

# Design of the Fuzzy Controller based on Oscillator Networks for a Quadruped Robot

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**Abstract:** This paper proposed a fuzzy control system based on oscillator networks for the locomotion control of the quadruped robot whose legs have no yaw freedom. The oscillator networks are used to generate stable, synchronized leg gait signal for the locomotion of the robot. The fuzzy controller is introduced to tune the parameters of the oscillator networks for generating adaptive leg motion curve for the out-door environments. The fuzzy controller consist four adaptive fuzzy rules sets to deal with the different out-door environments, respectively. The effectiveness of the proposed approach is examined in a virtual environment by computer simulations.

**Key Words:** Oscillator Networks, Quadruped Robot, Fuzzy Controller

## 1 INTRODUCTION

Locomotive robotics is a field that is in a state of rapid expansion. Using legs is one of the strategies for accomplishing locomotion. As one type of legged robots, quadruped robots can perform tasks in the environments with rough terrains and undertake more load than bipedal robots. It has attracted many researchers' interest and plenty extraordinary works have been done.

The design of a quadruped robot with mammal-like locomotion is an ingenious integration of nature's intelligence with a man-made machine. Inspired biologically, Oscillator networks have implemented to imitate the central pattern generator (CPG) signals generated at mammals' spinal cord and are used to generate leg locomotion gaits. There are a few successful applications up to the present days[1-4].

However, the environment adaptive walking of a quadruped robot depends on not only the gait implementation but also the postural and locomotion control. The gaits generated by oscillator networks still need to be processed according to the ground conditions, sensorial information feedbacks and external instructions. In this respect, effective control strategies are essential. As one of the intelligence control strategies, Fuzzy control is an attractive method for robot control. In the robotics, Fuzzy control has been implemented in the field of navigation [5], motion and postural control [6] and sensorial information integration, etc.

Our aim is to build a dinosaur-like quadruped robot. Each leg of the robot has only two rotary degree-of-freedoms (DOF) in the sagittal plane, no yaw DOF. This type robots is commonly thought to be difficult to turn direction and lack of stability and controllability, but due to its mechanical simplicity, some robot like SCOUTs [7] whose each leg has only one rotary DOF, are devised and has been put into practice. However, our quadruped robot prototype is larger and heavier than SCOUTs and these features make it more difficult to

control. In this study, an effective fuzzy control strategy based on CPG and fuzzy logic is proposed to manipulate oscillator networks for generating stable and adaptive leg gait for the out-door environments.

## 2 QUADRUPED ROBOT MODEL

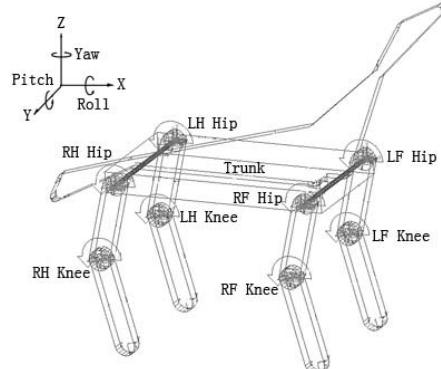


Fig.1 Quadruped robot Simulation Model  
(LF: Left-Front limb, RF: Right-Front limb,  
RH: Right-Hind limb, LH: Left-Hind limb)

The quadruped robot considered as control plant in this study is shown in figure 1, consisting of a trunk, two pairs of thigh links and two pairs of shank links. There are four rotate joints at the hip location link the corresponding thigh parts to the trunk, and four joints at the knee location link the shank parts to the corresponding thigh part in the sagittal plane. The length from the fore-hip joint to the hind-hip joint is 1000mm, the width from left fore-hip joint to right fore-hip joint is 450mm, the length of each thigh is 400mm and the length of each shank is 450mm. Each leg has only two rotary pitch freedoms at hip and knee joint and no yaw freedom. The trunk weighs 30.5Kg and each leg weighs 5.2Kg (thigh 3.7 Kg, shank 1.5 Kg), all the mechanical parameters are the same as the real machine currently under construction. In simulation, we add frictions to the rotate joints and collisions to the shanks 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 sensors on each tip of legs and each motor has an encoder so the rotary angle can be measured. In the simulations we set same sensors on the virtual machine to measure the motions and posture.

### 3 OSCILLATOR NETWORKS

Nonlinear oscillators are system of differential equations characterized by desired properties such as robustness, independence from initial conditions, easy tuning and synchronization. In this study, we design an oscillator networks made of the Van del Pol oscillators because this type of oscillators offer the advantage of stronger nonlinear property, robustness against disturbance (limit cycle behavior) and stronger synchronization, that may enhance the robot's capability of coping rough terrain conditions. Van del Pol oscillators have been studied as the human locomotion rhythm generators[8], and the differential equations describing the dynamic properties of oscillators in coupling can be shown as the following general form:

$$\dot{y}_i = \mu_i(p_i^2 - x_{si}^2)y_i - g_i^2 x_{si} + q_i \quad (1)$$

$$\dot{x}_i = y_i \quad (2)$$

$$x_{si} = x_i - \sum_{j, j \neq i}^n \lambda_{ji} x_j \quad (3)$$

Where variables  $x_i$  and  $y_i$  are the first-order derivatives of  $x_i$  and  $y_i$  with respect to time. The sets of the parameters involved in the equations are: amplitude parameters  $p_i^2$ , offset parameters  $q_i$ , frequency parameters  $g_i^2$  and proportional parameters  $\mu_i$ ,  $\lambda_{ji}$  denotes the coupling weight from oscillator  $j$  to oscillator  $i$ ,  $x_i$  is the neuron output.

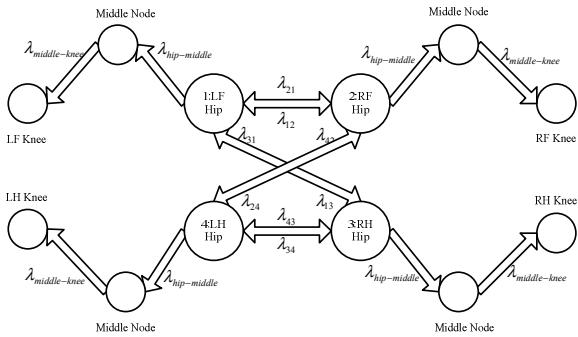


Fig.2. Structure of oscillator networks

In the oscillator network coupling schema we proposed in figure 2, each hip joint of the quadruped robot is assigned an oscillator, its output represents the rotate angle of the hip joint. The four hip joint neurons are linked as a crossing ring with coupling weight  $\lambda_{ji}$ . 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 networks are able to generate stable leg

trajectories with proper phase locking relations and provide flexibility to meet the locomotive desire.

Hip joints coupling weight:  $\lambda_{12} = \lambda_{21} = \lambda_{34} = \lambda_{43} = 0.2$ ,  $\lambda_{13} = \lambda_{31} = \lambda_{24} = \lambda_{42} = -0.2$ , otherwise is 0;

As for the corresponding knee joints, we let  $\lambda_{\text{hip-middle}} = \lambda_{\text{middle-knee}} = -0.2$  to make  $-\pi/2$  phase locking relations between the hip oscillators and the knee oscillators to satisfy coordination relations between hip joints and knee joints.

The Van del Pol equations have strong nonlinear characters, especially with mutual coupling, which gives the oscillator networks stronger stability, synchronization and phase locking properties. By try and trial, we choose the follow oscillator parameters:  $p = 0.7$ ,  $\mu = 2$ ,  $q = 0$  for each oscillator and  $g = 2.77$  for the hip nodes and  $g = 3.27$  for the middle nodes and knee nodes. With these parameters the expect leg gait of trot can be acquired (as the partial out wave shown in figure 3, the cycle time is two seconds and the hip amplitude is normalized to one, the amplitudes ratio between hips and knees is 3:2. the amplitudes are multiplied with 12 as actual output).

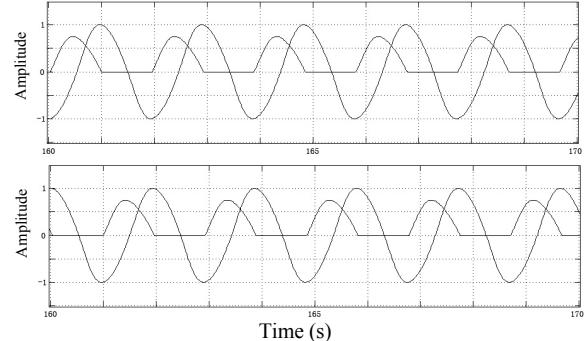


Fig.3. trot gait generated by the oscillator networks  
(top: LF and RH hip and knee, bottom: RF and LH hip and knee)

### 4 DESIGN OF THE FUZZY CONTROLLER

Fuzzy controller provides a means of dealing with uncertainties in the controller's inputs and outputs. The operation of a fuzzy controller is similar to the control actions that would be taken by a human operator. A benefit of these fuzzy controllers is that they depart from the idea of hard or crisp set-points and tend to be more flexible controllers. Also, it is possible to develop a fuzzy controller without having a precise mathematical model of the system. The advantage of in the use of quadruped controller is it can alleviate the disturbance influence brought by uncertain terrain conditions and the heuristic knowledge can be used as rules conveniently to achieve good control effects.

#### 4.1. Fuzzy controller architecture

Block diagram of the proposed fuzzy controller is shown in figure 4. The controller has four inputs and six outputs. The inputs of the controller are  $\Delta\phi_{\text{Yaw}}$ ,  $\phi_{\text{Pitch}}$ ,  $\Delta v_f$ ,  $\Sigma_z$ . The outputs of the controller is the parameters of the oscillator networks ( $q_{RH}$ ,  $q_{LH}$ ,  $q_{RF}$ ,  $q_{LF}$ ,  $p$ ,  $g$ ). Considering the convergence time of the oscillator networks, we take four seconds(2 oscillate cycles) as oscillator parameters adjusting interval(control

interval). The gait generation interval is 0.02s(50Hz).

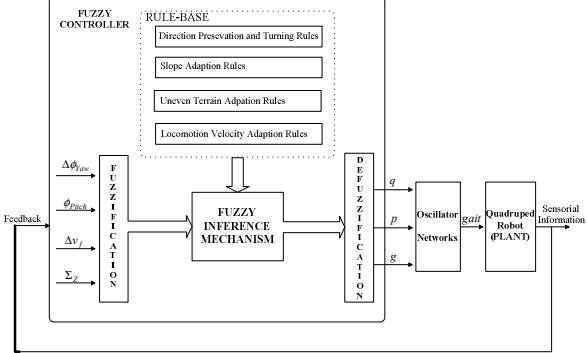


Fig.4 Block diagram of the fuzzy controller

#### 4.2. Membership functions of the inputs and outputs

The meaning and explanations of the fuzzy controller's inputs are as follows: (1)  $\Delta\phi_{yaw} = \phi_{tgt} - \phi_{Current}$ , it represents the difference between the current and the target yaw angle of the robot's trunk, the  $|\Delta\phi_{yaw}|$  is used to preserve or turn heading direction; (2)  $\phi_{pitch}$  represents the pitch angle of the trunk, it is used to justify whether the robot is at a status of up-slope or down-slope; (3)  $\Delta v_f = v_{tgt} - v_f$ ; where  $v_f = S_f / T$ , it represents the average velocity along heading direction during the last control interval, it is used to measure the current trunk locomotion velocity; (4)  $\Sigma_z = \sum |\delta_z|^2 / N$ , where  $\delta_z$  represents the translation of the mass center of the trunk along Z axis,  $N$  represent the sample number during one control interval, so  $\Sigma_z$  represents the average of the accumulation of the square translation along Z axis during the last control interval, it is used to measure the uneven level of the ground and the stability margin of the trunk.

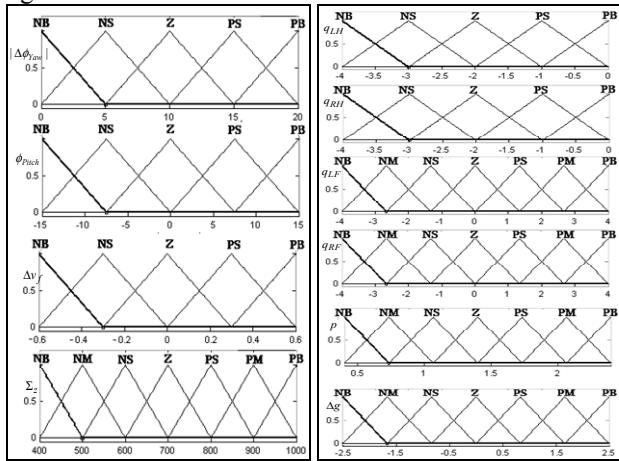


Fig.5 membership functions of the inputs and outputs of the fuzzy controller

The membership functions shown in figure 5 were used for the inputs and outputs variables of the fuzzy controller, the range of the membership functions are chosen by try and trial.

#### 4.3. Rules of the inference

According to the adaptive function, the fuzzy inference rules are divided into four rules sets. It is not feasible to list all

the rules here and the principles are clarified as follows:

##### 1) Direction Preservation and Turning Rules

Ref.[7] analyzed the dynamic of turning directions for a quadruped robot without yaw freedom, it conclude that turning directions was implemented by adding offsets to the nominal desired hip angles at impact for the left legs or right legs, and for small turning angles per step, the interaction between the walking and the turning dynamics is small and can be neglected. In this study, we changed the parameter  $q_{RH}$  or  $q_{LH}$  of the oscillator networks to preserve and turn direction for the quadruped robot.

(a) If  $\Delta\phi_{yaw}$  greater than zero (mean the robot should turn counter-clockwise), then let  $q_{RH} = 0$  and the larger  $|\Delta\phi_{yaw}|$ , the smaller  $q_{LH}$ ;

(b) If  $\Delta\phi_{yaw}$  less than zero (mean the robot should turn clockwise), then let  $q_{LH} = 0$  and the larger  $|\Delta\phi_{yaw}|$ , the smaller  $q_{RH}$ ;

(c) The larger  $|\phi_{pitch}|$ , the smaller  $q_{RH}$  or  $q_{LH}$ ;

(d) The larger  $\Sigma_z$ , the larger  $q_{RH}$  or  $q_{LH}$ ;

The fractional inference process of this fuzzy inference rules set is shown in the rule view of the window in MATLAB. Figure.6 indicates the 3D plot for the rule surface.

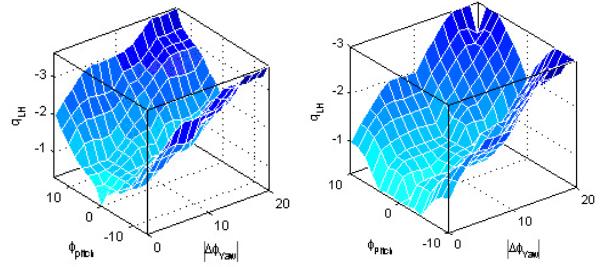


Fig.6 the viewer surface for  $q_{LH}$  when  $\Sigma_z$  is belong to PS(positive small) and NB(negative big)

2) *Slope Adaptation Rules*: the quadruped robot's posture can be manipulated by adjusting the hind-limbs swing center (from which the limbs swing in equal amplitude), which can be achieved by tuning corresponding oscillator's offset parameter  $q$ . When the robot climbs a slope, it should adapt to the translation of the center mass by lower fore-limbs for larger stability margin. For the same reason, when the robot walk down slope, it should lift its fore-limbs.

(a) The larger  $\phi_{pitch}$ , the smaller  $q_{LF}$  and  $q_{RF}$ ;

(b) The smaller  $\phi_{pitch}$ , the larger  $q_{LF}$  and  $q_{RF}$ ;

3) *Uneven Terrain Adaptation Rules*: This rules set change out wave's amplitude by adjusting the amplitude parameter  $p$ . The parameter  $p$  for each oscillator should be changed at the same time for not disturbing the inhibition relationship between the oscillators. This rules set is used to adapt the terrain condition.

(a) The larger  $\Sigma_z$ , the smaller  $p$ ;

(b) The larger  $|\phi_{pitch}|$ , the smaller  $p$ ;

4) *Locomotion Velocity Adaptation Rules*: Manipulation of the robot's locomotive speed is through changing the swing frequency of the legs by increase or decrease the

parameter  $g$  with  $\Delta g$  (the parameter  $g$  must be fixed in the range that satisfied the stability of the oscillator networks, in this study, the range of the parameter  $g$  is fixed between 2 and 7). By this rule we make the robot move fast as possible as it can (regard to the terrain condition and the stability of the robot)

(a) The larger  $\Sigma_z$ , the smaller  $g$  to increase the trot cycle time;

(b) When  $\Delta v_f$  greater than zero, with larger  $|\Delta v_f|$ , let  $g$  to be larger to increase legs swing frequency to make locomotion faster;

(c) When  $\Delta v_f$  less than zero, with larger  $|\Delta v_f|$ , let  $g$  to be smaller to reduce leg's swing frequency so as to slowdown robot's locomotion velocity;

The detail of the fuzzy inference rules set 3 and set 4 is shown in figure 7 that indicates the 3D plot for the rule surface.

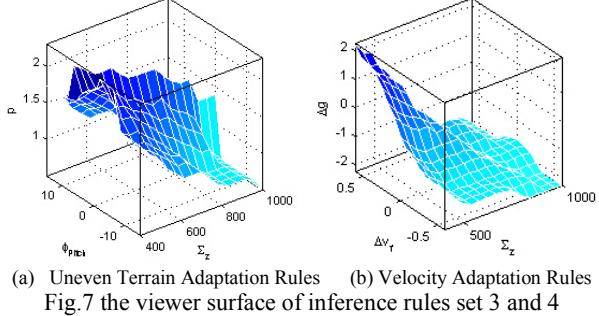


Fig.7 the viewer surface of inference rules set 3 and 4

#### 4.4. Inference mechanism

The inference mechanism employed in fuzzy logic controllers is generally based on various reasoning schemes. The inference result can be obtained by using several different algorithms. Mamdani's fuzzy reasoning method based on MAX-MIN inference operator is used to perform fuzzy inference in this application.

#### 4.5. De-fuzzification

The de-fuzzification produces a nonfuzzy action that best represents the inferred fuzzy output. Many strategies can be used for carrying out the de-fuzzification. The center-of-gravity method is adopted in this application, that is

$$w = \frac{\sum_{i=1}^n w_i \mu(w_i)}{\sum_{i=1}^n \mu(w_i)} \quad (4)$$

where  $n$  is the number of the elements of the discrete universe of discourse,  $w_i$  denotes the  $i$ th element of the universe of discourse, and  $\mu(w_i)$  represents the membership of the fuzzy set as the output of the fuzzy inference.

### 5 SIMULATION EXPERIMENTS

In this study, 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.

To examine the fuzzy controller's performance, we set up

a virtual environment in ADAMS, it include a 12-degree, 6 meters long up-slope, 8 meters long flat bridge and a 12-degree, 6 meters long down-slope.

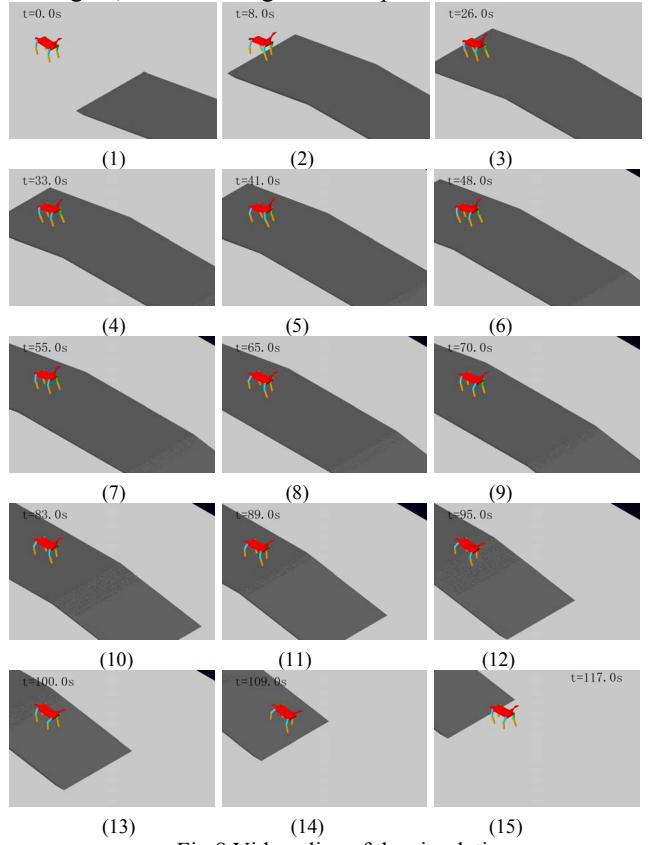


Fig.8 Video clips of the simulation

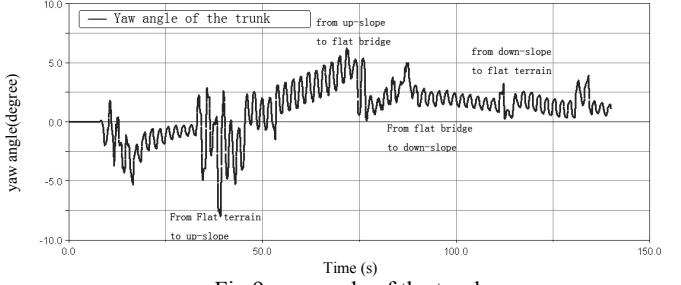


Fig.9 yaw angle of the trunk

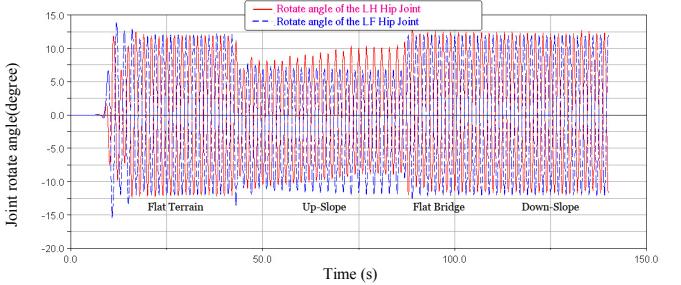


Fig.10 Right-hind limb and Left-hind limb hip joint motion curve

Figure 8 shows the process of the quadruped robot trot up-slope, then flat bridge and down-slope. From figure 9, the control process of the trunk's yaw angle shows the four locomotive stages: flat terrain, up-slope, flat bridge, down-slope. According the sensorial information feedback, the

controller manipulator the parameter sets of the oscillator networks to make the quadruped model adapt the terrain conditions. The control output is showed from the figure 10, the controller adjusts the limbs hip joints' motion curve's amplitude and offset (we take right-hind limb and left-hind limb hip joint as example).

## 6 CONCLUSION

In this paper, a fuzzy controller based on oscillator networks to make quadruped robots to adapt out-door environments is discussed in detail. By use of the feedback of sensorial information, the fuzzy controller adjusts the parameters of the oscillator networks to the leg joints motion adapt the ground condition. The Van del Pol oscillator networks have stronger synchronization and anti-disturbance properties which alleviate uncertain disturbance bought by the rough parameter adjustment. The fuzzy controller is able to make the control process more robust and smooth against the rough ground condition. The simulation results shows that the combination of the fuzzy control strategy and oscillator networks is able to make the control of quadruped robot locomotion more convenient and capable to cope out-door environments.

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