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BIOLOGICALLY INSPIRED
ROBOTICS GROUP (BIRG)

Adaptive Locomotion Controller for a Quadruped Robot

Semester Project

Midterm report

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1 Abstract

This paper tries to review the existing knowledges about the sensory feedback in animals and how it works as a functional unit. Then a close watch is taken at the existing controllers and models that have been implemented recently to achieve robust locomotion with biped and quadruped robots. Then the development of my model based on Righetti's work is explained. The implementation on Webots with the test of the model is then described. Finally the test of the implementation with the real AIBO will be discussed and a quick study of the portability of the model on another robot is done.

2 Sensory feedback review in animals

2.1 Introduction

Sensory feedback is an important component of locomotion and should not be neglected when designing central pattern generators for robust locomotion control. Even if steady-state locomotion can be achieved without sensory-feedback, it remains needed when walking on a natural environment and facing obstacles such as steps, slopes or uneven terrain.

There are two main hypotheses on the generation of the walking mechanism; the first is that a reflex-chain is triggering the walking patterns, thus sensory-feedback controls the walking pattern. However these last years, many experiences have shown that the most probable theory is that the locomotion mechanisms are mainly due to a central organization localized in the spinal cord. This theory also integrates the sensory feedback; this latter is believed to serve enhancing locomotion. This chapter will try to describe the various sensory feedback mechanisms during locomotion.

2.2 CPG & locomotion

It is generally accepted that the basic rhythm-generating network is contained within the spinal cord and afferent inputs can access this circuitry and modify the ongoing pattern (Whelan, 1996). This is usually modeled with a central pattern generator (CPG) generating the basic rhythm due to signals coming from the cerebellum and also integrating the sensory feedback. A classical schematic diagram of the control system for locomotion is shown on Fig.1. For further information on CPG for locomotion control, refer to (Ijspeert, 2007). There is mainly efferent motor-neuron and afferent sensory-neurons connected to the spinal cord. The motor-neurons trigger the different muscles activity and the afferent sensory-neurons retrieve the information from various sensors which is then integrated in the spinal cord.

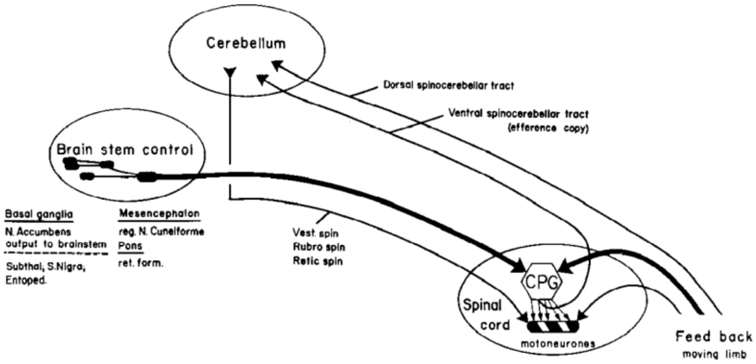


Figure 1: Schematic diagram of the control system for locomotion in vertebrates. Reproduced from [10].

2.3 Generalities on muscles

To understand how locomotion and sensory feedback interact, a clearer view of the limbs muscles mechanic is required. There exists different types of muscle tissue, however the ones we are interested in are the skeletal muscles (or voluntary muscles) which can be classified in different types; for the locomotion, we distinguish mainly flexor and extensor skeletal muscles. It is important to remember that muscles can only pull or contract, not push. Thus many muscles come in sets of antagonist that do the opposite jobs (Muscles). The spinal cord also retrieves information from muscles through special muscles receptors, see section 3.4.2.1 for more details.

The role of alpha and gamma motoneurons is also of big importance in motor control. Stretch of the sensory organ (muscle spindles, see 3.4.2.1) is transmitted as impulses to the spinal cord, where they excite the alpha motoneurons. This results in the so-called "stretch reflex": passive stretch on the muscle will make it contract, thus maintaining its previous length.

In voluntary contractions, alpha and gamma motoneurons usually work together (the "alpha-gamma linkage"). Suppose we would make a muscle contract through activation of the alpha motoneurons. The muscle including the spindles would shorten, and the sensory "strain gauge" organ would send less impulses to the spinal cord, thus diminishing the excitation of the alpha motoneurons. This would cancel out what the brain wanted. We thus need to increase the stretch on the "strain gauge" in proportion to the shortening of muscle we wished for. This is achieved by activation of gamma motoneurons simultaneous with the activation of the alpha motoneurons.

Likewise, if we wanted to let a muscle relax, the brain not only has to decrease the excitation of alpha motoneurons but it also has to decrease the excitation of gamma motoneurons. With such a mechanism, the "strain gauge" will then let the muscle relax in a lengthened state (Motoneurons).

2.4 Sensory feedback

2.4.1 Sensory receptors

We distinguish mainly two afferents sensory pathways; the proprioceptive afferent is the knowledge of its own body: we know where our legs are; if they are moving and how. The cutaneous afferent corresponds to the information coming from the skin.

2.4.2 Cutaneous receptors

Cutaneous receptors are found in the dermis or epidermis of the skin and dispatched over all the body. These receptors sense various information such as pain, pressure, vibrations or change in texture. However concerning the locomotion, we are mainly interested in the receptors located in the limbs; particularly on two spots: the dorsum and the ground contacting part of the feet.

The main role of cutaneous inputs appears to be the correct positioning of the foot during normal walking or the correct adaptive limb responses to perturbation in different phases of the step cycle (Rossignol, Dubuc, & Gossard, 2006) and recent experiments showed that removing cutaneous inputs from the hindlimbs did not prevent locomotion (Sherrington, 1910). It has been shown that the step cycle is affected by cutaneous inputs differently according to its phase (swing or stance) during perturbation and according to the strength and type of the stimulation (Whelan, 1996). For example, it appears that any obstacle impeding the movement of the foot during a swing phase directly and with very low threshold initiates an increased flexion so as to overcome the obstacle (Grillner, 1975); see 3.4.3.3 for a further study of this example.

2.4.2.1 Proprioceptors

In order to control movement, the nervous system must receive continuous sensory information from muscles and joints. For this purpose the body has specialized sensory receptors called proprioceptors. There exist two main types of proprioceptors; the muscle spindles and the Golgi tendon organs.

2.4.2.1.1 Muscle spindles

They are located inside the muscles itself, parallel with the muscles fiber and are sensitive to muscle length and convey information to the spinal cord through electric membrane potentials. Muscles spindles send feedback through mainly two types of sensory fiber, Ia and II. Group Ia is reactive to the rate of change of the muscle length and group II afferent firing rate is directly related to muscle's instantaneous length or position (Type_Ia_sensory_fiber). The muscle spindles afferent is best activated during stretch, which is due to an external force acting on the muscle, such as an increase in load or the contraction of an antagonist (Purves, Augustine, & Fitzpatrick, 1999).

2.4.2.1.2 Golgi tendon organ

Unlike muscles spindles, the Golgi tendon organs are in series with muscles fibers and they are located in the tendons that attach muscles to bones. Because the changes in muscle tension will provide different degrees of pull on the tendons, the Golgi tendon organ provides information about muscle tension; it corresponds to the output force of the muscle. The information is conveyed to the spinal cord through group Ib sensory fibers. Contrary to the muscle spindles afferent, the Golgi tendon organ afferent is best activated during muscle contraction (Purves, Augustine, & Fitzpatrick, 1999).

2.4.3 Functional view

The role of the sensory feedback is essentially to adapt the output of the CPG according to the real world and also to trigger "fast" reflexes such as unexpected obstacle avoidance.

2.4.3.1 Walking correction mechanism

Proprioceptive afferents may participate in adapting walking speed , in determining overall cycle duration, and in regulating the structure of the step cycle's subphases (i.e., swing, stance), which is required for speed adaptation and interlimb coupling (Frigon & Rossignol, 2006).

When walking, animals must adapt the propulsive force that need to be generated by the muscles according to environment they are walking in. For example, when a cat is walking uphill, the EMG amplitude of the extensors is increased while the flexor burst remains more or less the same (Pierroti, Roy, Gregor, & Edgerton, 1989). It is particularly important during stance phase, when the load of the cat is fully handled by the leg. By retrieving the force handled by the extensor muscle, the animal may reinforce its ongoing step cycle. Presumably, the positive feedback from the increased firing of Golgi tendon organ combined with negative feedback from spindles afferent would act to resist the stance stretching (Whelan, 1996).

2.4.3.2 Stance-to-swing transition

Initiation of the swing phase is a crucial phase of the step cycle. Physiological data (Duysens & Pearson, 1980) have indicated that this transition is influenced by at least two sensory signals: one from afferents arising in the hip region, signaling that the hip is fully extended and one from the ankle extensor muscles signaling the unloading of the leg. It has been demonstrated that loading the ankle extensors during decerebrate walking in cats markedly increased the extensor bursts while diminishing the flexor bursts. With that observation, it has been concluded that load signals from extensor muscles inhibit flexor components of the locomotor pattern and that unloading of ankle extensors is essential to initiate swing. In this model, force seems to play a larger role than muscle length (Frigon & Rossignol, 2006). This corresponds to reduction of positive feedback from extensor group Ib afferents at the end of the stance phase. Researchers (Pearson, Ekeberg, & Büschges, 2006) have demonstrated that a signal related to unloading of the ankle extensor muscles in each leg could, on its own, produce a robust walking behavior and alternating stepping in the hind legs in the absence of direct linkage between the two hind-leg controllers. They concluded that this signal is crucial to regulate the stance-to-swing transition.

2.4.3.3 Stumbling corrective response

Responses to mechanical stimulation of the foot are phase dependent (swing/stance) as well as task dependent (forward/backward walking) and also site dependant (paw/dorsum). This complex and refined reflex control is absolutely essential to generate avoidance responses appropriately tuned to the specific locomotor phases (Rossignol, Dubuc, & Gossard, 2006).

The most interesting response is due to a contact of the dorsum of the foot during swing, as when hitting an obstacle. This stimulus generates a robust response of the limb characterized by a prominent knee flexion that rapidly withdraws the foot and then a flexion of the ankle and hip to step over the obstacle and place the foot in front of it. It is interesting that a similar stimulus applied on the same spot during backward walking in intact cats did not induce the same complex sequential pattern but rather evoked a simultaneous co-activation of the knee and ankle flexors leading to a modestly increased backward swing. A very interesting fact is when the foot is stimulated during the stance phase, in the chronic spinal cat, flexor muscles do not respond but there is a short latency increase of reflex amplitude of the already active extensor muscles at the ankle and knee. Because these stimuli occur during a phase of weight support, the actual limb movement appear less obvious that with perturbations during swing.

2.5 Overview

We have seen that sensory feedback integration is very complex and a quick overview seems needed. The Fig.2 resumes quite well how sensory-sensors are connected and linked with the higher spinal centers. We can clearly see the two main sensory pathways: proprioceptive and cutaneous. We can also see all the possible presynaptic phasic inhibitions occurring, colored in yellow. We also remark the mediatory role of the interneurons: they are the principal source of motoneurons (effector neurons) synaptic contacts. Thus we could probably, in a computer model, use these interneurons as the main representation for the mix of sensory feedback and CPG signals.

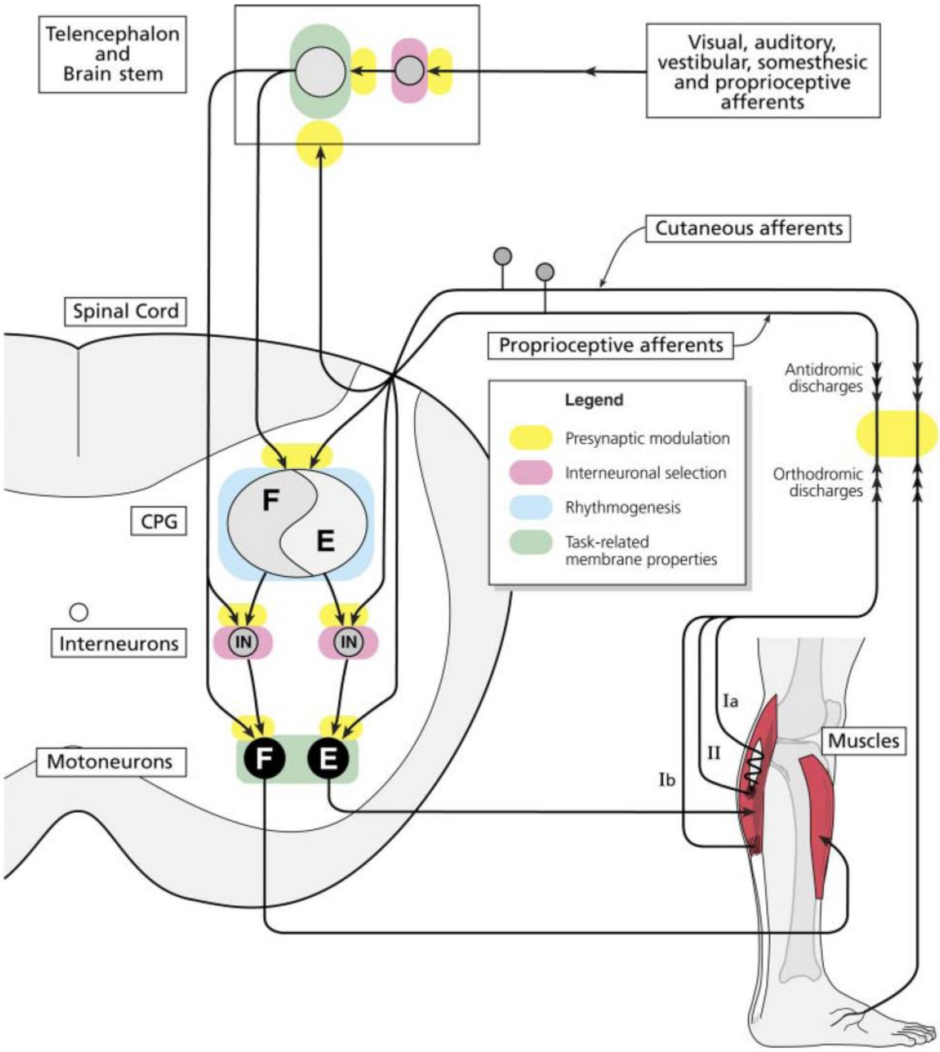


Figure 2: View of the most important sensorimotor interaction sites playing a role during locomotion. Reproduced from [8].

3 Existing controllers and models

3.1 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 different techniques such as procedural mechanisms or neural system models consisting of CPG and feedback mechanisms. The feedback is generally categorized in two main categories: responses which modulate the output of the CPG and reflexes that directly generate joint torque. Different CPG models along with reflexes and responses have been developed and tested in previous studies (Fukuoka, Kimura, & Cohen) (Aoi & Tsuchiya, 2005) (Righetti & Ijspeert, 2007).

This chapter tries to review the existing models. Most of the developed CPG models are based on two different neural oscillator systems; the Matsuoka oscillator model (Matsuoka), used in most recent experiences for biped (Endo, Nakanishi, Morimoto, & Cheng, 2005) (Taga, 1995) and quadruped locomotion (Fukuoka, Kimura, & Cohen) (Liyao, Haojun, Xuili, & Zhifeng, 2003) and an adaptive Hopf oscillator recently used by Righetti (Righetti & Ijspeert, 2007). Accordingly with those models, implemented reflexes and responses will be reviewed and discussed.

3.2 Models

Along my reviews, I have found out a dominant oscillator model: the neural oscillator proposed by Matsuoka. It has been widely used as CPG model in various study to generate biped locomotion and quadruped locomotion. This complex oscillator model is based on the biological concepts of extensor and flexor muscles. Endo (Endo, Nakanishi, Morimoto, & Cheng, 2005) 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. Finally 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 by Aoi (Aoi & Tsuchiya, 2005) 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 (Righetti & Ijspeert, 2007) 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.

3.2.1 Fukuoka model

The CPG model developed by Fukuoka (Fukuoka, Kimura, & Cohen) is based on the Neural oscillator (NO) proposed by Matsuoka consisting of two mutually inhibiting neurons, one extensor neuron and one flexor neuron to generate oscillation [Fig.1]. This system is inspired from physiological knowledge and closely mimics the muscles system. The following equation and schema introduce the principle mechanisms of the Matsuoka oscillator and its usage in CPG design.

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

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

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

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

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. $Feed_{\{e,f\}i}$ represents any feedback signal from the robot. 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.

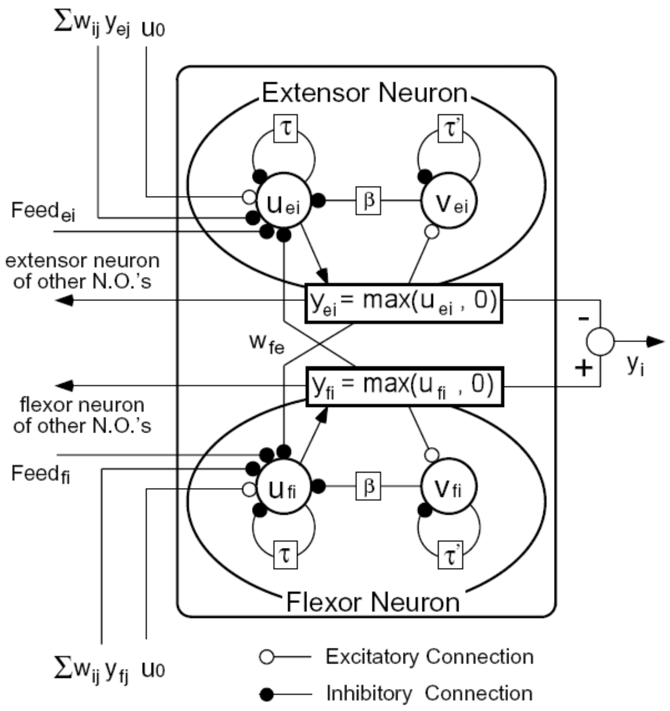


Figure 3: Neural oscillator as a model of CPG. (Reproduced from [1])

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. The Kimura model uses the following hip joint angle feedback as a basic sensory input to the CPG in his model. He called it a "tonic stretch response" in all experiments of his study. This negative feedback makes a CPG entrained with a rhythmic hip joint motion.

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

$$Feed_{\{e,f\}} = Feed_{\{e,f\} \cdot tsr} \qquad (5)$$

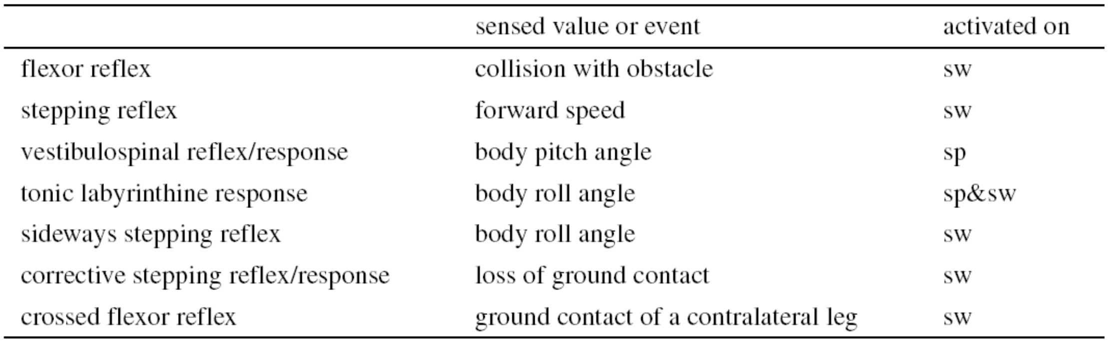
where θ is the measured hip joint angle, θ_0 is the origin of the hip joint angle in standing and k_{tsr} is the feedback gain.

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 the articles of Fukuoka (Fukuoka, Kimura, & Cohen). 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 by modifying the input of flexor and extensor neurons. 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.

3.2.1.1 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])

3.2.1.1.1 Flexor reflex

This reflex corresponds to stumbling corrective mechanism described in section 2.4.3.3. 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.

3.2.1.1.2 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" (Fukuoka, Kimura, & Cohen, 2007).

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 is modified in (5):

$$Feed_{\{e,f\}} = Feed_{\{e,f\}\cdot tsr\cdot vsr} + Feed_{\{e,f\}\cdot tlrr} \qquad (10)$$

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.

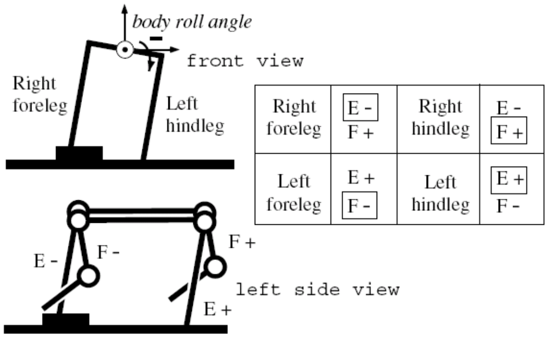


Figure 4: TLRR; E and F denote the extensor and flexor neuron of a CPG. (Reproduced from [1])

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.

3.2.1.1.3 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” (Hiebert, Gorassini, Jiang, Prochazka, & Pearson, 1994).

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.

3.2.2 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 (Liyao, Haojun, Xuili, & Zhifeng, 2003).

This model relies on the force sensing under the feet to modulate the 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 (Righetti & Ijspeert, 2007).

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 equations are:

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

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

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

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 the trajectory of the limbs, adding the control to the y_i variables will always produce a smooth output.

3.2.3 Feedback responses

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

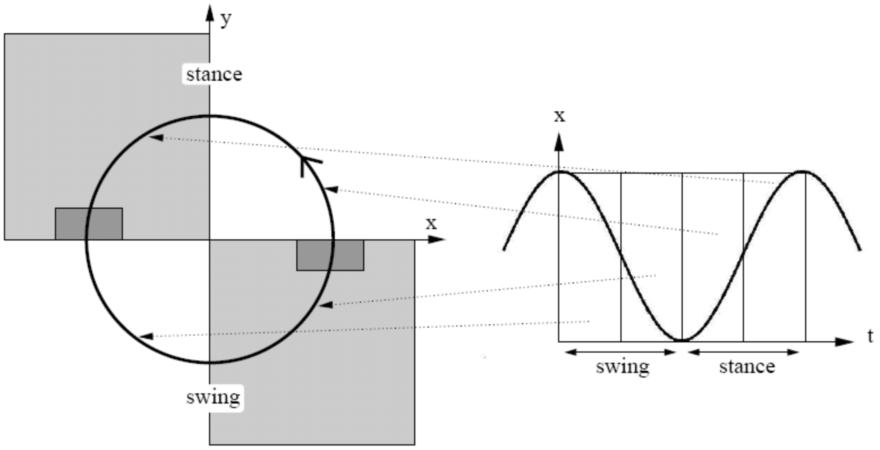


Figure 5: Phase space of an oscillator (left fig.) with its activation zone for the feedback (light gray for switch and dark gray for stop controls). The Correspondance with the x variable of the oscillator is shown on the right. (Reproduced from [7])

3.2.3.1.1 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 (Righetti & Ijspeert, 2007). 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).

3.2.3.1.2 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.

4 Model development

The development of the model is a critical part. Especially when modifying an existing model; in this case the model from Righetti (Righetti & Ijspeert, 2007). My aim is to design a feedback mechanism different that the “stop & force transition” already implemented and to try to find a feedback that could be mixed with the one already implemented. My approach has been to study a few different possibilities, choose an interesting one that could accord itself nicely with the previous feedback and find how to implement it. Finally I will have a look at new schema of the controller with a more global view.

4.1 Possibilities

Various possibilities of feedback could have been designed according to the model designed by Righetti. I will separate those possibilities according to the three main sensory pathways: higher brain efferent, cutaneous afferent and proprioceptive afferent.

4.1.1 Higher brain

The information descending from the higher brain comprises the voluntary (or conscious) movements, the auditory, visual and vestibular information. We know auditory and visual clues are used to modify the CPG response, however, those information would be a bit complex to induce a simple feedback and are highly pre-processed in the higher brain. The vestibular clues are interesting information. The vestibular clues give a certain knowledge about the overall body orientation and could effectively induce a simple feedback mechanism to improve the locomotion on inclined terrain by modifying the movement of the legs; particularly the amplitude of the legs and the knees angle.

4.1.2 Cutaneous

The cutaneous afferents bring various data such as pressure, heat, changes in texture. However the most interesting information, in the field of locomotion, is the pressure applied on the walking limbs. This information is required to know when a foot is in contact with the ground.

4.1.3 Proprioceptive

Proprioceptive information can be seen as the precise information of what muscle is in what state, however, it can also be simplified as the knowledge for each leg, of its phase state (i.e. swing, stance) and the position (timing) in this phase (beginning/end of the phase). These information usually trigger specific responses/reflexes according to other stimuli such as a foot contacting the ground.

4.2 Vestibular feedback

I chose to add a vestibular feedback mechanism to the model of Righetti because it seemed to me that it could significantly enhance the locomotion on inclined grounds and also because it should not interfere with the "stop & force transition" feedback mechanism previously implemented.

The required effect of the vestibular effect is to extend the legs which are on the downward side of the inclined slope and shorten the inward legs as already presented in 3.2.1.1.2. I differentiate the roll effect which corresponds to a left/right swinging movement and the pitch effect which correspond to the front/rear swinging movement. Those two effects are represented on Fig.6 and will be summed to obtain the final resulting behavior.

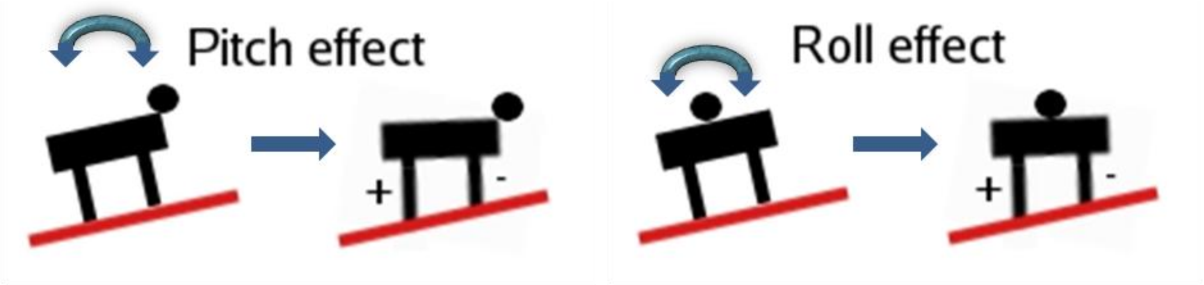


Figure 6: Effect of the pitch & roll vestibular clues

This can be retranslated in the equation of the oscillator by modifying the μ amplitude according to the actual vestibular values. Remark that in my equation, the pitch is positive when the body is inclined to the front and the roll is positive when inclined to the right. An interesting phenomenon with the vestibular clues is that they already vary in a continuous fashion so they can act on the legs without too much pre-processing; they induce a progressive modification of the amplitude and do not yield quick movement.

$$\dot{x}_i = \alpha\big((\mu + vest_{feed(i)}) - {r_i}^2\big)x_i - \omega y_i$$

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

$$vest_{feed(i)} = sigmoid(roll) * right(i) + sigmoid(pitch) * front(i)$$

$$right(i) = \begin{cases} 1 & if(i = right\_leg) \\ -1 & if(i = left\_leg) \end{cases}$$

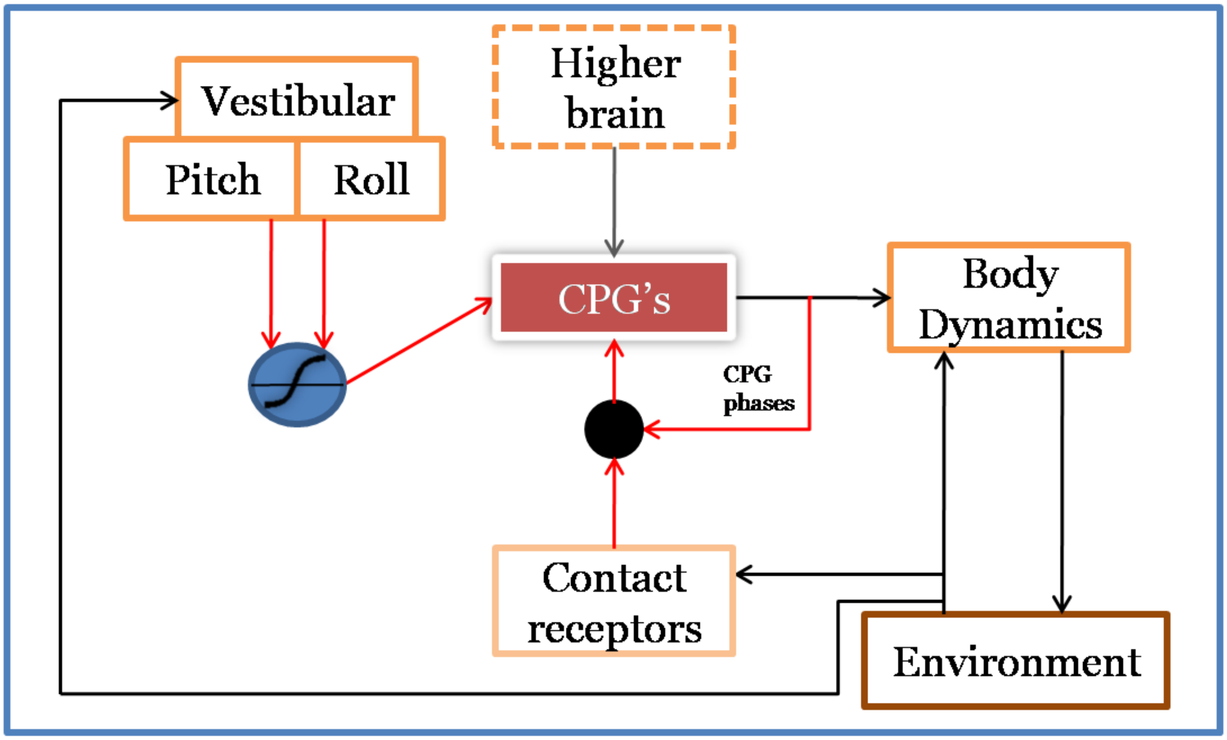
$$front(i) = \begin{cases} 1 & if(i = front\_leg) \\ -1 & if(i = hinder\_leg) \end{cases}$$

Where $vest_{feed(i)}$ corresponds to the new vestibular feedback mechanism. The right(i) and front(i) functions serve to modulate the vestibular effect according to each leg. The sigmoid function is used to modulate the response induced by the pitch and roll angles and is defined by

$$sigmoid(in) = \left(\frac{2}{1 + e^{-2*in*k}} - 1\right) * maxV$$

Where in correspond to the input value, k modifies the slope of the function and $maxV$ corresponds to the minimal negative value and maximal positive value reachable.

4.3 Model Schema



The final schema of my model shows the most important functions. The higher brain sends information (usually a periodic signal) to the CPG. These CPG are coupled and will trigger a gait movement due to the periodic signal received. Then the body reacts with the environment and will thus change the vestibular clues and also modify the contact sensors when touching the ground. The red arrows represent the feedbacks pathways that modify the CPG response. The black disc represents the black box of the "stop & force transition" mechanism implemented by Righetti. The blue disc represents the vestibular feedback mechanism due to pitch and roll clues. On this schema, both feedbacks are activated, however in my test, I often keep only one feedback mechanism enabled at a time in order to discriminate their effects.

5 Webots Implementation

I am currently working on the Webots implementation, so the following chapter only recalls the actual work done and shows some of the graphs already obtained.

5.1 Retrieving vestibular clues

The first step of the Webots implementation is to find how to retrieve the vestibular clues. My first idea was to add a GPS node (Webots Reference Manual)) for more information. As I was having troubles with the GPS, I used another solution by converting the local coordinates of the robot body to the global ones.

5.1.1 GPS node

With this GPS I should have been able to retrieve the Euler angles of the robot and thus have its vestibular clues. However, in Webots, the pitch and roll angle range seemed to depend on the yaw angle. So when I was running my simulation, the values sometimes changed suddenly by a difference of pi. This yielded a wrong feedback and disturbed the gait stability. However, I still obtained improvements of the locomotion as shown in Fig.7.

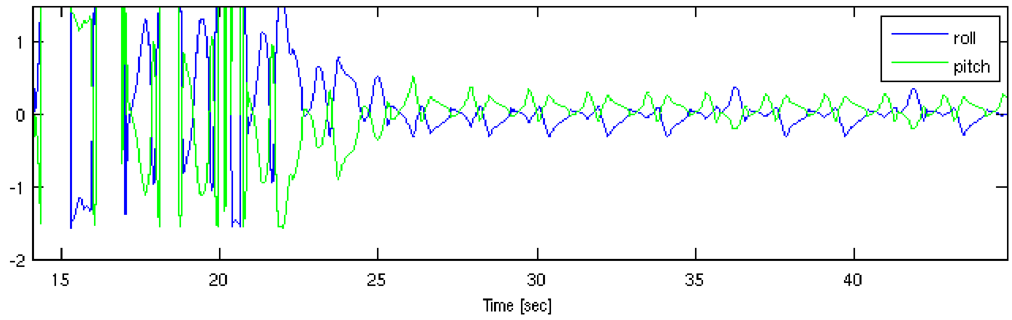


Figure 7: Roll and pitch angles in radian. The feedback is enabled after 20s.

5.1.2 Change of coordinate system

The first thing to know is that Webots allows us to retrieve the local coordinates of a node of the robot (its body in our case) at any moment of the simulation. Another point is that it is possible to convert those local coordinates in the global coordinates of the World. As we know in the global coordinates of the worlds that (0,1,0) represents the upper direction, then we just have to use some trigonometry to compute the angle that the y-axis of the body of our robot, in the global coordinates, has with this upper direction to obtain the roll angle. We can use the same mechanism to retrieve the pitch angle. I chose this method to pursue my experiments.

5.2 Flat ground experiments

In order to check the usability of my model, I first had to test if the model works on flat grounds before testing it with inclined or uneven terrains. It is also a good moment to tune the parameters of the sigmoid to modulate the influence of the feedback response and see the applicable range.

The next figures show plots of the pitch and roll angles without feedback, with only the vestibular feedback mechanism enabled, then with the feedback implemented by Righetti and finally with both of them. We can first observe the same kind of amelioration of the balance with all feedbacks compared to the plot without any feedback. We also remark a delay between activation of the feedback and the actual effect on the balance. Finally we see that both feedbacks seem to work well when they are both enabled. A better study with different plots and graphs should be done to tell more about how the designed feedback modulates the locomotion.

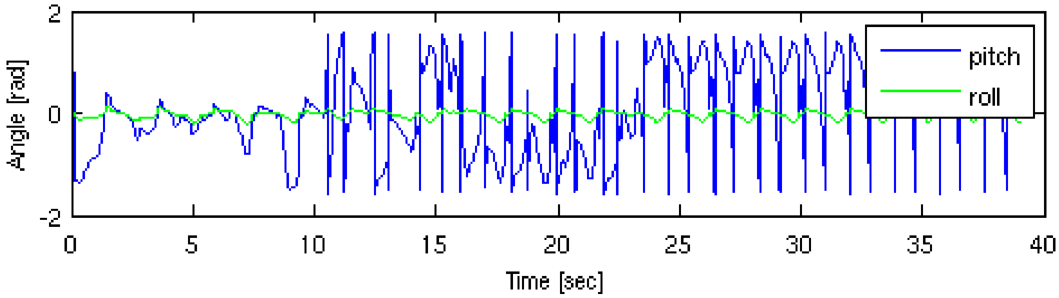


Figure 8: Roll and pitch angle. No feedback mechanism enabled.

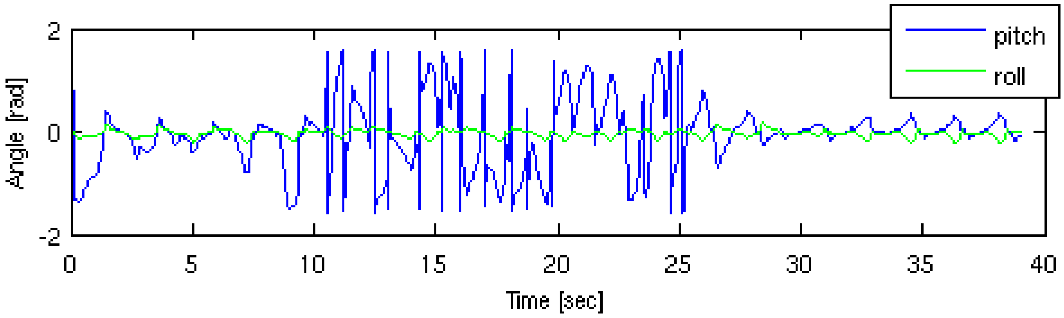


Figure 9: Roll and pitch angle. Vestibular feedback enabled after 20s.

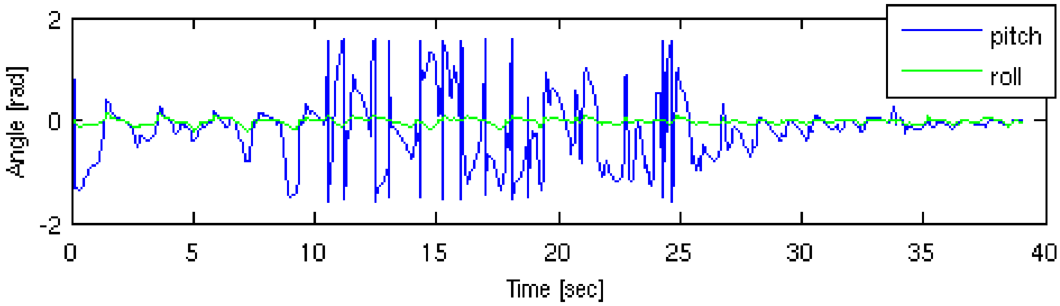


Figure 10: Roll and pitch angle. Righetti's feedback enabled after 20s.

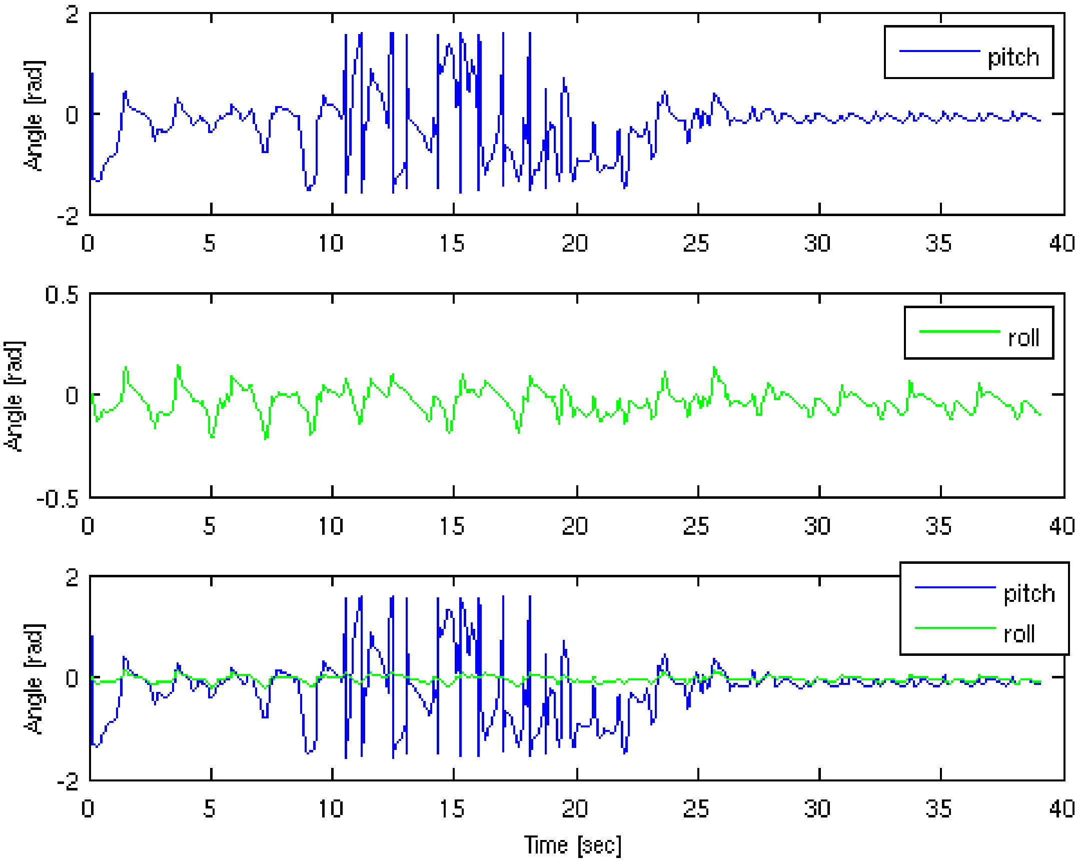


Figure 11: Roll and pitch angle. Both feedback enabled after 20s.

6 Future work

The model still has to be corrected, reviewed and tested with different obstacles and slopes to determine its robustness. Then the implementation on the real AIBO has to be done. Particularly the method to determine the vestibular clues of the AIBO from its accelerometers has to be defined. Then a study of the robustness of the real AIBO locomotion will be discussed and compared with implementation in simulation. Finally, if remaining time allows it, an implementation for a different model of robot will be done to study the portability of the model on different robots.

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