# Central Pattern Generators Based Adaptive Control for a Quadruped Robot 

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#### Abstract

This paper presents an adaptive control system of Central Pattern Generators (CPG) made of a network of mutually coupled Van Del Pol nonlinear oscillators. The CPG based controller is used to generate stable rhythmical locomotion trajectories. With the sensorial information feedback, a novel adaptive control strategy is implemented to help a quadruped robot with only two rotary Degrees Of Freedom (DOF)s per leg in the sagittal plane to adapt various terrain environments and response external instructions such as up-slope, down-slope, direction turning and preserving. Moreover, it provides an easy mean to manipulate the robot to move forward, backward and hold steps. The effectiveness of the proposed approach is examined with computer simulations.

Index Terms - Central Pattern Generator (CPG), Quadruped Robot, Adaptive Control


## I. INTRODUCTION

TThe control of locomotion of legged robots is a great challenge that has not yet been completely solved. Recently, inspired by neurobiology, the control strategies based on Central Pattern Generators (CPG) have been a hot research topic in the field of legged locomotive robots[1] [2] [3] [4]. Mostly, the CPG is made of coupling nonlinear oscillators in various types such as Hopf, Rayleigh, Matsuoka and Van del Pol etc. Nonlinear oscillators are system of differential equations characterized by desired properties such as robustness, independence from initial conditions, easy tuning and synchronization. Matsuoka oscillator is the most common type used to generate locomotive trajectories for legged robots due to its simplicity and easily application. However, the Van del Pol oscillators have the advantage of stronger nonlinear property, robustness against disturbance (limit cycle behavior) and stronger synchronization, that may enhance the robot's capability of coping tough terrain conditions.

Our aim is to build a dinosaur-like quadruped robot. Its each leg has only two rotary DOF in the sagittal plane, without the yaw DOF. this type robots are commonly thought to be difficult to change direction and lack of stability and controllability, but due to its mechanical simplicity, some

[^0]robot like SCOUTs[5] whose each leg has only one rotate DOF, are designed and has been tested. However, our quadruped robot weights more and has bigger size, so it makes the locomotion control more difficult. In this paper, we provide a practical adaptive, sensorial information feedback based control strategy for change of direction, up-slope and down-slope with utilizing the properties of the Van del Pol oscillator. Due to properties of the Van del Pol coupling oscillators, it also provide an easy way for the robot to move backwards and forwards, hold step and restart compliantly. Because the physical mechanical machine is still under construction, we examined the proposed control strategy in simulations.

## II. Neural Oscillator Model

Van del Pol oscillators have been studied as the human locomotion rhythm generators [6], the differential equations describing the dynamic properties of oscillators in coupling can be showed as the following general form

$$
\begin{align*}
& \dot{y_{i}}=\mu_{i}\left(p_{i}^{2}-x_{s}^{2}\right) y_{i}-g_{i}^{2} x_{s i}+q_{i}  \tag{1}\\
& \dot{x}_{i}=y_{i}  \tag{2}\\
& x_{s i}=x_{i}-\sum_{j, j \neq i}^{n} \lambda_{j i} x_{j} \tag{3}
\end{align*}
$$

Where
$\dot{x}_{i}$ and $\dot{y}_{i}$ are the first-order derivatives of $x_{i}$ and $y_{i}$ with respect to time,
$p_{i}^{2}$ is the amplitude parameters,
$q_{i}$ is the offset parameters,
$g_{i}^{2}$ is the frequency parameters,
$\mu_{i}$ is the proportional parameter which can effect system convergence time, frequency and amplitude,
$\lambda_{j i}$ is the coupling weight from neuron $j$ to neuron $i$, $x_{i}$ is the neuron output.
In the CPGs coupling schema we proposed in Figure 1, each hip joint is assigned a Van del Pol oscillator, whose output represents the rotate angle of the hip joint. Four oscillators of the hip joints are linked as a crossing ring with coupling weight $\lambda_{j i}$. Each knee joint is also assigned an oscillator, and it links to the corresponding hip oscillator through a middle oscillator. By carefully choosing linking weight, the oscillator network can generate stable leg trajectories with proper phase locking relations and provide
flexibility to meet the locomotive challenge.
According to the conclusion derived from [7], when coupling weights are equal $\pm 0.2$, the coupling oscillators generate gait signal with stable phase locking and synchronized relations easily, so we chose $\pm 0.2$ as linking weight to generate trot gait for the quadruped locomotive. the chosen coupling weights of the hip joints are: $\lambda_{12}=\lambda_{21}=\lambda_{34}=\lambda_{43}=0.2 ; \quad \lambda_{13}=\lambda_{31}=\lambda_{24}=\lambda_{42}=-0.2$; otherwise is 0 ; As for corresponding knee joints, we let $\lambda_{\text {hip-middle }}=\lambda_{\text {middle-knee }}=-0.2$ to give $-\pi / 2$ phase locking relations between hip oscillators and knee oscillators to satisfy coordination relations between hip joints and knee joints.


Fig.1. Structure of CPGs
(LF: Left-Fore limb, RF: Right-Fore limb, RH: Right-Hind limb, LH: Left-Hind limb)
The Van del Pol equations have strong nonlinear characters, especially with mutual coupling which gives the CPGs network stronger stability against disturbance, synchronization and phase locking properties. But in lieu of practical analytic methods for the solution of coupled, multiple-oscillator systems, computer simulation of coupled oscillators are heavily relied on, any analytical solutions for the equations are almost impossible to acquire. The proper parameters meet the desire amplitude, frequency and offset are not so easy to acquire. In our previous works, we designed a self-tuning Van del Pol neuron network with gradient studying algorithms which can learn from offline teaching signal. With its help, we acquired suitable parameter sets $\left(A m p_{\text {Hip }}=12\right.$ Degs,$A m p_{\text {Knee }}=8$ Degs,$\left.T=2 s\right)$ as Table 1 and with that the expected leg trajectories of trot gait can be acquired.

| Parameter sets <br> $(\mathrm{i}=\mathrm{LF}, \mathrm{RF}, \mathrm{LH}, \mathrm{RH})$ | Value |
| :---: | :---: |
| $p_{i}$ | 0.7 |
| $\mu_{i}$ | 2 |
| $g_{i}$ | 2.77 (hip),3.27(middle, knee) |
| $q_{i}$ | 0 |

Tab.1. parameters of the Van del Pol oscillator
With these parameter sets and the network coupling weight sets, the CPGs can generate stable and synchronized output signals which can be used as leg trajectories of trot gait for quadruped robots(the amplitude generated by CPGs are normalized, so the amplitude should be multiplied with expected output amplitude in practice).

## III. Simulation Model

Figure 2 shows the quadruped robot considered in this study, consisting of a trunk, two pairs of thigh links and two pairs of shank links. In the sagittal plane, there are four rotate joints at the hip location (LF, RF, LH, RH) link the corresponding thigh parts to trunk, and four joints at the knee location (LF, RF, LH, RH) link the shank parts to the corresponding thigh part. The length from the fore-hip joint to the hind-hip joint is 1 m , the width from left fore-hip joint to right fore-hip joint is 0.45 m , the length of each thigh is 0.4 m and the length of each shank is 0.45 m . Each leg has only two rotary pitch freedoms at hip and knee joint and no yaw freedom. The trunk weighs 30.5 Kg and each leg weighs 5.2 Kg (thigh 3.7 Kg , shank 1.5 Kg ), all the mechanical parameters are the same as real mechanic machine under construction now. In simulation, we added frictions to rotate joints and collisions to shank when the shank touched ground. On the real machine we set a gyroscope to measure the trunk posture, each hip and knee joint is set a DC motor, there are touchdown sensor on each tip of legs and each motor has a encode so the rotary angle can be measured. In simulations we set a same sensor on the virtual machine to measure the motions and posture.


Fig.2. Quadruped Robot Model

## IV. ADAPTIVE CONTROL

Adaptive control based on CPGs provide an effective way to control the posture and behaviors of legged robots[8][9][10], in [8], A neural system consisting of CPGs , response and reflexes with reference to biological concepts is introduced, with its help the TekkenII quadruped robots(3-DOFs each leg) walks well in the outdoor environments. In this study, we designed a set of control strategies also inspiring from biological concepts, ensure our robot (two-DOFs each leg, without yaw freedom) to adapt the outdoor environment and response the external instructions (such as up-slope, down-slope, walk in straight line, turning and preserving walking direction). The main diagram of the control strategy is shown in Figure 3:

The sensor information acquired by the controller includes: roll angle, yaw angle, pitch angle of the trunk: $\theta_{\text {Roll }}, \theta_{\text {Yav }}, \theta_{\text {Pitch }}$, translation offset of the trunk center of mass along 3 axis: $d_{x}, d_{y}, d_{z}$. These sensor information is pass through a
low-pass filter to reduce the periodical disturbance introduced by the periodical motion of legs. A fuzzy controller acquires these sensorial information and generate corresponding tuning for the CPGs to actuate motors on legs and knees. Meanwhile, the controller also response external instructions such as change step frequency, amplitude and motion direction by tuning relevant parameters of the CPG networks.


## A. Turn and preserve direction

When the quadruped robot performs trot gait, due to the difference of touch-ground time between right-limbs and left-limbs, it deviates its original heading direction. Ref.[5] analyzed the dynamic of turning directions for a quadruped robot without yaw freedom, it conclude that turning was implemented by adding offsets to the nominal desired hip angles at impact for the left limbs and right limbs. In this study, the parameter $q_{L H}$ or $q_{R H}$ of the oscillator networks are manipulated to preserve or turn the robot's heading direction. We designed a fuzzy-logic controller to ensure walking in straight line and make turning and preserving direction of the robot in a smooth modulation process, when the robot deviate its target direction, the sensorial information is put in the controller and the controller adjusting the parameters of CPGs and generates appropriate out-waves for the hind-hip joints of the robot, make it back to its correct direction or to its new heading direction. The fuzzy-controller is simply described as Figure 4:


The inputs to the controller are yaw angle $\theta_{\text {Yaw }}$ and pitch angle $\theta_{\text {Pitch }}$. Controller modulate $q_{L H}$ and $q_{R H}$ mainly according to the error between $\theta_{\text {Yaw }}$ and $\theta_{\text {target }}$, but it is also effected by the $\theta_{\text {Pitch }}$, because when the robot trot up-slope or down-slope, it need minor modulation of the $q_{L H}$ and $q_{R H}$ than at plain ground. If the CPGs are modulated as same level as at plain ground, the robot will lose its stability. After the fuzzy inference, a fuzzy Takagi-Sugeno module [11] is introduced to integrate the fuzzy inference results and
generate control output. Meanwhile, the CPGs also increase or decrease the amplitude or frequency of the out-waves by modulating the amplitude parameters $p_{i}^{2}$ and frequency parameters $g_{i}^{2}$ to adapt different ground conditions.

## B. Up-slope

In simulations, we found the quadruped robot's posture can be controlled by modulating the limbs' swing center (from which the limbs swing in equal amplitude), which can be achieved by adjusting corresponding oscillator's offset parameter $q_{i}$. When the robot climbs up a slope, it should adapt to the translation of the center of the robot's mass by lower fore-limbs, the follow law is chosen as controller action:

$$
q_{L \mathrm{~F}}=q_{R F}=-0.072 * \theta_{\text {Pitch }} ; \text { Where } \theta_{\text {Pitch }}>0 .
$$

## C. Down-slope

When the robot trots down slope, for the same reason in the up-slope circumstance, it should lower hind-limbs or lift fore-limbs to enlarge its stability margin. because the hind-limbs are used to maintain heading direction, we chose to lift fore-limbs, so the follow law is chosen:

$$
q_{L \mathrm{~F}}=q_{\mathrm{RF}}=0.045 * \theta_{\text {Pitch }} ; \text { Where } \theta_{\text {Pitch }}<0 .
$$

At situation as up-slope and down-slope, we exert the fuzzy-controller output to the hind-limbs to avoid losing the direction, meanwhile, the fuzzy-controller also adjusts $p_{i}^{2}$ to decrease output wave's amplitude to keep the stability.

## D. External command

Some basic locomotive purpose can be achieved through modulating the parameters of the CPG network. With utilizing the properties of CPGs, we can alter the robot's locomotion naturally (e.g. changing stride distance and legs' swing frequency, which can be simply achieved by modulating frequency parameter $p_{i}$ and amplitude parameter $q_{i}$ ). When we need the robot turn to backwards while it is walking forward, the phase locking relations between the hip oscillators and knee oscillators need to be changed. In this circumstance, we change the $\lambda_{\text {hip-middle }}$ from -0.2 to +0.2 , it will change the phase difference between hip and knee from $-\pi / 2$ to $+\pi / 2$ in about two oscillation cycle periods, and results the motion direction from forwards to backwards naturally and compliantly. When we need the robot to hold step, we change $\mu_{i}$ from 2 to $-1.2($ the inhabitation relationships should be release previously), the robot will decrease its step amplitude gradually and hold step, when need to restart it, we rebuild the inhabitation relations and reset the parameters $\mu_{i}$ from -1.2 to 2 , the robot will naturally restart trot again.

The CPG based on Van del Pol oscillators have strong nonlinear properties and keep the robot from most external disturbance and enhance its robustness in locomotion. By modulating the parameters of the oscillator, the natural and
compliant process of the motion transition can be achieved. But otherwise, the strong nonlinear properties of the Van del Pol oscillator make the gait transition more difficult., which has not been resolved yet.

## V. SIMULATION EXPERIMENTS

Because our physical mechanics robot is under construction now, we chose the MCS/ADAMS, MATLAB/Simulink and Real-Time Workshop as our experiment platform. In this section, we demonstrate our simulation experiment results to reveal the control strategies we proposed works well.

## A. Change of direction



Fig. 5 Robot Turning direction process and the controller's modulation
Figure 5 shows the process of turning direction (turn left twenty degs) and the outputs of controller ( $q_{L H}$ is shown. for at this circumstance, $q_{R H}=0$ ) that is generated according to the current rotate angle and target angle. From that, we can see the robot without yaw freedom changed the direction from 0 degs to 20 degs with the help of the controller.

## B. up-slope and down-slope

Figure 6 and Figure 7 show the process of the quadruped robot model trot up and down a twelve degrees slope. When the robot trot on the slope, the controller modulate the CPG to make the robot to adapt up-slope or down-slope circumstance. Fig. 8 illustrates alternation of the hip joint rotate angle when the robot trots up a twelve degree slope (we take LH hip joint and LF hip joint as example). From Figure 8, we can see the change of the oscillation center and amplitude which the controller made for adapting slope circumstance.


Fig. 6 the quadruped robot model trot up a twelve-degree slope


Fig.7. the quadruped robot model trot down a twelve degrees slope


Fig.8. the LB and LF hip joint rotate angles in the process of up-slope and down-slope

## C. External command

Figure 9 illustrates the robot's phase relations between hip joint and corresponding knee joint in forwards-backwardsforwards locomotion. From Figure 9, we can see the phase relation between the hip joint and knee joint changed from $-\pi / 2$ to $+\pi / 2$ according the external instruction (from forwards to backwards and from backwards to forwards).


Fig.9. the phase relations between hip and knee in forwards-backwards-forwards motion.
By the simulations, we examine the control results at different circumstance. The simulation results demonstrate we can make the quadruped robot without yaw freedom trot adaptively and response external instructions well by the proper designed controller. Even without the critical yaw DOF, the robot model still can turn and preserve the motion direction as our will.

## VI. Conclusion

This paper presents a new CPGs control strategy based on Van del Pol oscillators for a quadruped robot with only two-DOFs per leg in the sagittal plane. According to the properties of the Van del Pol oscillators, we designed a set of novel link pattern for the quadruped robot's trot gait, meanwhile, a new control strategy base on CPG has been implemented to adapt the outdoor environment and response external instructions. The developed control model has been simulated and tested in a virtual environment, and good results have been shown. However, due to the strong nonlinear and synchronization properties of the coupled Van del Pol oscillator, how to use that CPG networks to implement different gait alternation (e.g. from a trot to a walk, from a trot to a pace) in a stable and robust way, is still remain unsolved and we will continue work on it in our future research. Meanwhile, when physical machine is completed, the proposed control strategy based on Van del Pol CPG will be tested on a mechanic machine in real environments, we look forward for it and will keep our research results posted.

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