Development of quadruped walking locomotion gait generator using a hybrid method

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Development of quadruped walking locomotion gait generator using a hybrid method

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Abstract. The earth, in many areas is hardly reachable by the wheeled or tracked locomotion system. Thus, walking locomotion system is becoming a favourite option for mobile robot these days. This is because of the ability of walking locomotion to move on the rugged and unlevel terrains. However, to develop a walking locomotion gait for a robot is not a simple task. Central Pattern Generator (CPGs) method is a biological inspired method that is introduced as a method to develop the gait for the walking robot recently to tackle the issue faced by the conventional method of pre-designed trajectory based method. However, research shows that even the CPG method do have some limitations. Thus, in this paper, a hybrid method that combines CPG and the pre-designed trajectory based method is introduced to develop a walking gait for quadruped walking robot. The 3-D foot trajectories and the joint angle trajectories developed using the proposed method are compared with the data obtained via the conventional method of pre-designed trajectory to confirm the performance.

1. Introduction

The walking locomotion has become a favorable option in designing the mobile robot's locomotion system as its advantage that enable the robot to explore a wider area than the wheeled and tracked locomotion system can offer. However, the control architecture for the walking locomotion is not as simple as the wheeled locomotion able can offer.

The most common method utilized in designing the walking locomotion for robot is called the pre-designed trajectory based method; the trajectories of the robot are first designed and inverse kinematics are used to obtain the joint angles. This method requires the developer to acquire as much information as possible on the nature of the terrain as the design of the trajectory is closely related to that information. Work in [1], [2] and [3] adopting the pre-designed trajectory method in their design. The disadvantage of this method is the control mechanism become very complicated when the number of legs increases as each leg will need separate analysis and calculation. Furthermore, this method is no longer efficient if the ground condition changes since the trajectories need to be re-designed. Thus, a better approach is needed to tackle the problem of robots walking in unknown terrains.

In order to compensate the limitations that the pre-designed trajectory method has the biological inspired, CPG method is introduced. Central Pattern Generator (CPG) is described as a set of neural networks that can continuously produce rhythmic patterned signals without input from the rhythmic sensory system or the central control system (i.e. the brain) [4]. Ijspeert [5] reviewed in his paper that the implementation of CPG in robotics is categorized into three types; the connectionist model [6], the vector map and the systems of coupled oscillators [7]. However, most of research work utilized the concept of coupled oscillators to form a CPG network in the CPG design for locomotion control in robotics. Generally, the implementations of CPG in robotics locomotion control involve sets of coupled differential equations that are numerically integrated on a microcontroller or microprocessor. The coupled oscillators generate a rhythmic signal that is processed and analyzed as the joint trajectories (i.e. the joint angle). The output signals from the CPG network are usually modified using common mathematical transformation method such as Fourier transform before analyzed as the joint trajectories. There are generally two types of oscillator that are used in forming the CPG network; the neural oscillators such as the Matsuoka model [8] and Wilson-Cowan Weakly Neural Networks [9] and the non-linear oscillators, for instance the Hopf oscillator [10], and the Van Der Pol (VDP) oscillator [11]. However, this approach requires at least one oscillator to be assigned at respective joint so that the oscillator's output can generate the joint angle trajectory for the joint. As a result, with complex oscillators network will be needed and the modelling the coupled oscillators will become tedious especially when the robot consists of large number of joints.

A better method is required to balance the deficiency that both approaches carry individually, Liu, Chen and Wang has proposed a method that combines the methods [12]. The hybrid method suggests that the CPG network is used to generate the foot trajectories for the robot via a mapping process, instead of directly generate the joint angle trajectory for the joints. As a result, only one oscillator is needed to represent one foot that simplifies the modelling and analysis. Then the foot trajectories obtained via the CPG network are utilized to generate the joint angle trajectories of each joint available in a leg using the forward and inverse kinematics analysis. In this paper, the same basic method is implemented, however, different oscillator's model is used that is the Van Der Pol oscillators and since different hardware platform is used (i.e. Bioloid Premium Quadruped Robot shown in Figure 1), the forward and inverse kinematics is dissimilar from [12].

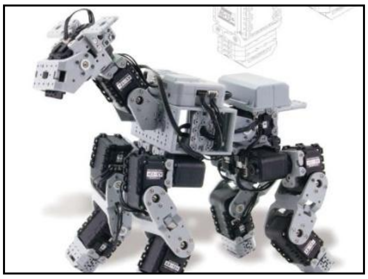


Figure 1: The Bioloid Puppy Robot

2. Walking gait locomotion gait generator using hybrid method

The method implemented in this paper is the hybrid method that combines the conventional pre-designed trajectory method and the biological inspired method, CPG. Basically, CPG is utilized in generating the foot trajectory of the robot. Instead of having to design the foot trajectory and for each leg by ourselves, the CPG signals are used to generate the trajectories and the trajectories can be easily modified by only modulating the CPG parameters. Thus, the locomotion gait generator is made to be more adaptable to any changes on the terrain condition.

The suitable CPG signals that describe the gait are then mapped onto a set of mapping function to obtain the 3D (x, y, and z direction) foot trajectories. Based on the 3D foot trajectories gained, the forward and inverse kinematics is performed to generate the joint angle trajectories for each leg. The set of joint angle for all 4 legs are fed to the robot control to make it move. The methodology is illustrated in the flowchart in Figure 2.

2.1. VDP-CPG network modelling

In this paper, the CPG network is developed using 4 VDP oscillators. The VDP oscillator is chosen for its stable limit cycle feature. Furthermore, this type of oscillator is used in representing most of the biological system.

1 oscillator is allocated for 1 leg to generate the rhythmic movement for each leg. Then the output signal of each oscillator is coupled with the signal from other oscillators. The network is illustrated in Figure 3.

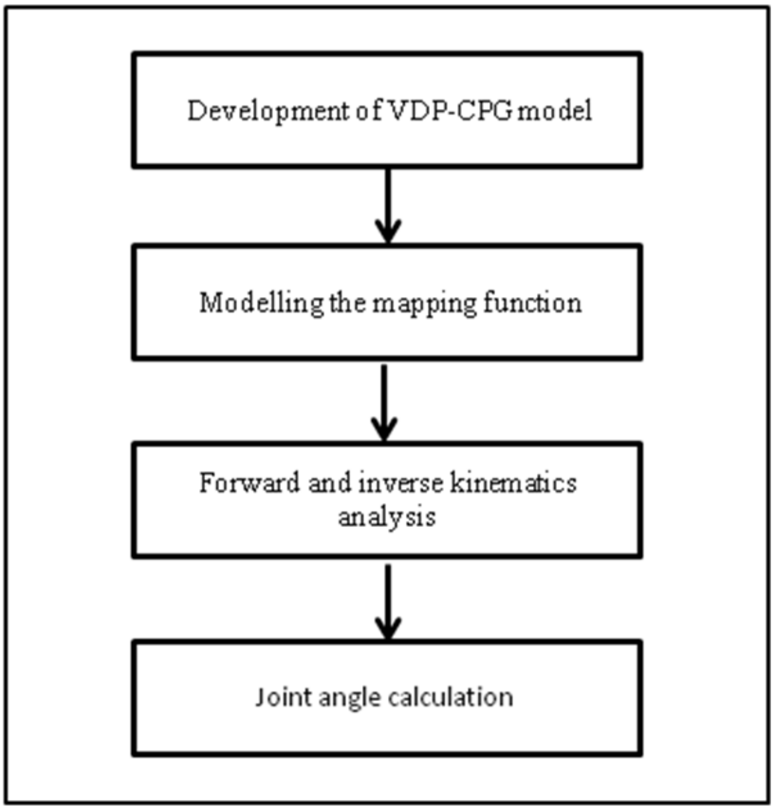


Figure 2: Flowchart of the design methodology

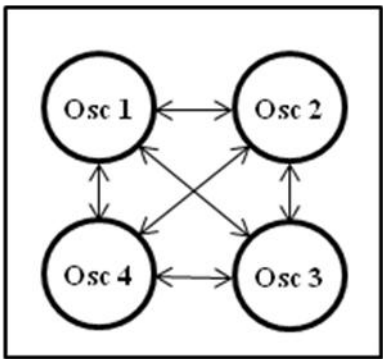


Figure 3: The CPG network

The general expression to describe the relationship between each coupled oscillator is described as below [13]:

$$\ddot{x}_i = \mu_i(p_i^2 - x_{ai}^2)\dot{x}_i - g_i^2 x_{ai} + q_i \quad (1)$$

where x_i represents the output of the oscillator i, μ_i generally responsible in shaping the shape of the signal, p_i^2 is the constant that modulates the amplitude of the signal, while g^2 modulates the frequency of the wave and finally q as the offset parameter. x_{ai} represents the expression that described the relationship between the oscillators and it is expression in (2):

$$x_{ai} = x_i + \sum \lambda_{i,j} x_j \quad (2)$$

where $\lambda_{i,j}$ is the relationship coefficient between oscillator i and j. Substituting (2) in (1), the general expression becomes:

$$\ddot{x}_i = \mu_i \left(p_i^2 - \left(x_i + \sum \lambda_{i,j} x_j\right)^2\right)\dot{x}_i - g_i^2\left(x_i + \sum \lambda_{i,j} x_j\right) + q_i \quad (3)$$

In CPG, one of the most important and challenging task is to make sure that the parameters setting are precise to produce the rhythmic output that is desired. In this research work, the parameters are determined via trial and error, and through the experiments that have been conducted, the parameters are set to be; $p_i^{\,2}= 1$, $q_i = 0.12$, $g_i^{\,2} = 0.15$ and $\mu_i = 0.1$. Among all 5 parameters, $\lambda_{i,j}$ is found to be the most important since that parameter will determine how one signal of one oscillator relates to the other. The relationship coefficients are set to be:

$$\omega = \begin{bmatrix} \lambda_{1,1} & \lambda_{1,2} & \lambda_{1,3} & \lambda_{1,4} \\ \lambda_{2,1} & \lambda_{2,2} & \lambda_{2,3} & \lambda_{2,4} \\ \lambda_{3,1} & \lambda_{3,2} & \lambda_{3,3} & \lambda_{3,4} \\ \lambda_{4,1} & \lambda_{4,2} & \lambda_{4,3} & \lambda_{4,4} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -0.3 & 0 \\ 0 & 0 & 0 & -0.3 \\ 0 & -0.3 & 0 & 0 \\ -0.3 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

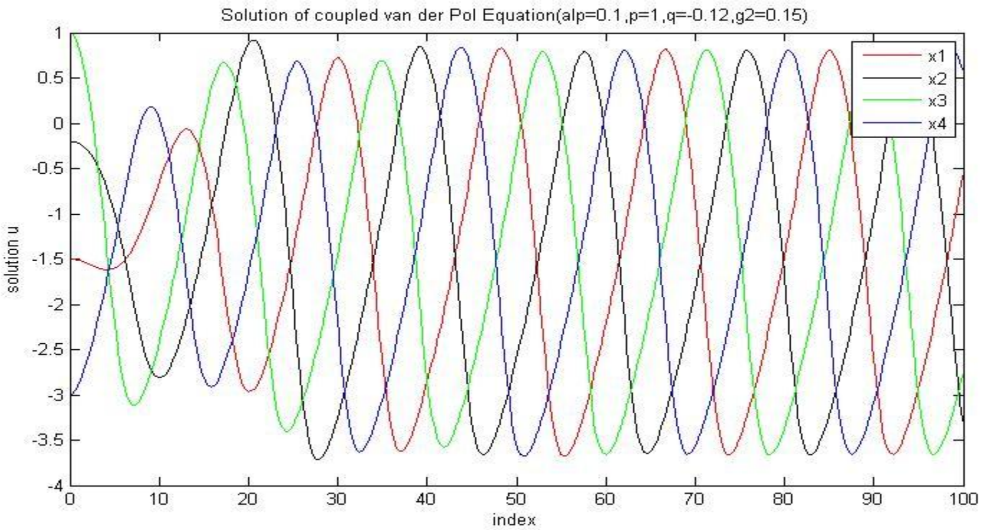


Figure 4: The output signal of VDP-CPG network model used

2.2. *Mapping function modelling*

The output signal from the VDP-CPG network is mapped onto a set of function to generate the 3D foot trajectories. The trajectories formed through this process are with respect to the ground coordinate which will be addressed as locus trajectories in this paper. Figure 5 shows the ground based coordinate assignation for the robot.

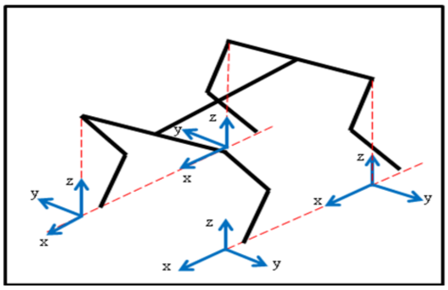


Figure 5: Ground based coordinate assignation

The foot trajectories can be divided into 2 phases; the swing phase (the foot is lifted) and the stance phase (the foot is on the ground). Therefore, the mapping function is modelled based on the requirement that satisfies both phases. Figure 6 and 7 illustrates the foot trajectories for swing and stance phase respectively.

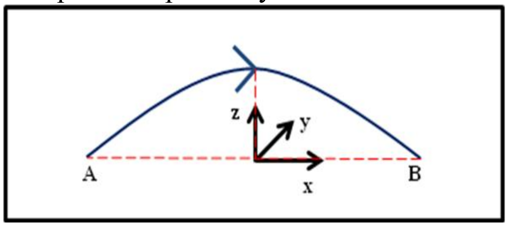


Figure 6: Foot trajectory for swing phase

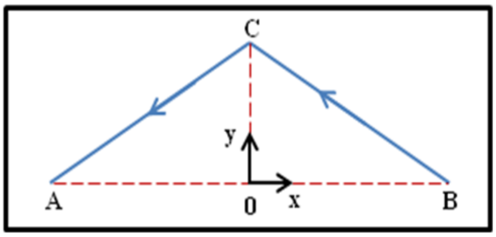


Figure 7: Foot trajectory for stance phase

The mapping function for the swing phase [14] is defined as:

$$x_{locus}(i) = K_x.\left(t_{sw(index)}(i) - \frac{T_{sw}(i)}{2}\right) \tag{5}$$

$$y_{locus}(i) = 0 \tag{6}$$

$$z_{locus}(i) = K_z.(X_{index}(i)) \tag{7}$$

On the other hand, the mapping function for the stance phase is described as:

$$x_{locus}(i) = K_x.\left(\frac{1}{2} - \frac{t_{st(index)}(i)}{T_{st}}\right) \tag{8}$$

$$y_{locus}(i) = \left(-\frac{2\gamma}{K_x}x_{locus}(i) + \gamma\right) \quad \text{for xlocus(i) >= 0} \tag{9}$$

$$y_{locus}(i) = \left(\frac{2\gamma}{K_x}x_{locus}(i) + \gamma\right) \quad \text{for xlocus(i) < 0} \tag{10}$$

$$z_{locus}(i) = 0 \tag{11}$$

i represents the leg number, K_x and K_z represents the gain coefficient for x and z direction respectively. $t_{sw(index)}(i)$ and $t_{st(index)}(i)$ represents the current swing and stance time respectively whereas T_{sw} and T_{st} represents the total time of swing phase and stance phase respectively. $X_{index}(i)$ is the output signal from the CPG. Finally γ is the compensatory variable that relates x-trajectory and y-trajectory.

Since the foot trajectories that are obtained so far are based on the ground coordinate, thus, a transformation is needed to generate the trajectories based on the hip coordinate (root trajectories). This is important because the trajectories w.r.t hip coordinate is needed to perform inverse kinematics in the next process to generate the set of joint angles. Thus, the transformation matrix is described below:

$$\begin{pmatrix} x_{root} \\ y_{root} \\ z_{root} \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -z\_dist \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_{locus} \\ y_{locus} \\ z_{locus} \\ 1 \end{pmatrix} \tag{12}$$

2.3. Forward and inverse kinematics analysis

Before inverse kinematics analysis can be performed, the set of transformation matrix that the foot encountered need to be determined first. The root trajectories can be defined as:

$$\begin{pmatrix} x_{root} \\ y_{root} \\ z_{root} \\ 1 \end{pmatrix} = {}^{H}T_F \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \tag{13}$$

in which ${}^{H}T_F$ is the series of movement that the foot has made and the original position is assumed to be at homogenous coordinate *(0,0,0)*. Taking Leg 1(Front left leg) as sample, the ${}^{H}T_F$ for Leg 1 can be described as:

$$({}^{H}T_F)_{leg1} = \begin{bmatrix} C_1C_3 + S_1(C_2S_3) & S_1S_2 & C_1S_3 - S_1C_2C_3 & S_1C_2(L_2C_3 + L_1) - L_2S_3C_1 \\ -S_2S_3 & C_2 & S_2C_3 & -S_2(L_2C_3 + L_1) \\ S_1C_3 - C_1C_2S_3 & -C_1S_2 & S_1S_3 + C_1C_2C_3 & -L_2S_1S_3 - C_1C_2(L_2C_3 + L_1) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

Inserting (14) into (13), the root trajectories for Leg 1 is expressed as:

$$\begin{pmatrix} x_{root} \\ y_{root} \\ z_{root} \\ 1 \end{pmatrix}_{leg1} = \begin{pmatrix} S_1C_2(L_2C_3 + L_1) - L_2S_3C_1 \\ -S_2(L_2C_3 + L_1) \\ -L_2S_3S_1 - C_1C_2(L_2C_3 + L_1) \\ 1 \end{pmatrix} \tag{15}$$

Performing the inverse kinematics analysis on above equation, the joint angle parameters (θ_1, θ_2, and θ_3) can be obtained and described as below:

$$\theta_1 = \tan^{-1}\left(\frac{x}{z}\right) + \tan^{-1}\left(\frac{L_2 \sin(\theta_3)}{(L_1 + L_2 \cos(\theta_3).\cos(\theta_2))}\right) \tag{16}$$

$$\theta_2 = \sin^{-1}\left(\frac{-y_{root}}{L_2 \cos(\theta_3) + L_1}\right) \tag{17}$$

$$\theta_3 = \cos^{-1}\left[\frac{x^2 + y^2 + z^2 - L_1{}^2 - L_2{}^2}{2L_1L_2}\right] \tag{18}$$

Figure 8 illustrates the position of the joint angle parameters for Leg 1.

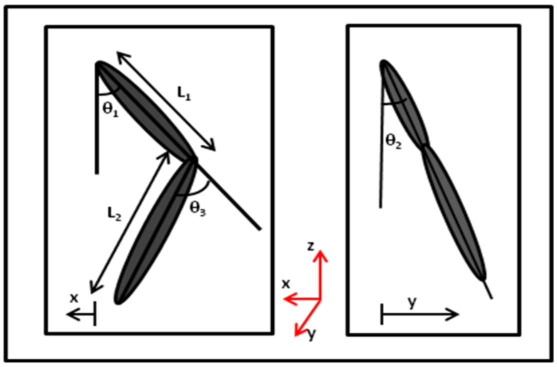
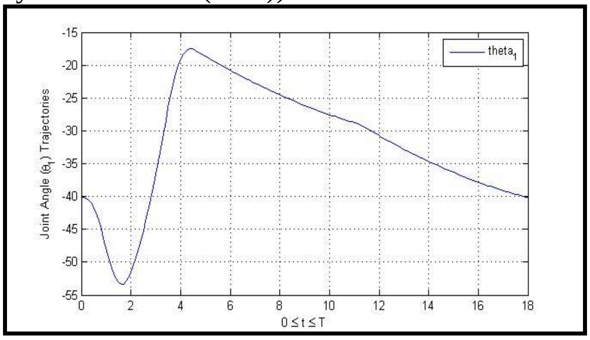


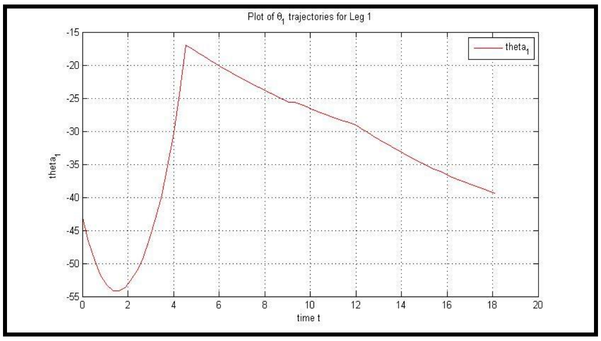
Figure 8: Model of left front leg (Leg1). Left: Side elevation for the calculation of shoulder-joint (θ_1) and knee-joint (θ_3) angle. Right: Front elevation for the calculation of shoulder-joint (θ_2) angle.

3. Results and analysis

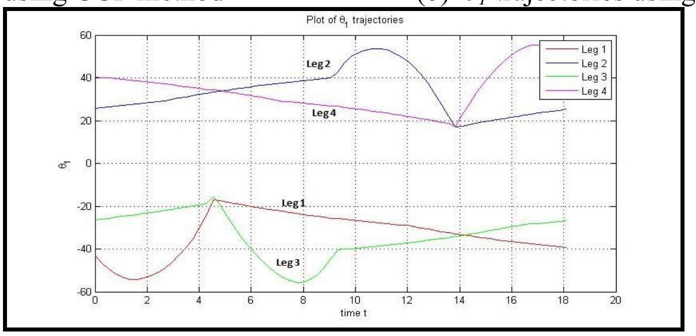
The main purpose of this research work is to investigate the efficiency of the hybrid method proposed to generate the walking gait for the quadruped robot. In order to prove that, the joint angle trajectories (θ_1, θ_2, and θ_3) obtained via this method are compared to the benchmark method (i.e. composite cycloid function (CCF)).



(a) θ_1 trajectories using CCF method

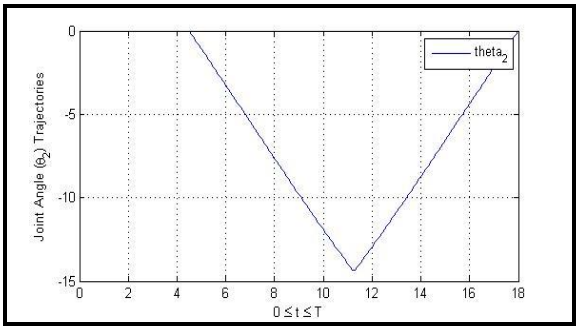


(b) θ_1 trajectories using hybrid method

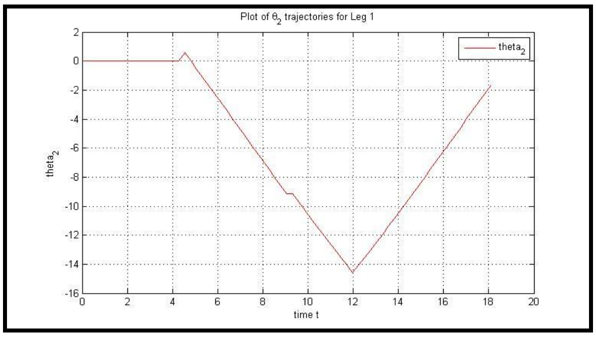


(c) θ_1 trajectories for all 4 legs using proposed method

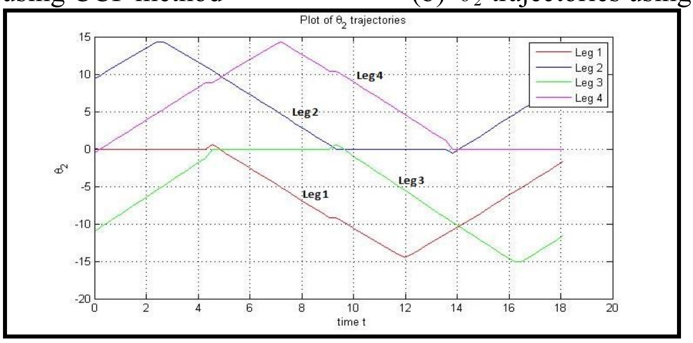
Figure 9: Plots of θ_1 trajectories using CCF (Figure (a)), and proposed method (Figure (b) and (c)).



(a) θ_2 trajectories using CCF method

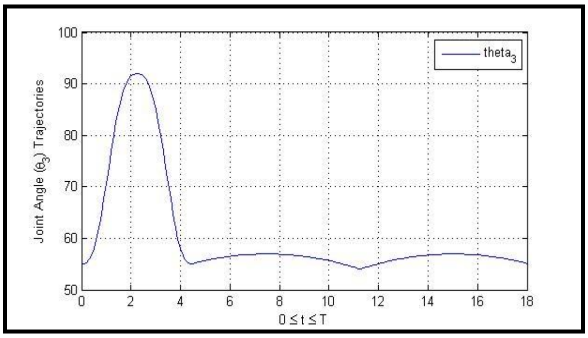


(b) θ_2 trajectories using hybrid method

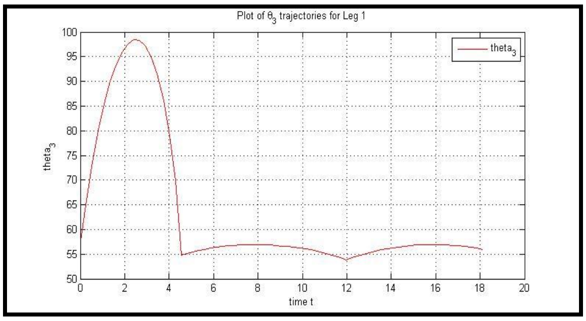


(c) θ_2 trajectories for all 4 legs using proposed method

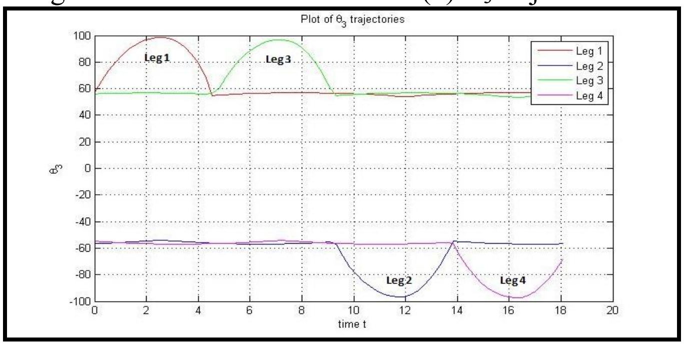
Figure 10: Plots of θ_2 trajectories using CCF (Figure (a)), and proposed method (Figure (b) and (c)).



(a) θ_3 trajectories using CCF method



(b) θ_3 trajectories using hybrid method



(c) $\theta 3$ trajectories for all 4 legs using proposed method

Figure 11: Plots of θ_3 trajectories using CCF (Figure (a)), and proposed method (Figure (b) and (c)).

From the plots presented above, it can be deduced that the joint angle trajectories obtained using the hybrid method proposed do not deviate much from the benchmark method. Generally, the shape of the curve shows similarity between both methods illustrating that the movement of that particular leg is the same. Fig 9(c), Fig 10(c) and Fig 11(c) shows the trajectories for all 4 legs with respect to time. If the plots are observed carefully, the shape of the curve for all legs is basically portrays the same pattern. The only difference is on the positivity and the negativity of the angles and also the timing to change the angle. For instance in Fig 9(c), θ1 for Leg 2 and Leg 4 is at the positive region, whereas, Leg 1 and Leg 3 lies on the negative region. However, the pattern of the angle's changes is still the same for both groups. Of course, the timing of the angle's changes will not be the same for all four legs to indicate that at a time, each leg will be in different position to ensure the forward movement and stability of the quadruped.

4. Conclusion

This paper proposed a hybrid method that can compensate the weaknesses identified in available method. Using this method, the gait can be easily altered by only manipulating the parameters of the CPG network, and only one oscillator is needed to develop the joint angles trajectory for each leg. The results show that the proposed method able to perform as good as the conventional method in generating the gait. However, this research work is focusing on the walking gait as this is considered as a starting platform on developing an adaptive and intelligent locomotion system for walking robot. Future works that can be worked on are on improving the parameters selection system for the CPG network since the current method is based on trial and error and also on the investigating the efficiency and smoothness of the method in gait transition.

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