ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Adaptive Locomotion Controller for a Quadruped Robot

Step 2:

Existing Models and Controllers

Simon Ruffieux

07

1 Introduction

Various models and controllers have been developed to simulate quadruped walking and elucidate its mechanisms. Adaptive walking on irregular terrain has been studied using neural system models consisting of CPG and feedback mechanisms. The feedback is categorized in two main categories: responses which modulate the output of the CPG and reflexes that directly generate joint torque [2]. Different CPG models along with reflexes and responses have been developed and tested in previous studies [1][6][7].

In this step, I will try to review existing models. Most of the CPG models are based on two different neural oscillator systems; the Matsuoka oscillator model [3][4], used in most recent experiences for biped [8] and quadruped locomotion [1][2][5] and a modified Hopf oscillator recently used by Righetti[7]. Accordingly with those models, implemented reflexes and responses will be reviewed and discussed.

2 Models

Along my reviews, I have found out a dominant oscillator model: the neural oscillator proposed by Matsuoka [3][4] . It has been widely used as CPG model in various study to generate biped locomotion [8] [9] and quadruped locomotion [1][2][5]. This complex oscillator model is based on biological concepts of the extensor and flexor muscles. Endo [8] developed a CPG model for biped walking with this type of oscillator. He simplified the Matsuoka model by modifying the oscillator connections and allocating them in a task space coordinate system to reduce the open parameters in the neural oscillator. The model also allows stopping the oscillatory movements when a large input signal is applied to the oscillator, such as a large external perturbation. Then the feedback pathways, the roll angle and the vertical forces of both legs, are used to maintain the balance by adjusting the length of each leg.

Another interesting approach for robust biped walking is using nonlinear oscillators. The model developed in [6] by Aoi uses five coupled rhythm generators. These oscillators consists of two rhythm generators for the legs, two for the arms, one for the trunk and an inter oscillator that has interactions with the others. The legs and arms oscillators have been tuned to generate the desired trajectories and are maintained to the desired phase difference by the inter oscillator. The motion and posture of the trunk has been designed to generate a stable walking by inverse kinematics and numerical analysis. This model allows the step cycle, precisely the swing phase duration, to change according to the timing of the foot's landing on the ground. It uses a proportional-derivative of the expected value and real value to modify the ongoing step cycle by resetting the leg oscillator to a desired stable value when the foot touches the ground.

The second model reviewed is the one developed at EPFL by Righetti [7] based on adaptive Hopf oscillators. This model is much simpler and intuitive than the models using Matsuoka oscillators; however it has less similitude to the biological concepts of extensor and flexor muscles but focus more on swing and stance phases' control. Its main advantages are the few open parameters which allow a model to be easily implemented on various different robots.

Extensive study has been made with CPG models to generate different gaits in function of simple signals accordingly with biological concepts. These gaits are usually generated by modifying the coupling of oscillator's networks. However I will not focus on this part of the models as only the walk gait will be used for adaptive walking in my study.

2.1 Fukuoka model

The CPG model developed by Fukuoka & al [1][2] is based on the Neural oscillator (NO) proposed by Matsuoka[3][4] consisting of two mutually inhibiting neurons, one extensor neuron and one flexor neuron to generate oscillation[Fig1.]. This system is inspired from physiological knowledge (see step1).

Each neuron is represented by the following nonlinear differential equations for each NO:

$$\tau\dot{u}_{\{e,f\}i} = -u_{\{e,f\}i} + w_{fe}\, y_{\{e,f\}i} - \beta v_{\{e,f\}i} + u_0 + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij}\, y_{\{e,f\}j} \quad (1)$$

$$y_{\{e,f\}i} = \max\ \left(u_{\{e,f\}i}, 0\right) \quad (2)$$

$$\tau'\dot{v}_{\{e,f\}i} = -v_{\{e,f\}i} + y_{\{e,f\}i} \quad (3)$$

Where the suffix *e,f* denote an extensor neuron or a flexor neuron and the i denotes the *i*th NO. $u_{\{e,f\}i}$ is the inner state of an extensor or flexor neuron of the *i*th NO. $v_{\{e,f\}i}$ is a variable representing the self-inhibition effect of a neuron. $y_{\{e,f\}i}$ are the output of extensor or flexor neurons and are input with a connecting weight w_{fe} . u_0 is an external output with a constant rate. $Feed_{\{e,f\}i}$ is a feed-back signal from the robot, that is, a joint angle, angular velocity, and so on. β is a constant representing the degree of the self-inhibition influence on the inner state. The quantity τ and τ' are time constant of $u_{\{e,f\}i}$ and $v_{\{e,f\}i}$; w_{ij} is a connecting weight between neurons of the *i*th and *j*th NO.

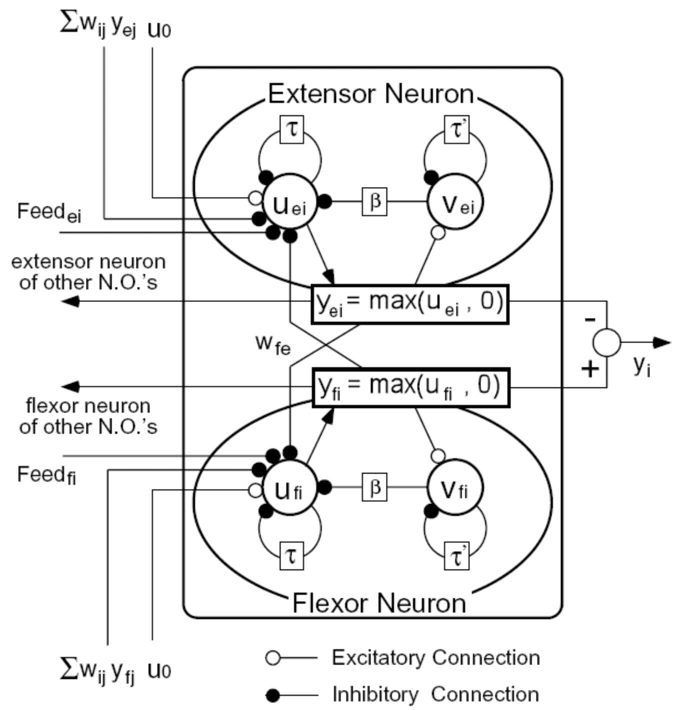


Figure 1: Neural oscillator as a model of CPG. (Reproduced from [1])

The output of a CPG is a phase signal:

$$y_i = -y_{ei} + y_{fi}$$

A positive or negative value of y_i corresponds to activity of a flexor or extensor neuron, respectively. It uses the following hip joint angle feedback as a basic sensory input to a CPG called a "tonic stretch response" in all experiments of his study. This negative feedback makes a CPG entrained with a rhythmic hip joint motion.

$$Feed_{e \cdot tsr} = k_{tsr}(\theta - \theta_0) \ , \ Feed_{f \cdot tsr} = -k_{tsr}(\theta - \theta_0) \qquad (4)$$
$$Feed_{\{e,f\}} = Feed_{\{e,f\} \cdot tsr} \qquad (5)$$

where θ is the measured hip joint angle, θ_0 is the origin of the hip joint angle in standing and k_{tsr} is the feedback gain.
Finally by connecting the CPG of each leg, CPGs are mutually entrained and oscillate in the same period and with a fixed phase difference.
The explanation for this model has been taken directly from [1] and [2]. This model is interesting from a biological point of view as it mimics closely the mechanisms of the extensor and flexor muscles. Thus reflexes and responses can be designed in the same manner as they act in a real body. However the complexity of the model (4 phase dimensions) leads to a huge search space for parameters and limits the portability of the model to various robots.

2.1.1 Reflexes and responses

Kimura implemented various reflexes and responses for his model to obtain a robust locomotion; the table 1 resumes all the reflex and responses developed on

Tekken2. I briefly resume the main ones and their implementation in the following sections.

	sensed value or event	activated on
flexor reflex	collision with obstacle	sw
stepping reflex	forward speed	sw
vestibulospinal reflex/response	body pitch angle	sp
tonic labyrinthine response	body roll angle	sp&sw
sideways stepping reflex	body roll angle	sw
corrective stepping reflex/response	loss of ground contact	sw
crossed flexor reflex	ground contact of a contralateral leg	sw

Table 1: Reflexes and responses implemented for Tekken2. (Reproduced from [2])

2.1.1.1 Flexor reflex

This reflex corresponds to stumbling corrective mechanism described in section 4.2.3 of step1. When the ankle of the robots is blocked, detected by the angle of the ankle, the knee joint is flexed, allowing the robot to avoid falling.

2.1.1.2 Inclination response

"When the vestibule in a head detects an inclination in pitch or roll plane, a downward-inclined leg is extended while an upward-inclined leg is flexed" [2].

The response for an inclination in the pitch plane is called "vestibulospinal response" and it is called "tonic labyrinthine response for rolling" for the rolling plane (TLRR). These responses have been implemented by modifying the tonic stretch response feedback mechanism to take into account the body pitch and roll angle of the robot.

To simulate the vestibulospinal response, equation (4) and (5) are replaced by:

$$\theta_{vsr} = \theta - (body\ pitch\ angle)$$

$$Feed_{e\cdot tsr\cdot vsr} = k_{tsr}(\theta_{vsr} - \theta_0)\ ,\ Feed_{f\cdot tsr\cdot vsr} = -k_{tsr}(\theta_{vsr} - \theta_0) \tag{6}$$

$$Feed_{\{e,f\}} = Feed_{\{e,f\}\cdot tsr\cdot vsr} \tag{7}$$

The TLRR has been implemented with the following equations:

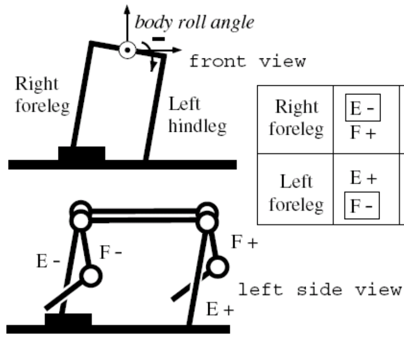
$$Feed_{e\cdot tlrr} = \delta(leg)k_{tlrr} * (body\ roll\ angle) \tag{8}$$

$$Feed_{f\cdot tlrr} = -\delta(leg)k_{tlrr} * (body\ roll\ angle) \tag{9}$$

And the new feedback becomes:

$$Feed_{\{e,f\}} = Feed_{\{e,f\}\cdot tsr\cdot vsr} + Feed_{\{e,f\}\cdot tlrr} \tag{10}$$

Where $\delta(leg)$ is 1 for a right leg and -1 for a left leg. This TLRR results in increasing or decreasing the extensor or flexor activity of a neuron as it is shown in Fig.2. The result is a better stability along the rolling axis.



Right foreleg	E - F +	Right hindleg	E - F +
Left foreleg	E + F -	Left hindleg	E + F -

Figure 2: TLRR; E and F denote the extensor and flexor neuron of a CPG. (Reproduced from [1])

Finally, a sideway stepping reflex has been implemented. It corresponds to a modification of the hip yaw angle in function of the body roll angle in order to stabilize the weight of the robot when walking along an inclined slope. The result of that reflex is that the hip yaws of the downward inclined legs move to the outside of the body and the other legs move to the inside of the body.

2.1.1.3 Corrective stepping reflex and response

When loss of ground is detected at the end of a swing phase while walking over a ditch, a cat activates corrective stepping to make the leg land at a more forward position and to extend the swing phase [10].

This mechanism has been implemented by defining reference angles, θ^*_{csr} and φ^*_{csr}, of pitch hip and knee joints at the landing moment of swinging leg in the normal case. When contact with the ground is not detected at the end of the swing phase, then the corrective reflex and response are activated on the corresponding leg. For the corrective stepping reflex, hip and knee joints are proportional-derivative controlled to the desired angles θ^*_{csr} and φ^*_{csr}. For the corrective stepping response, the external input $(u_0\ in\ eq.1)$ of the corresponding leg extensor neuron is increased in order to extend the stance phase.

2.2 Righetti Model

This model uses coupled oscillators in which we can independently control the ascending and descending phase of the oscillations (i.e. the swing and stance phases of the limbs). This model uses the fact that the speed of locomotion in quadruped animals is controlled by the duration of the stance phase and on the other hand, the duration of the swing is almost constant and has no relation with the speed of locomotion [5][7].

This model relies on the force sensing under the feet to modulate onset of the stance and swing phases. In this system, one limb should stay in swing phase as long as the foot does not touch the ground; if the foot touches the ground sooner than expected, then the controller should switch to stance phase. This approach is very interesting for sensory feedback integration because the CPG can be seen as a system that is controlled by sensory information; sensory information will change the phase space of the CPG [7].

The mathematical modeling of this model is much simpler than the one of Fukuoka, the main difference lies in the oscillator model. A modified Hopf oscillator is used instead of the oscillator designed by Matsuoka. With the adaptive Hopf oscillator, it is possible to independently control the swing and stance phase durations.

Its equation is

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

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

$$\omega = \frac{\omega_{stance}}{e^{-by}+1} + \frac{\omega_{swing}}{e^{by}+1}$$

where $r = \sqrt{x^2 + y^2}$, ω is the frequency of the oscillations in $rad \cdot s^{-1}$, $\sqrt{\mu}$ is the amplitude of the oscillation, ω_{stance} and ω_{swing} are the frequency of stance and swing phases respectively. α and β are positive constant that control the speed of convergence to the limit cycle.

The oscillators are then coupled in a network structure to generate gaits. A coupling architecture has been defined to generate the various gaits.

Then a feedback term is inserted in the equation with the coupled oscillators

$$\dot{x}_i = \alpha(\mu - {r_i}^2)x_i - \omega y_i$$

$$\dot{y}_i = \beta(\mu - {r_i}^2)y_i + \omega x_i + \sum k_{ij}\, y_j + u_i$$

where k_{ij} is the coupling matrix shown in Fig.3 and u_i represents the feedback term. The feedback is added on the y_i variables for 2 reasons. First reason is that this variable defines if we are in a stance ($y_i > 0$) or swing phase ($y_i < 0$). Secondly, since x_i variables are used as the policy for trajectory of the limbs, adding the control to the y_i variables will always produce a smooth output [7].

2.2.1 Feedback responses

Two feedback mechanisms are designed; a mechanism to avoid (delay) a transition and another one to force the transitions.

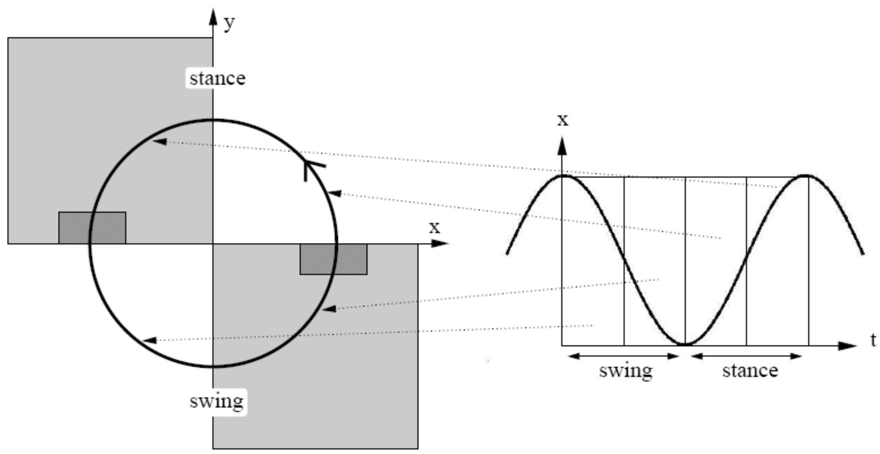


Figure 3: Phase space of an oscillator (left fig.) with its activation zone for the feedback (light gray for switch and dark gray for stop controls). The Correspondance with the x variable of the oscillator is shown on the right. (Reproduced from [7])

2.2.1.1 Delaying transition

A transition must be delayed in two cases

- during swing to stance transition: if the limb is not contact with the ground
- during stance to swing transition: if the limb still supports the body weight

Stopping the transition is obtained by the following control signal:

$$u_i = -\omega x_i - \sum k_{ij}\, y_j$$

This choice is motivated by the fact that the oscillator has to stop at the transition, i.e. when y =0. For more details refer to [7]. The result is that the limb converges to $-\sqrt{\mu}$ when $y > 0$ and to $\sqrt{\mu}$ when $y < 0$ which is the desired behavior (stop right before transition).

2.2.1.2 Force transition

A transition must be forced in two cases

- During stance: if the weight under the foot becomes low.
- During swing: if the foot touches the ground

Forcing a transition is obtained by the following control signal:

$$u_i = -sign(y_i)F$$

This choice allows y_i variable go to 0. So after a delay of $\frac{y(t_{switch})}{F}\, sec$, the transition will occur. The delay can be modified by changing the value of F.

3 References

[1] Fukuoka Y, Kimura H, Cohen A.H. "Adaptive Dynamic Walking of a Quadruped Robot on Irregular Terrain Based on Biological Concepts", IJRR, Vol.22, pp.197-202, No.3-4, March-April 2003.
[2] Fukuoka Y, Kimura H, Cohen A.H. "Adaptive Dynamic Walking of a Quadruped Robot on Natural Ground Based on Biological Concepts", IJRR, Vol.26, pp.475-490, No.5, May 2007.
[3] Matsuoka K. "Sustained Oscillations Generated by Mutually Inhibiting Neurons with Adaptation", Biological Cybernetics, 1985.
[4] Matsuoka K. "Mechanism of a Frequency and Pattern Control in the Neural Rhythm Generator", Biological Cybernetics, 1987.
[5] Liyao Z, Haojun Z, Xiuli Z, Zhifeng C. "Realization of the Biologically-Inspired Dynamic Walking Controller of a Quadruped Robot", International Conference on Robotics, Intelligent Systems and signal Processing, October 2003.
[6] Aoi S, Tsuchiya K. "Locomotion Control of a Biped Robot Using Nonlinear Oscillators", Autonomous Robots, Vol.19, pp.219-232, 2005.
[7] Righetti L, Ijspeert A. "Pattern Generators with Sensory Feedback for the Control of Quadruped Locomotion", not yet published, 2007.
[8] Endo G, Nakanishi J, Morimoto J, Cheng G. "Experimental Studies of a Neural Oscillator for Biped Locomotion with QRIO", ICRA, April 2005.
[9] Taga G. "A Model of the Neuro-musculo-skeletal System for Human Locomotion", Biological Cybernetics, 1995.
[10] Hiebert G, Gorassini M, Jiang W, Prochazka A, Pearson K. "Corrective responses to loss of ground support during walking II, comparison of intact and chronic spinal cats. Journal of Neurophysics, Vol.71, pp.611-622, 1994.