A Central Pattern Generator based Nonlinear Controller to Simulate Biped Locomotion with a Stable Human Gait Oscillation

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Abstract

This paper describes the designing of a nonlinear biological controller inspired from stable human gait locomotion, which we implement for a stable biped motion on a Biped Robot. The design of a Central Pattern Generator (CPG) which consists of a four coupled Rayleigh Oscillators. A Two-Way oscillator coupling has been used for modeling the CPG. The parameters of the CPG are then optimized by Genetic Algorithm (GA) to match with the stable human gait oscillation. The stable human gait oscillation data was obtained using the Intelligent Gait Oscillation Detector (IGOD) biometric suit, which simultaneously measures both the human hips and knee oscillations. After checking the Limit Cycle behavior of the CPG it has been successfully simulated on the Spring Flamingo robot in YOBOTICS environment.

Keywords: Rayleigh Oscillator, Central Pattern Generator (CPG), Intelligent Gait Oscillation Detector (IGOD), Genetic Algorithm (GA), Nonlinear Dynamics System (NDS), YOBOTICS.

1. INTRODUCTION

Over the long decade humans have struggled to start surviving on this beautiful planet. Then the invention of rock, wheel, fire, vehicles etc. has been carried out by humans along with a tremendous innovation namely known as digital computer. Over the year’s new technologies are introduced to implement human thoughts to meet certain goals in our life. Humans also proactively updated those technologies as per their own necessity. Eventually they are succeeded to develop some industrial robots which are used to perform some tasks to a limited extent. These types of robots are commonly acquainted as pre programmed robots. Then the technology took a new turn in an evolutionary approach. Gradually it has kept its own footprints in the field of humanoid robotics with a tremendous appeal. The humanoid robots are being considered as a human being which can think rationally and act like a human to accomplish any kinds of complex task. Unlike all the activities performed by human, these humanoid robots learn to execute all the activities of human being like walking, handshaking, running etc. The humans offer maximum stress on the household robots in order to meet the completion of any kinds of household tasks. The humanoid robot can also act like a soldier in a war. The most elementary activity of humanoid robot includes walking pattern in complex environments. It offers a challenge to make the robots intelligently so that it could produce efficient walking patterns like human being in a complex environment. It includes extreme effort to deal with the complex parameters of humanoid robot for generating the accurate gait patterns in an efficient manner.

The basic concept of Central Pattern Generator (CPG) is actively related to the number of living species which produces a sequence of cyclic motor patterns. There has been represented a set of pattern generating systems or a class of neural circuits which are able to produce cyclic movements [9-11]. As per the biomechanical concept is concerned about the construction of CPG it happens to be a group constituted by the artificial neurons. These artificial neurons are called oscillators which are capable of producing an oscillatory signal output without any external periodic input. This concept of artificial neural network which is based on the central pattern generator has been used in the field of human gait biomechanics along with in robotics [11].

The main objective of this work is *“To build a CPG based model by using Rayleigh Oscillators and train this CPG by stable human gait oscillation to generate the human like biped locomotion for biped robot”.*

Contribution Done in This Paper

- ✓ Active participation of only four major joints for two legs in our work i.e. left hip, knee and Right hip, Knee.
- ✓ The design prototype of CPG model has been satisfied by establishing the coupling equation for Two-Way coupling between four different Rayleigh Oscillators for four joints to design our CPG model.
- ✓ Acquisition of the stable human walking data by a self made biometric suit called IGOD [1] and manipulates the optimized coupling parameters for our CPG model with that captured data using GA.
- ✓ Generate the human like walking pattern for the biped robot and check the stability.
- ✓ Simulate the generated human like biped locomotion by our designed CPG model into Spring Flamingo robot in YOBOTICS environment.

2. RELATED WORK

In the robotics society, we are progressively using the C.P.G. models. The different views of CPG models are designed for robots including connectionist models (e.g. Lu, Ma, Li; Arena, 2000, & Wang, 2005), and some models created by coupled oscillators (e.g. Ijspeert et al.; Kimura et al.; Williamson et al.;) [16-22]. In some infrequent cases, some spiking neural models are used (e.g. Lewis et al.) [23]. Almost all implementations consist of some sets of Coupled Differential Equations which are integrated numerically on the processor or on a microcontroller. Most likely the only exceptions that are CPGs. these CPGs are unswervingly realized in hardware, which is on a chip (e.g. Schimmel et al. 1997, DeWeerth et al.) [27] or with the analog electronics (Still & Tilden, 1998). Also up to some scope which is associated to CPG research are quasi-cyclic movements governed by chaotic maps.

The CPG models have been widely used in the control of a variety of distinct robots and also in control of different modes of locomotion. The CPG models have already been used for hexapod and octopod robots. This has been inspired by pest locomotion like Arena, Frasca, etc.

Practical implementation of CPG in knee active prosthetic limb development was proposed by G. C. Nandi et al. [12, 13]. Some CPG model simulation in Matlab was done by M. H. Kassim et al.

and A. Carlos De Filho [14, 15]. Behavior control of robot using Nonlinear Dynamics was proposed by Nakamura et al. [24-26]. Table 1 shows some more related work.

Author	Methodology	Robot
Aoi et al. [28]	Turning walk of biped robot, locomotion control using Euler angle, joint angle Lagrange equation & vision base turning control.	Biped robot
Ding et al.[29]	Motion control & dynamic modeling.	Amphibious bio-mimetic robot
Takahashi et al. [30]	Control strategy for more natural & efficient biped locomotion using Matsouka oscillator & Lagrange equation.	Mechanical model
Inada et al. [31]	CPG parameter search by genetic algorithm using Matsouka oscillator	Biped robot
Liu et al. [32]	Locomotion control using 4 mutually coupled Vanderpol oscillator.	AIBO robot
Xiao et al. [33]	Biped locomotion generation using Matsouka oscillator with parameters optimize by genetic algorithm.	Biped robot with heterogeneous leg(BRHL)
Kurita et al. [34]	Rotation, manipulation of dexterous hand using Matsouka oscillator.	Finger Gait type robot
Nishikawa et al. [35]	Dynamics of Hopf oscillator within limit cycle for designing the CPG.	Biped robot
Matsuo et al. [36]	Bio-mimetic motion control using Matsouka oscillator.	Multilink mobile robot
Osaku et al. [37]	CPG technique to swing of arm using Matsouka oscillator.	Humanoid model & environment model
Huang et al. [38]	Aim to achieve coordination to CPG & asymptotically stable walking behavior using Matsouka oscillator.	Biped robot

TABLE 1: Related Work.

3. EXPLANATION OF RELEVANT TERMS USED IN THIS PAPER

3.1 Biped Locomotion

Biped locomotion means walk or running on two legs in an upright position. Static stability on both legs is simple however maintaining a dynamic stability during locomotion is extremely difficult since it transferred from one leg to another with intermediate phase where the entire weight of the body is on one of the legs. Figure 1 describes the different phases of the biped locomotion.

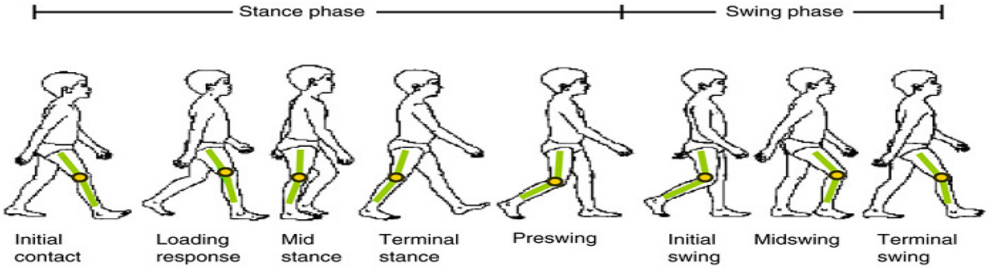


FIGURE 1: Details of biped locomotion.

3.2 Central Pattern Generator (CPG)

The concept of Central Pattern Generator is inherited from nature [3]. In this approach it is not mandatory to know the entire information about the robot dynamics. This method implies more adaptive to generate controllers for two leg walking. In this method there are some type of reflexes which are used to control the balance and the effect generated by the external force. These reflexes can also be used as the feedback for the system [2].

The CPG are oscillator based controller. So the theory of limit cycle is used and this is very well-situated for the bipedal walking phenomenon. These oscillators can regenerate the stability against some weak external input. These can persist also in the stable state on the small disturbance in the preliminary circumstances. This method can be of two types, the open loop and the closed loop method.

The concept of limit cycle was taken from Nonlinear Dynamic System *"The Limit cycle is a cycle that is isolated and closed trajectory"* [5]. Figure 2 shows the limit cycle according to the system stability.

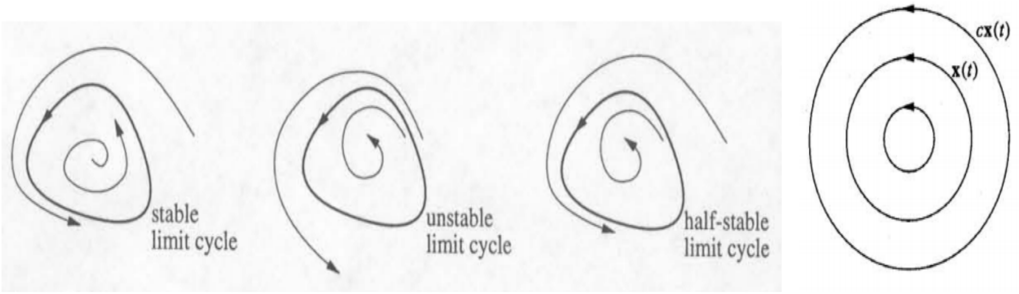
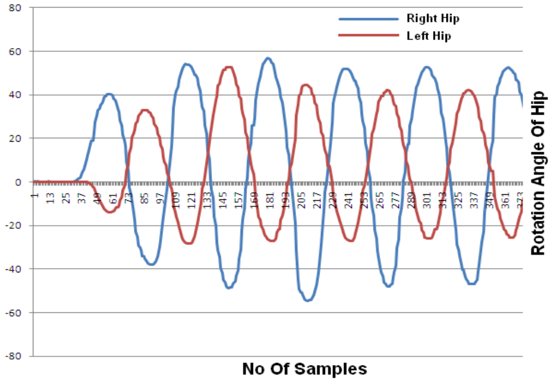


FIGURE 2: Limit Cycle according to the stability.

3.3 Intelligent Gait Oscillation Detector (IGOD)

Intelligent Gait Oscillation Detector (IGOD) is a self made rotation sensor based biometric suit which is used to capture different major joints [(Hip, Knee, Shoulder, Elbow) × 2] in terms of angle value oscillations involved in human locomotion [1]. In our work we have only considered two hip joints and two knee joints. Figure 3 depicts the rear and front view of IGOD suit. Figure 4 and 5 shows the human gait pattern for both hip joints and both knee joints respectively captured by IGOD suit for a particular person's locomotion.

FIGURE 3: (a) Rear (b) Front view of IGOD [1].



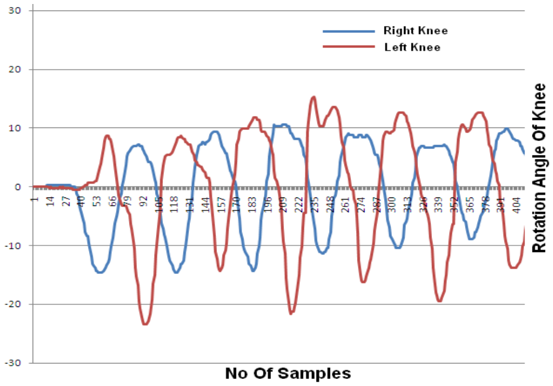


FIGURE 4: Gait pattern of both hip joints [1].

FIGURE 5: Gait pattern of both knee joints [1].

3.4 Rayleigh Oscillators

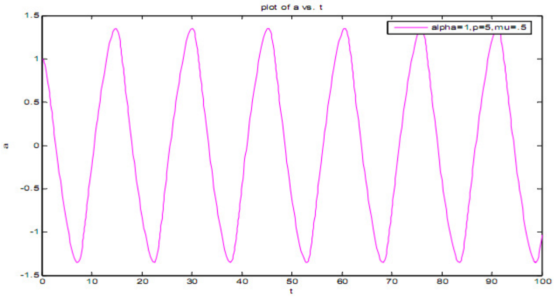
Rayleigh Oscillator is a Relaxation Oscillator. It means the oscillator is based upon performance of the physical system and with the condition of returning to the equilibrium position after being perturbed (small external force).

The second order differential equation of the Rayleigh oscillator is

$\ddot{a} - \alpha(1 - \dot{a}) + \mu^2 a = 0$ Without forced condition and

$\ddot{a} - \alpha(1 - \dot{a}) + \mu^2 a = \gamma \sin At$ For forced condition.

Here μ parameter controls the amount of voltage (energy) goes into our system. α is frequency controlling the technique in which voltage flows in the system. Now we are trying to show that how different parameters of this oscillator will affects the pattern. Figure 6 represents the Matlab plot of **a** vs. time **t** and Figure 7 represents the limit cycle of a Rayleigh Oscillator where α=1, μ=0.5, p=1. Figure 8 show that **a** vs. **t** plot where α=1, μ=0.5, p=50 and Figure 9 show that **a** vs. **t** plot where α=1, μ=0.2, p=1.



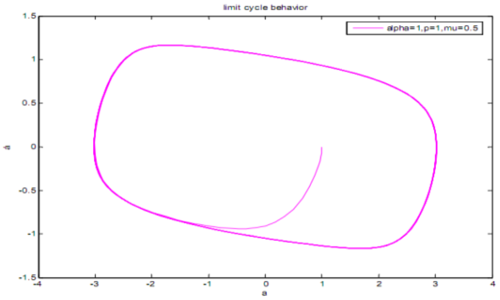
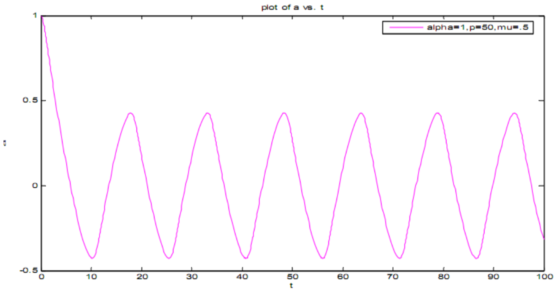


FIGURE 6: Plot of **a** vs. time **t.** where α=1, μ=0.5. **FIGURE 7:** Limit Cycle of Rayleigh Oscillator where α=1, μ=0.5, p=1.



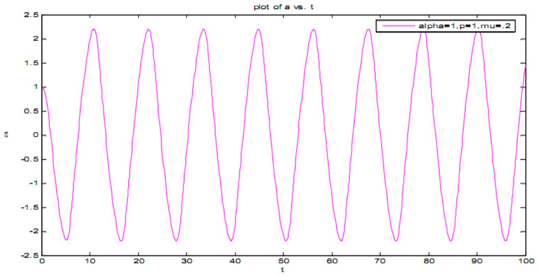
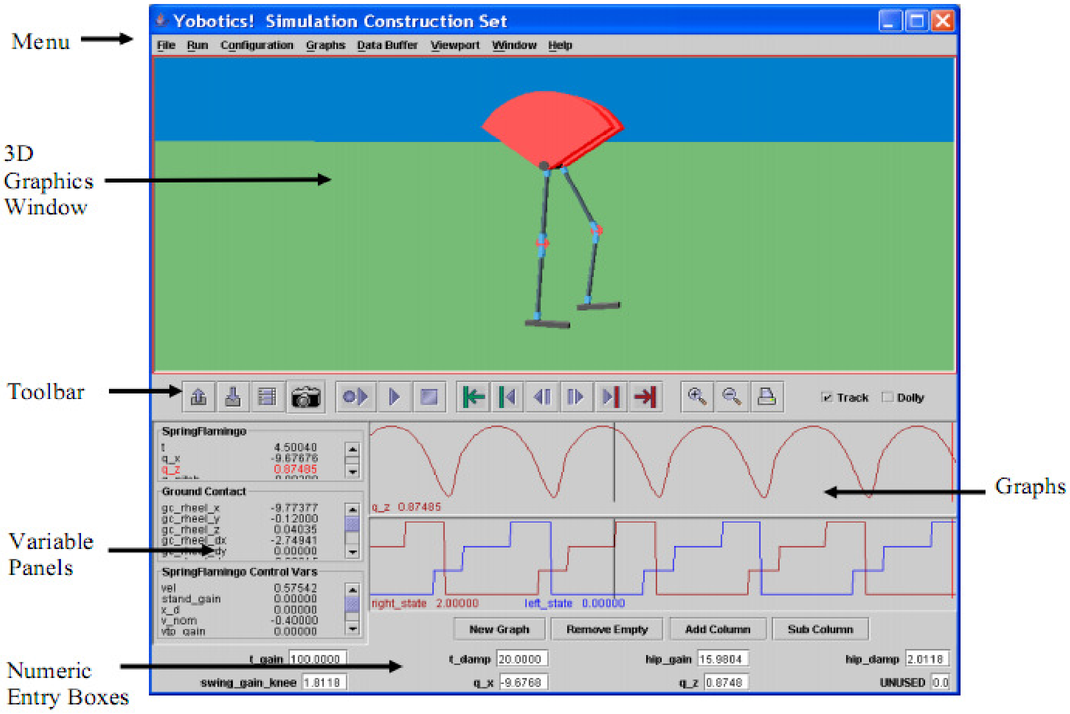


FIGURE 8: Plot of **a** vs. time **t.** where α=1, μ=0.5, p=50.

FIGURE 9: Pot of **a** vs. time **t.** where α=1, μ=0.2, p=1.

3.5 YOBOTICS SIMULATOR

YOBOTICS is a simulation tool for robot simulation. It is a very good software package to simple and rapidly generating simulations for mechanical system like biped locomotion, biomechanical model regarding robots [4]. This simulator has Java based API. Figure 10 shows the different components of YOBOTICS robotics simulation tool.



SpringFlamingo
t 4.50040
q_x -9.67676
q_z 0.87485

Ground Contact
gc_rheel_x -9.77377
gc_rheel_y -0.12000
gc_rheel_z 0.04035
gc_rheel_dx -2.74941
gc_[illegible]dy 0.00000

SpringFlamingo Control Vars
vel 0.57542
stand_gain 0.00000
x_d 0.00000
v_nom -0.40000
vtp_gain 0.00000

q_z 0.87485
right_state 2.00000
left_state 0.00000

t_gain 100.0000
t_damp 20.0000
hip_gain 15.9804
hip_damp 2.0118
swing_gain_knee 1.8118
q_x -9.6768
q_z 0.8748
UNUSED 0.0

FIGURE 10: GUI window of YOBOTICS simulation software with a Spring Flamingo robot.

4. MODELING THE CPG

In our work we modeled the CPG according to the concept of Nonlinear Dynamic System (NDS). According to the NDS concept if we can couple the relaxation oscillators then the system can be able to produce different rhythmic patterns and also we can be able to check the system stability according to this concept. The CPG model with all four Two-Way coupled Rayleigh oscillators is shown in Figure 11 (a) and Figure 11 (b) showing the different coupling parameters.

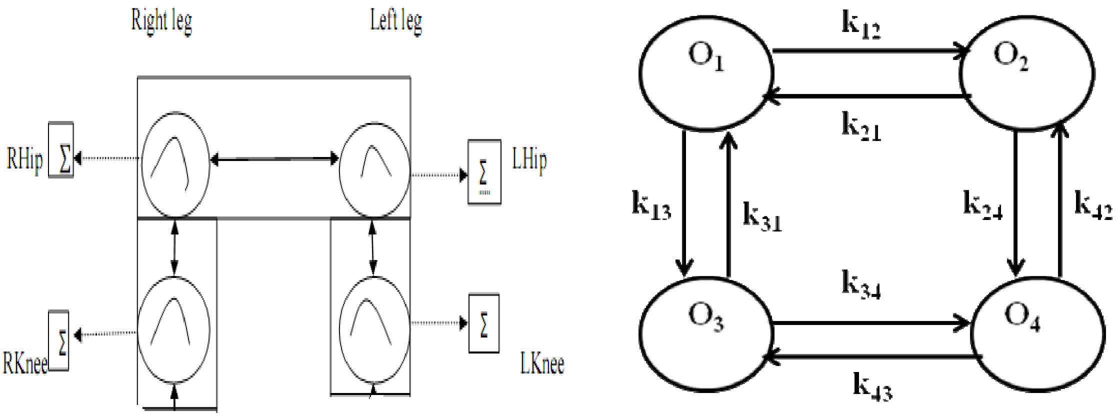


FIGURE 11: CPG Model (a) Oscillators position with Two-Way coupling and (b) Different coupling parameters.

In this figure O_1, O_2, O_3, O_4 represent four Rayleigh oscillators. k_{12}, k_{21} are coupling parameters between oscillator O_1 and O_2. k_{24}, k_{42} are parameters between oscillator O_1 and O_4. The parameters between oscillator O_3 and O_4 are k_{34} and k_{43}, and k_{31}, k_{13} are parameter between oscillator O_1 and O_3.

4.1 Rayleigh Oscillator Coupling

As we already did the basic architecture of the modeling of the CPG then the implementation phase comes into under consideration. The implementations are categorized into two different parts.

First part in our model, we started placing the Rayleigh oscillators at the different rhythm generating position i.e. left side knee, right side knee, left side hip and right side hip location. These four Rayleigh oscillators are as follows that are in the form of second order differential equation.

For Right side Hip oscillator equation: $\ddot{a}_1 - \alpha_1 (1-d_1 \acute{a}_1^2) \acute{a}_1 + \mu_1^2 (a_1-a_{10}) = 0$ -------- **(A)**
For the Left side Hip oscillator equation: $\ddot{a}_2 - \alpha_2 (1-d\ {}_2\acute{a}_2^2) \acute{a}_2 + \mu_2^2 (a_2-a_{20}) = 0$ --------- **(B)**
For the Right side Knee oscillator equation: $\ddot{a}_3 - \alpha_3 (1-d_3\acute{a}_3^2) \acute{a}_3 + \mu_3^2 (a_3 - a_{30}) = 0$ -------- **(C)**
For Left side Knee oscillator equation: $\ddot{a}_4 - \alpha_4 (1-d_4\acute{a}_4^2) \acute{a}_4 + \mu_4 (a_4 - a_{40}) = 0$ ---------- **(D)**

Here these parameter d_1, d_2, d_3, d_4, μ_1^2, μ_2^2 μ_3^2 μ_4^2, α_1, α_2, α_3, α_4 refer to positive constants in the Rayleigh oscillators. Changing these parameters permit the modification of the frequency of generated signal and amplitude of generated signal.

Solve the second order differential equation is very complicated. So, now we are representing the first order equation of A, B, C and D are written below:

Form equation (A) we found
$\acute{a}_1 = z_1$ and $\acute{z}_1 = \alpha_1 (1-d_1 z_1^2) z_1 . \mu_1^2 (a_1 - a_{10})$ ---------- **(e)**
Form equation (B) we found
$\acute{a}_2 = z_2$ and $\acute{z}_2 = \alpha_2 (1-d_2 z_2^2) z_2 . \mu\ {}_2^2 (a_2 - a_{20})$ ---------- **(f)**
Form equation (C) we found
$\acute{a}_3 = z_3$ and $\acute{z}_3 = \alpha_3 (1-d_3 z_3^2) z_3 - \mu_3^2 (a_3 - a_{30})$ ---------- **(g)**
Form equation (D) we found
$\acute{a}_4 = z_4$ and $\acute{z}_4 = \alpha_4 (1-d_4 z_4^2) z_4 - \mu_4^2 (a_4 - a_{40})$ --------- **(h)**

The four Rayleigh oscillators in our model will produce four output signals autonomously. Here, all oscillators are not affecting each other because there is no coupling. In order to produce the preferred rhythmical output pattern next task is to be linked with all oscillators with each other or coupling them.

Secondly we have done interconnection among all the four oscillators related with each other. In this work the coupling concept has been introduced which basically includes two types of coupling. One is refereeing One-Way coupling and other is directing to Two-Way coupling. In this paper a Two-Way coupling technique has been applied. In Two-Way coupling type, if two or more oscillators are interrelated then all the oscillators' effect on each other. It has been observed that first oscillator effects on second oscillator and second oscillator effects on first one for linking the all of four Rayleigh oscillators that are used for left side knee, right side knee, left side hip and right side hip location. In order to provide encouragement this idea came from the association among left side knee, right side knee, left side hip and right side hip joints of humans at the time of simple walking. If we talk about biped locomotion in human being a situation is arrived at locate one leg is in stance phase (on ground) the other side leg is in the situation of swing phase (in air) [refer to Fig. 1]. As a result, we can always exempt phase association stuck between the left side knee's joint angle & right side knee's joint angle the hip angle differently other is knee joint angles are synchronized. If we talk about hip difference angle then we can say that it gives an oscillatory performance throughout locomotion, angle difference oscillates in mean while positive value and then negative values.

Therefore all the four oscillators are interlinked to do so facts discussed in above section. These second order differential equation showing all four oscillators has considered only one term in account of feedback from one to other oscillator. Following are the equation for this system after coupling oscillators:

$$\ddot{a}_1 - \alpha_1 (1 - d_1 \acute{a}_1^2)\, \acute{a}_1 + \mu_1^2 (a_1 - a_{10}) - k_{13} (\acute{a}_3 (a_3 - a_{30})) - k_{12} (\acute{a}_1 - \acute{a}_2) = 0 \text{ ---- (i)}$$

$$\ddot{a}_2 - \alpha_2 (1 - d_2 \acute{a}_2^2)\, \acute{a}_2 + \mu_2^2 (a_2 - a_{20}) - k_{24} (\acute{a}_4 (a_4 - a_{40})) - k_{21} (\acute{a}_2 - \acute{a}_2) = 0 \text{ ---- (j)}$$

$$\ddot{a}_3 - \alpha_3 (1 - d_3 \acute{a}_3^2)\, \acute{a}_3 + \mu_3^2 (a_3 - a_{30}) - k_{31} (\acute{a}_1 (a_1 - a_{10})) - k_{34} (\acute{a}_3 - \acute{a}_4) = 0 \text{ ---- (k)}$$

$$\ddot{a}_4 - \alpha_4 (1 - d_4 \acute{a}_4^2)\, \acute{a}_4 + \mu_4^2 (a_4 - a_{40}) - k_{42} (\acute{a}_2 (a_2 - a_{20})) - k_{43} (\acute{a}_4 - \acute{a}_3) = 0 \text{ ---- (l)}$$

4.2 Optimization of CPG Parameters Using GA

Now we need to optimize the different parameters of CPG. In our work we choose Genetic Algorithm (GA) as an optimization technique. The fitness function for GA is the difference between angles that is joint angles generated by our CPG model and the joint angle captured by IGOD suit. Here e(t) is the difference between the angle value in time **t**. So the fitness function is

$$E_d(t) = \beta_1 e(t) + \beta_2\, de(t) / dt + \beta_3 \int e(t)\, dt \text{ ------- (p)}$$

β_1, β_2 and β_3 considered as Proportional Constant, Differential Constant and Integral Constant respectively. According to our fitness function reduce the function value means reduce the angle difference that means we are going towards the generation of natural human like walking pattern by our CPG model for our robot.

Now differentiating the equation (p) with respect to t :

$$\beta_1\, de(t)/dt + \beta_2\, d^2e(t)/dt^2 + \beta_3 e(t) = dE_d(t)/dt \text{ -- (q)}$$

Now consider that the system is in steady state condition that means system within the virtual static state. In condition of steady state is $de(t)/dt \to 0$, $d^2e(t)/dt^2 \to 0$. We know that $E_d(t)$ is constant and $\beta_3 e(t) = 0$, but β_3 is not equals to 0 because this is considered as positive constant, that means $e(t) \to 0$ **------- (r).**

Hence we can say that the fitness function reduces the fault. Therefore the fitness function (p) will decrease the steady state error to 0.

5. ANALYSIS OF OUR CPG MODEL

In this part we will show the CPG parameters we obtain from GA and the walking pattern generated by our CPG model. In our work the fitness function (p) is converged to 0.001, that means $e(t) \to 0.001$ **.** So the optimized value we get from GA is k_{12}=.2111, k_{13}=.1125, k_{24}=.1129, k_{21}=.3010, k_{31}=.1125, k_{34}=.2012, k_{42}=.1129, k_{43}=.2012, α_1=.0314, α_2=.0220, α_3=.0208 and α_4=.0308.

Figure 12 shows the rhythmic patterns generated by our CPG model.

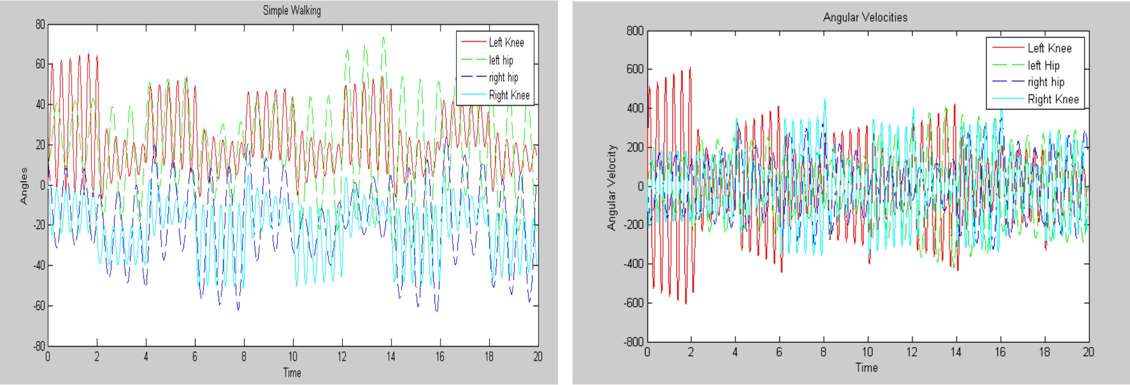


FIGURE 12: The pattern generated by our CPG model of different joints (a) Angle vs. Time graph were angle is in degree and time is in Second. (b) Velocity vs. Time graph.

Now coming to the phase space trajectory graphs those are also known as limit cycle which should be in stable state for stable walking of a Robot. Figure 13, 14, 15 and 16 shows the phase space trajectory graph for left knee, left hip, right knee and right hip respectively. All these phase diagram start from Origin and converged to constant oscillatory swinging action and have a stable limit cycle.

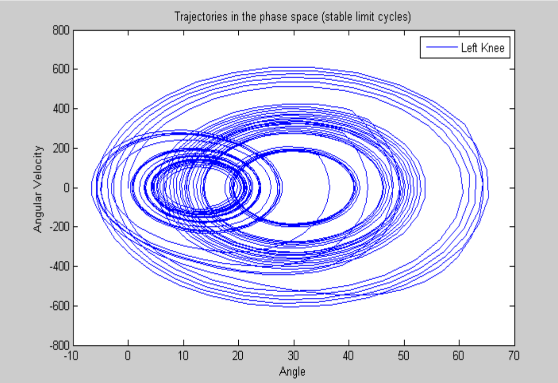


FIGURE 13: Phase diagram of Left Knee joint.

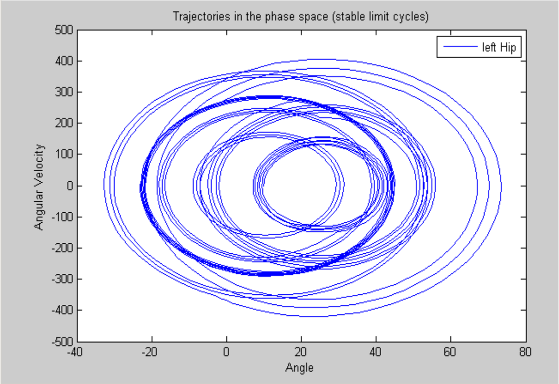


FIGURE 14: Phase diagram of Left Hip joint.

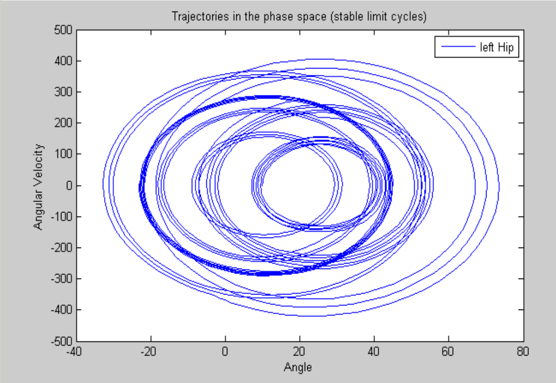


FIGURE 15: Phase diagram of Right Knee joint.

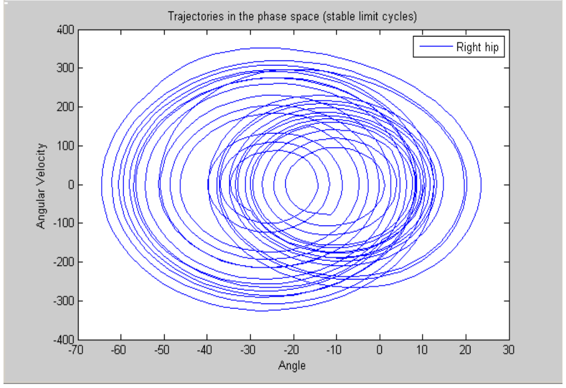


FIGURE 16: Phase diagram of Right Hip joint.

6. SIMULATION

In our work we have used Matlab 7.5 and YOBOTICS robotics simulation environment. The Differential equation solver presented in Matlab 7.5 is used for modeling the CPG. The implementation part of GA is also done in Matlab 7.5. This experiment provides us some patterns those are being tested on YOBOTICS simulator with a Spring Flamingo Robot. It also gives the oscillatory activity of the CPG where angle are considered in radian.

In this environment spring damper system is used for modeling the ground. The coefficient of the spring is 40000N/m and 100N/m for damping. The Ts is time interval having value 0.5ms. The pattern we have got from CPG given to this simulator is in the form of CSV (Comma Separated Value) file format. In this simulator we can export the CSV file and run it freely. Since CPG is matched to an actual human gait oscillation; the ratio of the limb dimension has been kept similar to that of a human. After running it we will get the pattern and intended to prove of our CPG model is working or not. Figure 17 is the snap shot of a walking Spring Flamingo robot from three camera view in YOBOTICS environment. Figure 18 shows the each joint oscillation activity when the Spring Flamingo robot is walking. Figure 19 shows the state diagram of our robot within a particular gait cycle when the robot is walking. Figure 20 shows the plot of the robot state diagram.

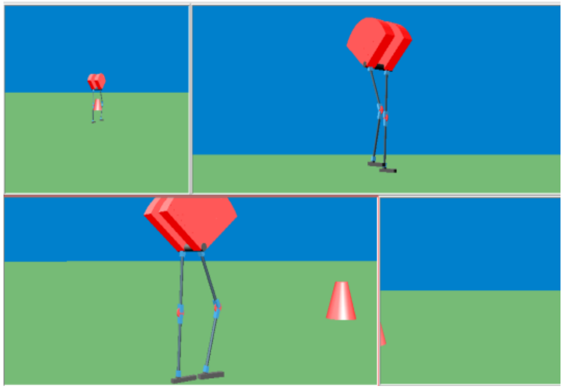


FIGURE 17: Walking of a Spring Flamingo robot.

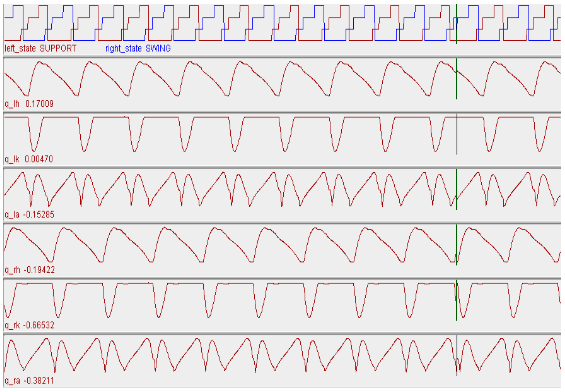


FIGURE 18: Oscillation activity of each joint.

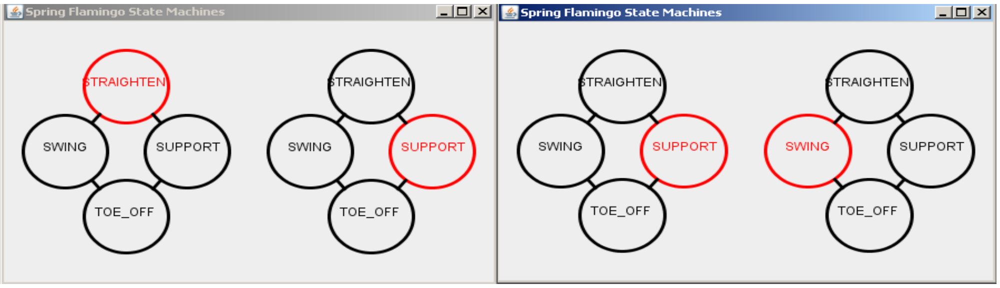


FIGURE 19: Shows the state of left and right legs when the robot is walking. (A) Left leg is in straightening state while right is in support state. (B) Left leg is in support state while right is in swing state.

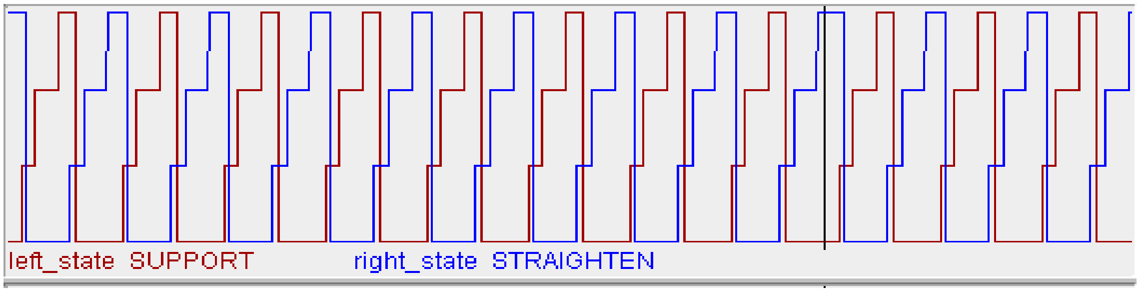


FIGURE 20: Plot of the state diagram when the robot is walking.

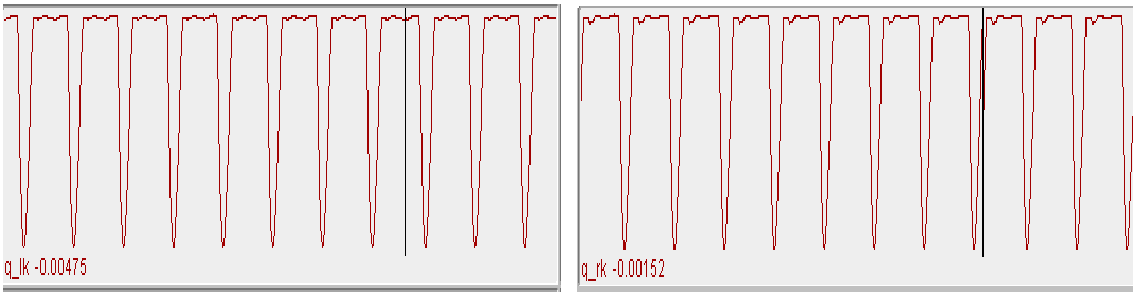


FIGURE 21: Angle (in radian) vs. Time (in ms) graph (a) for left knee and (b) for right knee.

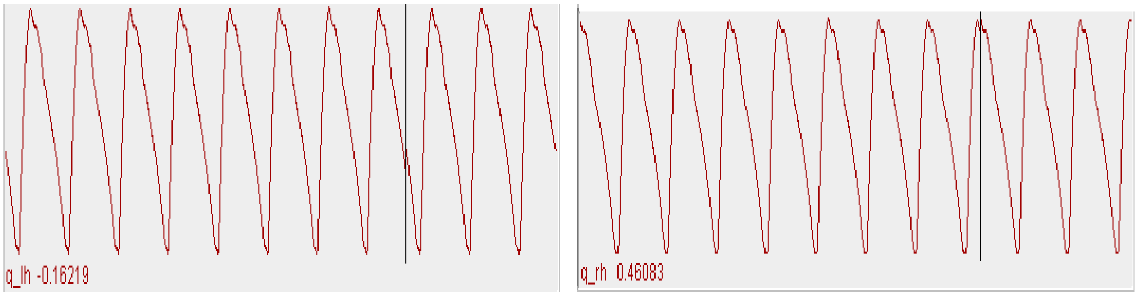


FIGURE 22: Angle (in radian) vs. Time (in ms) graph (a) for left hip and (b) for right hip.

Figure 21 (a), 21 (b), 22 (a), 22 (b) shows the different robot joint oscillations (e.g. left knee, right knee, left hip and right hip respectively) angle (in radian) vs. time (in ms) plot. All these four figures are extremely correlated with the actual human data captured by the IGOD suit [refer to Figure 4 and 5].

7. CONSLUSION & FUTURE WORK

In our entire research work we have shown the major contribution of Rayleigh oscillator for the modeling of the nonlinear based CPG controller for biped locomotion. This model involves only four joints in our research work. It allows us to measure the accurate gait pattern influenced by four joints. The application of CPG based model can be depicted on humanoid robot HOAP 2 (Humanoid Open Architecture Platform 2) to deal with 26 joints of full body oscillation. An exclusive CPG based controller can be designed to generate accurate gait pattern for biped oscillation of humanoid robot. A Sensory feedback control can be considered to deal with perturbation like wind slopes etc to give huge impact on nonlinear dynamical system. The sensory feedback control is pertaining with the extension of sensory inputs which are needed to deal with the environment in an interactive way.

It is a very complex task to generate rhythmic movement of bipedal robot. So a CPG based model has been constructed using Rayleigh oscillator inspired by biologically CPG based model. It gives us drawbacks which can be resolved by another technique called CPG based controller using MATSUOKA oscillator [6-8]. In this work we have considered only 4 major joints to simulate the gait oscillations but the inclusion of more other joints of human body indicates the construction of a robust nonlinear oscillator for generation of rhythmic pattern of bipedal robot. Despite of the simulation work presented on human gait oscillation we would suggest to use this nonlinear controller on real humanoid robot in the real environment.

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