–1213, 2007.

[11] C., Zhou , Q., Meng, **"Reinforcement learning with fuzzy evaluative feedback for a biped robot,"** in *Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on*, Vol. 4, pp. 3829–3834, 2000.

[12] J., Hu, J., Pratt, and G., Pratt, **"Stable adaptive control of a bipedal walking; robot with CMAC neural networks,"** in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, Vol. 2, pp. 1050–1056, 1999.

[13] A., Kun , W.T., Miller III, **"Adaptive dynamic balance of a biped robot using neural networks,"** in *Robotics and Automation, 1996. Proceedings., IEEE International Conference on*, Vol. 1, pp. 240–245, 1996.

[14] D., Kim, S.J., Seo, and G.T., Park, **"Zero-moment point trajectory modelling of a biped walking robot using an adaptive neuro-fuzzy system,"** *IEE Proceedings-Control Theory and Applications*, Vol.152, No. 4, pp. 411–426, 2005.

[15] D., Kim, S.J., Seo, and G.T., Park, **"Zero-moment point trajectory modelling of a biped walking robot using an adaptive neuro-fuzzy system,"** *IEE Proceedings-Control Theory and Applications*, Vol. 152, No. 4, pp. 411–426, 2005.

[16] C., Sabourin, K., Madani, and O., Bruneau, **"Autonomous biped gait pattern based on Fuzzy-CMAC neural networks,"** *Integrated Computer-Aided Engineering*, Vol.14, No.2, pp. 173–186, 2007.

[17] M.Y., Shieh K.H., Chang, **"An optimized neuro-fuzzy controller design for bipedal locomotion,"** *International Journal of Fuzzy Systems*, Vol.11, No.3, pp. 137–145, 2009.

[18] A.J., Ijspeert, **"2008 Special Issue: Central pattern generators for locomotion control in animals and robots: A review,"** *Neural Networks*, Vol.21, No.4, pp. 642–653, 2008.

[19] P., Arena, **"The central pattern generator: a paradigm for artificial locomotion,"** *Soft Computing*, Vol.4, No.4, pp. 251–266, 2000.

[20] S., Hasanzadeh , A.A., Tootoonchi, **"Adaptive optimal locomotion of snake robot based on CPG-network using fuzzy logic tuner,"** in *Robotics, Automation and Mechatronics, 2008 IEEE Conference on*, pp. 187–192, 2008.

[21] K., Matsuoka, **"Mechanisms of frequency and pattern control in the neural rhythm generators,"** *Biological Cybernetics*, Vol.56, No.5–6, pp. 345–353, 1987.

[22] F., Iida , R., Tedrake**, "Minimalistic control of biped walking in terrain,"** *Autonomous Robots*, Vol. 28, No.3, pp. 355–368, 2010.

[23] H., Inada , K., Ishii, **"Behavior generation of bipedal robot using central pattern generator (CPG)(1st report: Cpg parameters searching method by genetic algorithm),"** in *Intelligent Robots and Systems, 2003.(IROS 2003). Proceedings. 2003 IEEE/RSJ International Conference on*, Vol.3, pp. 2179–2184, 2003.

[24] J.J., Kim, J.W., Lee, and J.J., Lee, **"Central pattern generator parameter search for a biped walking robot using nonparametric estimation based Particle Swarm Optimization,"** *International Journal of Control, Automation and Systems*, Vol.7, No. 3, pp. 447–457, 2009.

[25] Y., Farzaneh, A., Akbarzadeh, and A.A., Akbari, **"New automated learning CPG for rhythmic patterns,"** *Intelligent Service Robotics*, Vol. 5, No. 3, pp. 169–177, 2012.

[26] R., Hassan, B., Cohanim, O., Weck, and G., Venter, **"A comparison of particle swarm optimization and the genetic algorithm,"** in *Proceedings of the 1st AIAA multidisciplinary design optimization specialist conference*, 2005.

[27] J., Kennedy , R., Eberhart, **"Particle swarm optimization,"** in *Neural Networks, 1995. Proceedings., IEEE International Conference on*, Vol. 4, pp. 1942–1948, 1995.