

Implementation of CPG-based Locomotion Controller on Minimule Robot

Nimmy Paulose[†], P. Murali Krishna[‡], and Shubhi Purwar[†]

[†]Motilal Nehru National Institute of Technology, Allahabad, U.P., India

[‡]Centre for Artificial Intelligence and Robotics (DRDO), Bangalore, Karnataka, India

Abstract—Creating effective locomotion for legged robots is a very challenging task especially in an unknown environment (flat terrain or uneven terrain). Currently, most research works on locomotion control are focused on the trajectory based method. Here we are implementing a biologically inspired Central Pattern Generator (CPG) based controller for a quadruped Minimule robot. This local control system of quadruped animals is modeled through an artificial neural oscillator based structure. The robot was first modeled using MSC ADAMS and integrated with MATLAB for simulation. This paper deals with parameter modulation of the CPG network, the gait transition for the robot and environment adaptability through limit cycle stability. Various parameters for locomotion like frequency, velocity, and gait can be obtained just by changing a single parameter, the duty factor. The CPG based controlled Minimule robot can achieve both trot and walk gait and its transition by varying the phase relationship between the limbs and is stable due to the inherent property of CPG oscillator.

Keywords— Central Pattern Generator, Hopf oscillator, trot gait, stability.

NOMENCLATURE

ω	=	the frequency of the oscillation in units of rad/sec
x, y	=	are the oscillator's states
μ	=	square of the amplitude of oscillations in limit cycle
ω_{st}	=	the stance frequency
ω_{sw}	=	the swing frequency
T_{st}	=	the stance period
T_{sw}	=	the swing period
β	=	duty factor
i, j	=	is a subset of $\{LH, LF, RF, RH\}$
θ_j^i	=	is the required relative phase between i and j
$R(\theta_j^i)$	=	the rotation matrix
φ_i, φ_j	=	the relative phases
x_{oi}, y_{oi}	=	the coordinates of the tip of the limb for the i^{th} leg
x_{ti}	=	the x component of the trajectory for i^{th} leg about x_{oi}, y_{oi}
y_{ti}	=	the y component of the trajectory for i^{th} leg about x_{oi}, y_{oi}

x_{ij}	=	x_{oi}, y_{oi} the j^{th} oscillator of i^{th} leg
S	=	the stride length of the trajectory
H	=	is the displacement in the vertical direction
L_1, L_2	=	the length of the first link and the second link
θ_1, θ_2	=	the angle between the robot body and link 1, and the angle between link 1 and link 2
X, Y	=	the coordinates of the end-point
S_o	=	the outside stride length
S_i	=	the inside stride length
b	=	the breadth of the quadruped

I. INTRODUCTION

FOLLOWING the general trend of replacing manual work with robots, in military also, there is a requirement for a unmanned robot that can carry a certain payload and traverse any terrain. Though wheeled robot is easy to control, legged robots are preferred over wheeled robots due to their adaptability to unknown terrain. For this, animal locomotion has been extensively studied over the years by researchers from both robotics and biology fields. Studies of vertebrate locomotion, namely on the neural networks responsible for the locomotion have revealed that the coordinated, rhythmic motion of the body of vertebrates is not directly controlled by the brain but rather by specific neural networks that are situated along the spine. These networks, known as central pattern generators (CPGs), are formed by inter-connected oscillatory centers that generate bursts of rhythmic activity that control muscles, and whose coupling is essential for coordination of movements. CPGs present several properties, like distributed control and robustness against perturbations, which make mathematical models of CPGs very suitable for robot locomotion control.

Most of the researches for legged locomotion are based on trajectory-based method. The trajectories are predefined and the joint angles are calculated using inverse kinematics method in-order that it attains stability. Since the pre-defined trajectories are unchangeable, it is difficult to fit ground conditions. Although trajectories can be switched for different terrain, it cannot cover all the situations faced in an unknown environment.

It has been found that different forms of locomotion in animal life are characterized as rhythmic coordinated movement of limbs. However, the seemingly repetitive

movement is under continuous subtle adaptations in a real-time manner which makes it possible for the locomotion movement to be sustained in the presence of environments changes such as a slope or a rough terrain. Taking inspiration from this, a biologically inspired control technique was implemented for legged locomotion. This method involves Central Pattern Generators or CPGs.

The concept of CPG originated from the neurophysiologic studies of vertebrate animals. A CPG is a network of Neuron Oscillators that produces rhythmic oscillations without any rhythmic inputs. This biologically inspired control technique is well suited to control robots with multiple degrees of freedom as it can generate coupled control signals for all joints. In general, CPG is composed of many coupled oscillators which provide reference trajectories for the control. Therefore, this paper focuses on a bio-inspired approach of walking control by the modelling of local control system of quadruped animals through a neural network structure.

II. LITERATURE REVIEW

There are numerous publications on designing controllers for quadruped locomotion. They have long been focused on dynamic walking control as in [1]. The necessary conditions for dynamically stable walk is explained in previous researches ([2], and [3]). In [4], another control method using delayed feedback control has been discussed.

As many biological studies of motion control progressed, it has become generally accepted that animals' walking is mainly generated at the spinal cord by a combination of a CPG and reflexes receiving adjustment signals. The existence of CPG has been established in animals [5], and in vertebrates [6]. A great deal of the previous research on this attempted to generate walking using a neural system model, including studies on dynamic walking in simulation and real robots ([2], [3], [7]). The CPG control technique for locomotion [8] was explored in different robots taking inspiration from legged animals in nature like hexapod, quadruped and even human like bipeds ([9], [10], [11]).

The various neural oscillator models for CPG network is discussed in [12], [13], and [14], where different neuronal oscillators like Stein neuronal model, Vander Pol model etc., has been detailed. The implementation and coupling of CPG network has been discussed in [11], [12], [13], [15], [16], [17], and [18]. Various methods have been proposed to improve the gait implementation and transition ([7], [19]). Artificial Intelligence ([20], [4], [21], [22]) and optimisation techniques [23] has also been implemented for locomotion control.

Several improvements for the locomotion control of quadruped robots were proposed. In [18], a new CPG architecture that relies on Hopf oscillators is proposed that allows to independently control the duration of the ascending and descending phases of the oscillators (that correspond to swing and stance phases of the limbs). This approach was complemented in [24], in which sensory feedback was introduced to accelerate the transitions between the two phases

when limbs touch and lift of the ground. The ability to control the duration of the locomotion phases together with the possibility to perform transitions allows a correct identification of swing and stance phases. This has been proven to increase performance concerning robot speed and controller robustness to incorrect control parameters choice. One of the most relevant disadvantages of this work is the fact that the limbs of the quadruped robots for which it was designed move back and forth, instead of rotating around an axis.

Central Pattern Generators (CPGs) have in the past years been a growing subject when talking about control systems for walking, running, crawling and swimming robots. The ability to be stable, adaptive and not require many parameters and input signals in order to produce motor control signals for e.g. a walking gait of a quadruped is normally hard to combine into a control system. In the past few years, many studies and projects have shown that CPGs hold the secret to such controllers, and that the area of CPGs controllers has not been fully discovered yet. The foundation of this work is the idea of using a CPG-based controller to generate different gaits for a quadruped robot.

III. CENTRAL PATTERN GENERATORS

The controller used in this paper is based on a biologically inspired technique of CPG. The CPG found in the vertebrates are made of neural oscillators. Thus if we want to simulate a CPG, we first have to simulate one of these neural oscillators. One approach could be to build a model as close as possible to the behaviour of the real neurons. The real neurons have very complex behaviours and are far from being fully understood by the biologists. Second, such a model would be pretty complicated and therefore it would be difficult to embed it on a real robot. So, the model used in this project is a simple Hopf oscillator.

A. Oscillator Model

The Hopf oscillator is an example of a dynamical system that possesses limit cycle stability and such properties as its solutions converge to a closed curve centred in the origin of the phase space with constant radius. Its x and y variables thus exhibit a sine behaviour in steady state. The standard Hopf oscillator is governed by the following set of differential equations

$$\dot{x} = (\mu - r^2)x + \omega y \quad (1)$$

$$\dot{y} = (\mu - r^2)y - \omega x \quad (2)$$

where

$$r = \sqrt{x^2 + y^2} \quad (3)$$

The oscillator has a stable limit cycle defined by the constant value μ and the system exhibits Hopf bifurcation at $\mu = 0$. A Hopf oscillator has stability against perturbations. This is due to the limit cycle being an attractor acting against the perturbation. The limit cycle of this system consists of stable periodic solutions of x and y of the form

$$\begin{cases} \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{cases} \begin{bmatrix} 0 \\ 0 \end{bmatrix}, & \mu < 0 \\ \begin{bmatrix} \sqrt{\mu} \cos(\omega t) \\ \sqrt{\mu} \sin(\omega t) \end{bmatrix}, & \mu > 0 \end{cases} \end{cases} \quad (4)$$

B. Frequency Transformation

As mentioned earlier the amplitude of the oscillation is given by $\sqrt{\mu}$. The condition $\mu > 0$ should be satisfied for limit cycle behaviour. The frequency of oscillations is given by

$$\omega = \frac{1}{2\mu} \quad (5)$$

The oscillator described by (1), (2), and (3) generates an x oscillatory trajectory in which the ascending and descending parts have equal durations. In order to achieve an independent control of the duration of these parts, we employ the following equation proposed by [24],

$$\omega = \frac{\omega_{st}}{e^{-az_{i+1}}} + \frac{\omega_{sw}}{e^{az_{i+1}}} \quad (6)$$

where ω alternates between ω_{st} and ω_{sw} , depending on z and a is the rate at which it changes the frequency.

By controlling the durations of the ascending and descending phases of the x trajectory, we are controlling the durations of the swing and stance step phases, respectively by setting the following,

$$\omega_{sw} = \pi/T_{sw} \quad (7)$$

$$\omega_{st} = \pi/T_{st} \quad (8)$$

It is thus possible to generate gaits with a desired duty factor, β , by keeping the swing frequency constant and specifying the stance frequency according to the duty factor value as follows

$$\omega_{st} = \frac{1-\beta}{\beta} \omega_{sw} \quad (9)$$

The relative phase for each leg is given by where β is the duty factor which controls the gait, for trot β is 0.5 and 0.75 for walk.

C. CPG Coupling and Network

The basic CPG network consists of an oscillator for each leg. The coupling between these units determines the relative phase between the legs or the gait.

The coupling between the CPG units are given by

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \end{bmatrix} = \begin{bmatrix} \alpha(\mu_i - r_i^2) & -\omega \\ \omega & \alpha(\mu_i - r_i^2) \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} + \sum_{j \neq i} R(\theta_i^j) \begin{bmatrix} x_j \\ y_j \end{bmatrix} \quad (10)$$

where

$$R(\theta) = R^{-1}(-\theta) \quad (11)$$

$$\theta_i^j = (\varphi_i - \varphi_j) \cdot 2\pi \quad (12)$$

D. Trajectory Generation

Another set of oscillators per leg in addition to the basic set are defined which has 90° phase difference with the basic set. The trajectory of each leg will be derived from these two oscillator outputs by the equations:

$$x_{ti} = x_{oi} - S \cdot x_{i1} \quad (13)$$

$$y_{ti} = y_{oi} + H \cdot x_{i2} \quad (14)$$

Once the trajectories are obtained, the locomotion can be obtained by mapping the oscillations to the joint angles.

E. Mapping of Angles

Two-joint robotic arm is as shown in **Figure 1**. Given the angles of the joints, the kinematics equations give the location of the tip of the arm, this is called forward kinematics. Given a desired location for the tip of the robotic arm, the angles of the joints can be calculated so as to locate the tip of the arm at the desired location. Since it has multiple solutions it is a difficult problem to solve. So we reduce the problem to just finding the two angles involved. The first angle is between the first arm and the reference plane. The second angle is between the first arm and the second arm.

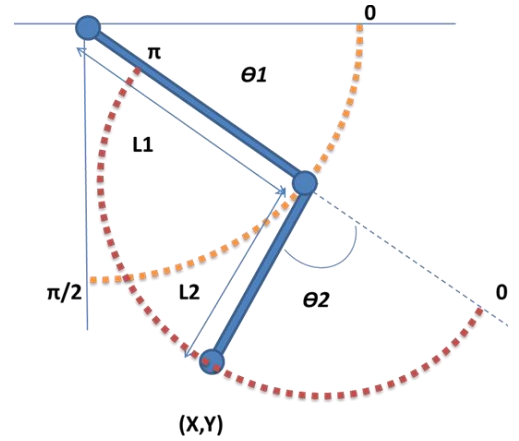


Figure 1 Illustration showing the two-joint robotic limb with the two angles, θ_1 and θ_2

The forward kinematics equation gives the end-point coordinates in terms of the angles. They are

$$x = L_1 \cdot \cos(\theta_1) + L_2 \cdot \cos(\theta_1 + \theta_2) \quad (15)$$

$$y = L_1 \cdot \sin(\theta_1) + L_2 \cdot \sin(\theta_1 + \theta_2) \quad (16)$$

Computing the angles from the coordinates poses a bigger challenge, hence we use intelligent methods [25] for mapping. Here a neural network to map the angles to the x - y coordinates.

For the data generation for the neural network, we assume that the first joint has limited freedom to rotate and it can rotate between 0° and 90° . Similarly, assume that the second joint has limited freedom to rotate and can rotate between 0° and 180° . Hence,

$$0 \leq \theta_1 \leq \pi/2 \quad (17)$$

$$0 \leq \theta_2 \leq \pi \quad (18)$$

Once the data-set is obtained using forward kinematics, two separate networks for the hip angle θ_1 and knee angle θ_2 are created. Each network has two inputs for x and y coordinates, one output of the angle, a hidden layer with ten neurons, and an output layer with one neuron. The next step is to train the network with the data-set obtained from forward kinematics.

F. Turning along a curve

The quadruped can turn at various radius of curvature. The direction can be specified through the interface. According to the direction, the inside and outside stride lengths are calculated to get the desired radius of curvature.

$$\begin{aligned} S_o &= S \cdot \left(1 + \frac{b}{(2 \cdot \text{radius})}\right) \\ S_i &= S \cdot \left(1 - \frac{b}{(2 \cdot \text{radius})}\right) \end{aligned} \quad (19)$$

IV. SIMULATION AND RESULTS

A. Phase Entrainment

The oscillations of two Hopf oscillators are shown in **Figure 2** to **Figure 5** for various phase difference between them. The Hopf oscillations for $\beta = 0.5$ and $\omega_{st} = 2\pi$ and for various φ (phase difference between the oscillations) are given below,

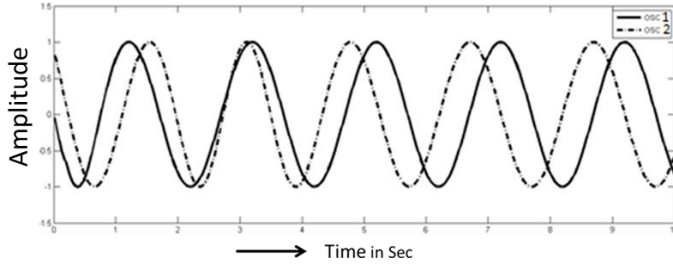


Figure 2 Oscillator output for $\varphi = \pi/2$

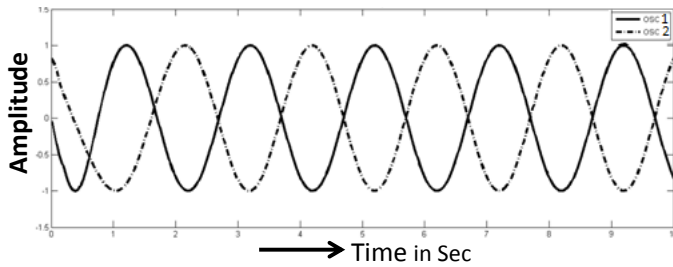


Figure 3 Oscillator output for $\varphi = \pi$

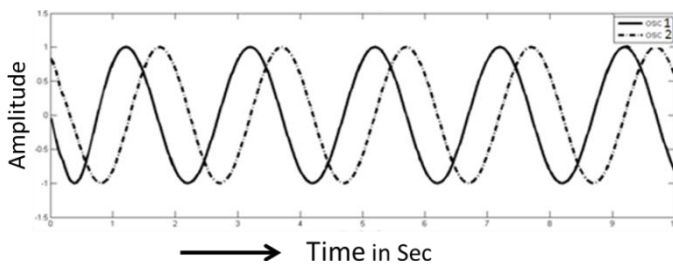


Figure 4 Oscillator output for $\varphi = 3\pi/2$

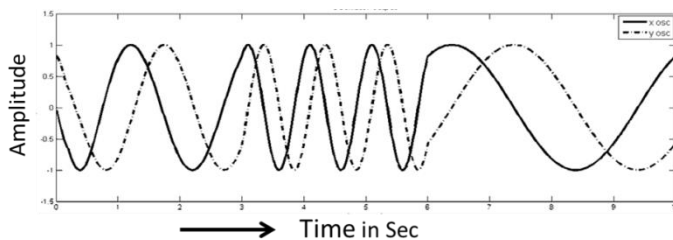


Figure 5 Smooth transition for frequency modulation

The frequency of the oscillations can be varied by varying ω_{st} that in turn will vary the overall frequency. Figure 5 shows the frequency modulation when ω_{st} changes from π to 2π at $t = 3$ sec, and 2π to $\pi/2$ at $t = 6$ sec.

The importance of smooth frequency modulation is that we can change the velocity of the robot by varying the frequency. Faster stepping means faster movement.

B. Effect of Duty Cycle

By varying the duty cycle we can change the ratio of the swing and stance phase. This is shown in **Figure 6** and **Figure 7** in the following illustrations.

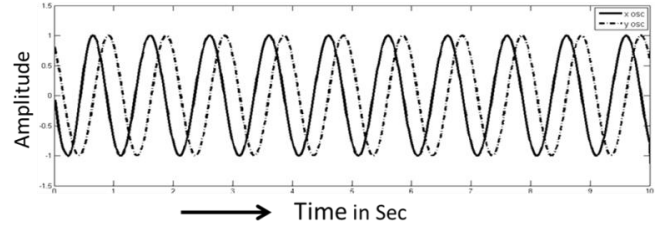


Figure 6 Oscillations for $\beta = 0.5$ showing equal swing and the stance phase

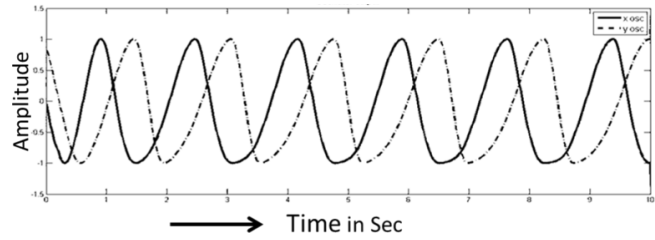


Figure 7 Oscillations for $\beta = 0.75$ showing longer swing phase than the stance phase

Controlling the duty cycle ratio is another way of varying the velocity of the robot. By decreasing the stance phase, the leg is in touch with the ground for a less time. Hence, more speed is gained. The figures clearly show the difference in the swing and stance period in $\beta = 0.75$ (**Figure 7**), while in $\beta = 0.5$ (**Figure 6**) the swing and stance phases are equal.

C. Entrainment of Limit Cycle

The effect of perturbations is shown in **Figure 8** by the abrupt change in oscillations with the occurrence of perturbations. After a while, the oscillations show entrainment which proves the limit cycle stability of the oscillations. These are shown in **Figure 9** and **Figure 10**.

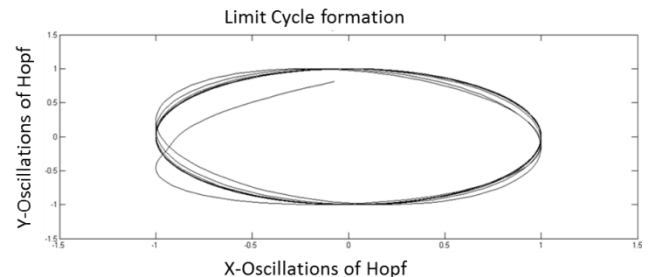


Figure 8 Limit cycle formation by the two states of the Hopf oscillator which results in sustained oscillations

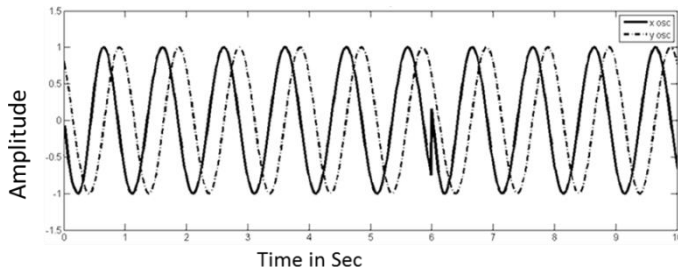


Figure 9 The oscillations show stability against perturbations which is equivalent to phase change occurring while an obstacle is encountered.

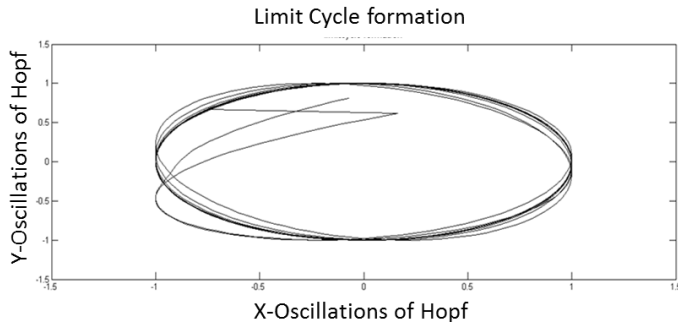


Figure 10 The limit cycle stability against perturbations

D. Hardware Implementation

The quadruped has a PIC 30f4011 Microcontroller as its main control. The actuators are Dynamixel RX64, connected with daisy chain and supports RS485. The power supply is a 14.4 V, 5.8 A-h battery. The robot was controlled real time using RS485 connector.

A user interface was developed using Microsoft Visual C# 2010. From the interface, one can vary the duty cycle β gradually within interval 0.5-0.75, and the gait switches from trot to walk smoothly.

The beta is varied from 0.5 to 0.75. The gait changes from trot to walk as beta varies, which is shown by the relative phase between the joint angles in Figure 12 and Figure 13. As seen in the figures, the phase transition from trot to walk occurs smoothly. The results were obtained by integrating MSC ADAMS software and MATLAB Simulink. The angles from the 3-D model were plotted in ADAMS Post-Processor.

Figure 14 and **Figure 15** show the clippings from the video of the quadruped robot. The gait transition from walk gait to trot gait and back (Trot gait to walk gait) and the turning gait was successfully implemented in the hardware.

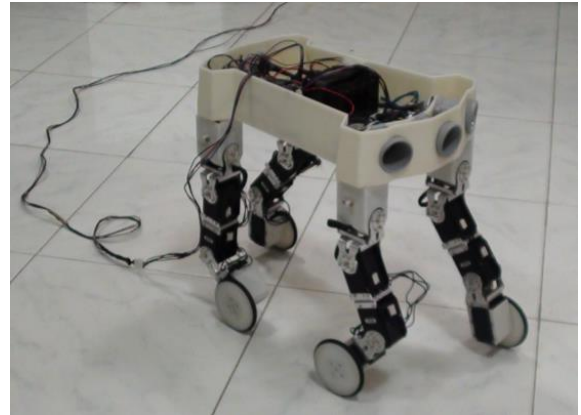


Figure 11 Minimule robot with CPG based controller

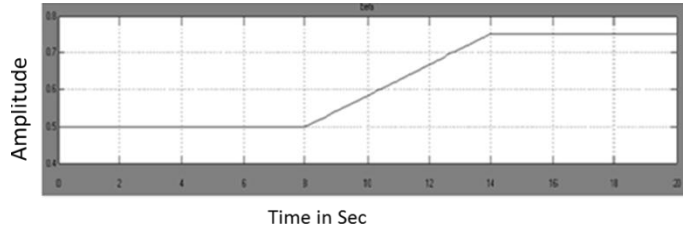


Figure 12 Joint angle J1 for the quadruped showing variation with beta

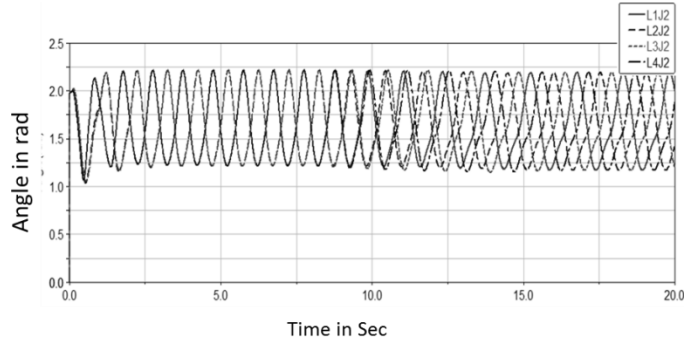


Figure 13 Joint angle J1 for the quadruped showing variation with beta

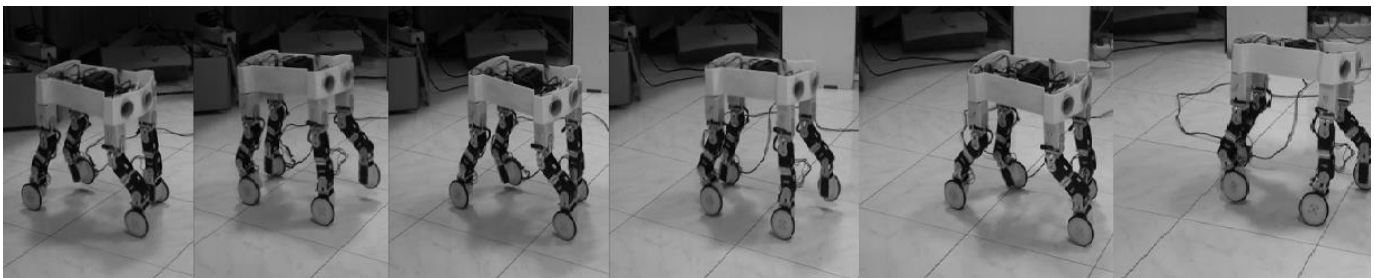


Figure 14 Quadruped trotting on a straight path

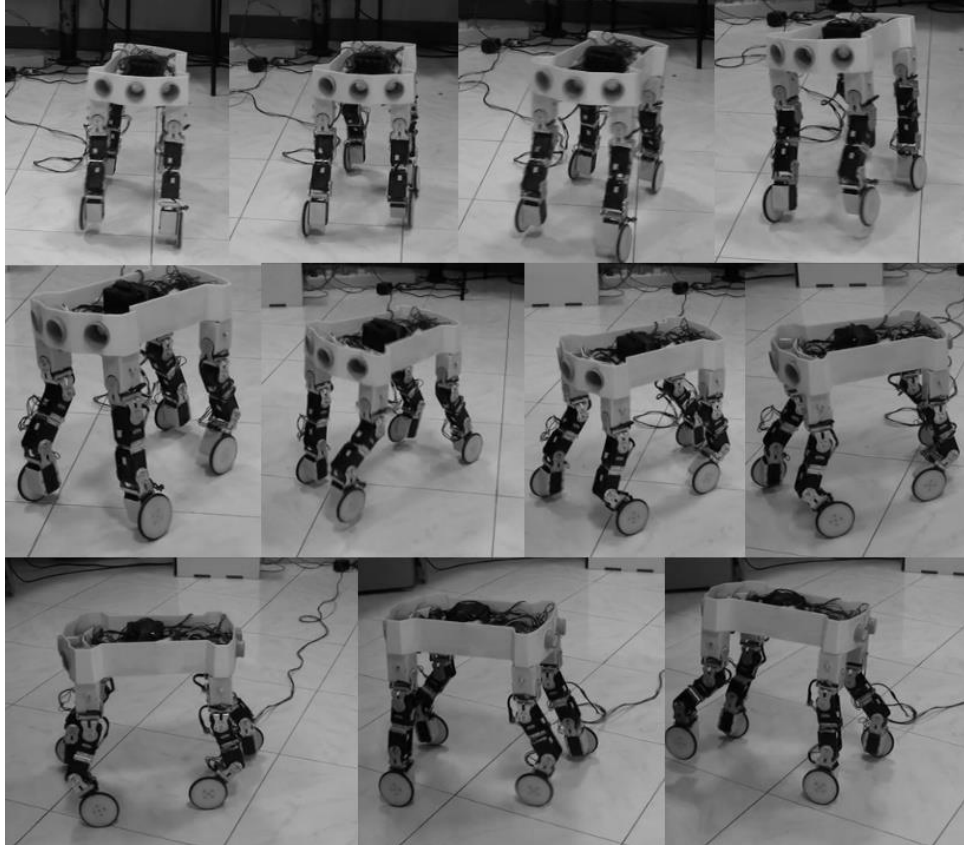


Figure 15 Quadruped turning with a radius of curvature 0.5 m while in trot

V. CONCLUSION

In this contribution, we have presented a way of designing a CPG based controller for a quadruped robot. An oscillator was designed for locomotion control in which we can independently control the duration of swing and stance phases. The network architecture of the CPG was designed using dynamical system theory in a simple and scalable manner. The Central Pattern Generator - based controller was simulated and successfully implemented on hardware. The results show the smooth transition of the gaits from walk to trot depending on a single parameter. Furthermore, the frequency and amplitude can also be modulated. The oscillators exhibit limit cycle behaviour and therefore inherently reject disturbances. The present model does not have sensors or feedback for simplicity; it is an open loop controller. The CPG-based controller was successfully implemented in hardware. The robot has inherent stability due to the limit cycles. Combined with symmetrical gaits, it is enough for locomotion over flat terrain.

VI. FUTURE SCOPE

For adaptability over rough terrain, sensory feedback must be included for sensing the irregularities in the environment and balance the robot accordingly. Including a third degree of freedom will improve the flexibility and adaptability of the robot.

To improve the locomotion of the quadruped various parameters like attainable velocity, energy efficiency can be optimised using evolutionary algorithms and heuristic methods like Genetic Algorithms, etc.

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REFERENCES

- [1] L. Righetti and A. J. Ijspeert, "Design methodologies for central pattern generators: an application to crawling humanoids," in *Proceedings of Robotics: Science and Systems*, pp. 191-198, 2006.
- [2] G. Bard Ermentrout, Carson C. Chow, "Modeling neural oscillations", *Physiology & Behavior* 77 (2002) 629– 633. [CrossRef](#)
- [3] Yasuhiro Fukuoka, Hiroshi Kimura, Avis H. Cohen, "Adaptive Dynamic Walking of a Quadruped Robot on Irregular Terrain Based on Biological Concepts", *The International Journal of Robotics Research* Vol. 22, No. 3–4, March–April 2003, pp. 187-202. [CrossRef](#)
- [4] Gen Endo, Jun Nakanishi, Jun Morimoto , and Gordon Cheng, "Experimental Studies of a Neural Oscillator for Biped Locomotion with QRIO", *Proceedings of the 2005 IEEE International Conference on Robotics and Automation Barcelona, Spain, April 2005*. [CrossRef](#)

- [5] Marilyn MacKay-Lyons, "Central Pattern Generation of Locomotion: A Review of Evidence" *Physical Therapy*. Volume 82. Number 1. January 2002.
- [6] Sten Grillner, Peter Wallén, Kazuya Saitoh, Alexander Kozlov, Brita Robertson, "Neural bases of goal-directed locomotion in vertebrates — An overview", *Brain Research Review* S57(2008)2–12. [CrossRef](#)
- [7] Chengju Liu, Yifei Chen, Jiaqi Zhang, Qijun Chen, "CPG Driven Locomotion Control of Quadruped Robot", *Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics San Antonio, TX, USA - October 2009*. [CrossRef](#)
- [8] Zu Guang Zhang, Hiroshi Kimura and Yasuhiro Fukuoka, "Autonomously generating efficient running of a quadruped robot using delayed feedback control", *Advanced Robotics*, Vol. 20, No. 6, pp. 607–629 (2006). [CrossRef](#)
- [9] Kazuki Nakada, Tetsuya Asai, and Yoshihito Amemiya, "Design of an artificial central pattern generator with feedback controller", *Intelligent Automation and Soft Computing*, Vol. 10, No. 2, pp. 185-192, 2004. [CrossRef](#)
- [10] R. Jacob Vogelstein, Francesco Tenore, Ralph Etienne-Cummings, M. Anthony Lewis, Avis H. Cohen, "Dynamic control of the central pattern generator for locomotion", *Biological Cybernetics*, 95:555–566, 2006. [CrossRef](#)
- [11] Lei Sun, Max Q.-H. Meng, Wanming Chen, Huawei Liang, Tao Mei, "Design of Quadruped Robot Based CPG and Fuzzy Neural Network", *Proceedings of the IEEE International Conference on Automation and Logistics August 18 - 21, 2007, Jinan, China*.
- [12] J.J. Collins, S.A. Richmond, "Hard-wired central pattern generators for quadruped locomotion", *Biological Cybernetics* 71, 375-385, Springer-Verlag 1994.
- [13] Hiroshi Kimura, Kazuaki Sakurama and Seiichi Akiyama, "Dynamic Walking and Running of the Quadruped Using Neural Oscillator", *Proceedings of the 1998 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems Victoria, B.C., Canada October 1998*.
- [14] Pietro-Luciano Buono, Martin Golubitsky, "Models of central pattern generators for quadruped locomotion", *J. Math. Biol.* 42, 291–326, 2001. [CrossRef](#)
- [15] Duane W. Marhefka, David E. Orin, James P. Schmiedeler, and Kenneth J. Waldron, "Intelligent Control of Quadruped Gallops", *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 4, December 2003. [CrossRef](#)
- [16] Liu, G. L., Habib, M. K., Watanabe, K., and Izumi, K. "The Design of Central Pattern Generators Based on the Matsuoka Oscillator to Generate Rhythmic Human-Like Movement for Biped Robots", *Journal of Advanced Computational Intelligence and Intelligent Informatics* Vol.11 No.8, 2007.
- [17] Duc Trong Tran, Ig Moo Koo, Gia Loc Vo, Se-gon Roh, Sangdeok Park, Hyungpil Moon, and Hyouk Ryeol Choi, "A new method in modeling Central Pattern Generators to control quadruped walking robots", *The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems October 11-15, 2009 St. Louis, USA*.
- [18] L. Righetti and A. J. Ijspeert, "Pattern generators with sensory feedback for the control of quadruped locomotion," *Proceedings of the 2008 IEEE International Conference on Robotics and Automation (ICRA 2008)*, vol. 26, pp. 819{824, May 19-23, 2008.
- [19] Vitor Matos, Cristina P. Santos, "Omnidirectional Locomotion in a Quadruped Robot: A CPG-based Approach", *The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems October 18-22, 2010, Taipei, Taiwan*.
- [20] Hiroshi Kimura, Yasuhiro Fukuoka and Avis H. Cohen, "Adaptive Dynamic Walking of a Quadruped Robot on Natural Ground Based on Biological Concepts", *International Journal of Robotics Research*, vol.26, 2007.
- [21] Sahin Yildirim, "Four legged walking robot control using neural networks", *Journal of Scientific & Industrial Research*, Vol.65, November 2006, pp-887-893.
- [22] Pablo Gonzalez de Santos, Elena Garcia and Joaquin Estremera, "Quadrupedal Locomotion An Introduction to the Control of Four-legged Robots", *Springer-Verlag London Limited 2006, ISBN-13: 9781846283062*.
- [23] Cristina P. Santos, Vitor Matos, "Gait transition and modulation in a quadruped robot: A brainstem-like modulation approach", *Robotics and Autonomous Systems* 59, 2011 [CrossRef](#)
- [24] RobotsCarla M.A. Pinto, Cristina P. Santos, Diana Rocha, Vitor Matos, "New Developments on Online Generation of Trajectories in Quadruped", *Journal of Numerical Analysis, Industrial and Applied Mathematics (JNAIAM)* vol. 7, no. 1-2, 2012, pp. 39-57.
- [25] Jonathan Wright, Ivan Jordanov, "Intelligent Approaches in Locomotion", *WCCI 2012 IEEE World Congress on Computational Intelligence June, 10-15, 2012 - Brisbane, Australia*.